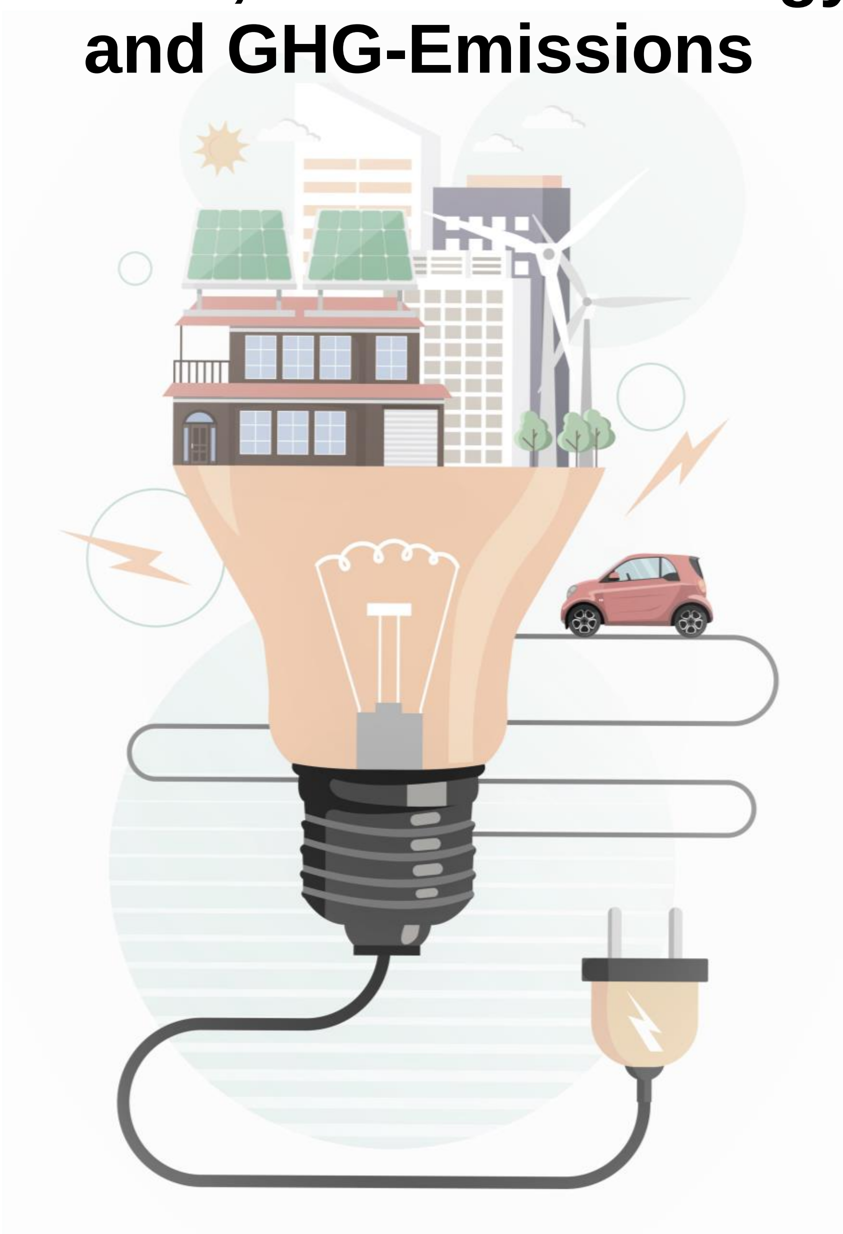
ASSET Study on

Impact of Wooden Buildings on Climate, Embodied Energy and GHG-Emissions



AUTHORS

Kjell Bettgenhaeuser (Guidehouse)

Gereon Rupp (Guidehouse)

Tom Berg (Guidehouse)

Annemarie Kerkhof (Guidehouse)

Andreas Hermelink (Guidehouse)

EUROPEAN COMMISSION

Directorate-General for Energy
Directorate for Renewables, Research and Innovation, Energy Efficiency
Unit: C2 – Innovation, clean technologies and competitiveness

Contact: Eric Lecomte

E-mail: Eric.LECOMTE@ec.europa.eu

European Commission
B-1049 Brussels

Legal Notice

Luxembourg: Publications Office of the European Union, 2020

PDF ISBN 978-92-76-26949-6 doi: 10.2833/53479 MJ-04-20-678-EN-N

About the ASSET project

The ASSET Project (Advanced System Studies for Energy Transition) aims at providing studies in support to EU policy making, research and innovation in the field of energy. Studies are in general focussed on the large-scale integration of renewable energy sources in the EU electricity system and consider, in particular, aspects related to consumer choices, demand-response, energy efficiency, smart meters and grids, storage, RES technologies, etc. Furthermore, connections between the electricity grid and other networks (gas, heating and cooling) as well as synergies between these networks are assessed.

The ASSET studies not only summarize the state-of-the-art in these domains, but also comprise detailed qualitative and quantitative analyses on the basis of recognized techniques in view of offering insights from a technology, policy (regulation, market design) and business point of view.

Disclaimer

The study is carried out for the European Commission and expresses the opinion of the organisation having undertaken them. To this end, it does not reflect the views of the European Commission, TSOs, project promoters and other stakeholders involved. The European Commission does not guarantee the accuracy of the information given in the study, nor does it accept responsibility for any use made thereof.

Authors

This study has been developed as part of the ASSET project by Guidehouse.

Lead Author: Kjell BETTGENHAEUSER (Guidehouse)
Authoring Team: Gereon RUPP (Guidehouse), Tom BERG (Guidehouse), Annemarie KERKHOF (Guidehouse), Andreas HERMELINK (Guidehouse)

Table of Contents

Executive summary

This study determines the greenhouse gas reduction potential in the European building sector by using wood as the main construction material for new buildings instead of mineral materials such as brick, stone, and concrete. The study's conclusions are summarised in the following five key findings for the EU28:

1. On an **individual building level**, >90% of greenhouse gas emissions can be saved for manufacturing and construction currently when using wood as the main construction material instead of an average mix of mineral materials – without considering the CO_2-storage effect of wood.
2. 62 Mt of greenhouse gas emissions can be avoided in the year 2050 and 827 Mt cumulatively until 2050 through the **substitution of mineral materials** in new buildings if the current wood market share for new buildings steadily increases from 5.5% in 2020 to 75% by 2050 (with the assumption of current energy mix and processes).
3. **The EU28 Forest** has significant potential to provide for additional wood use in the buildings sector. Recent studies quantify the additional capacity between 60 - 235 Mm^3 per year (on top of the current annual wood use - not only in buildings - with 700-800 Mm^3). For 75% of the wood market share approx. 90 Mm^3 would be required. However, even if wooden buildings would reach a 75% market share, the forest would still remain a net-sink.
4. In addition to the substitution effect, as a building material, **wood can store** up to 83 Mt of CO_2 in the form of carbon in the year 2050 (compared to approx. 6 Mt of CO_2 today) in the form of carbon. Over the entire time span until 2050, would buildings could accumulate a total of 1,112 Mt and continue to store it for a long time. This is quite significant compared to the GHG emissions of current buildings for the use phase, equalling approx. 650 Mt CO_{2_eq} per year.
5. The storage effect of wooden buildings could be maintained for a long time, as long as disposed or burned wood is replaced with new wood products. In this way the **"carbon sink" of the building sector** would eventually saturate, but the carbon removed from the atmosphere would be permanent. However, wood should be reused as often as possible as material to avoid the carbon content to be released.
6. In total, the substitution and storage effect account for up to 145 Mt in 2050 and 1939 Mt cumulated until 2050.
7. The emission trading system and environmental taxes are the central **EU policy instruments** regarding the promotion of wood in the construction sector, but they need to be aligned with other supporting policies.

New buildings across the EU must comply with the nearly zero-energy buildings (nZEBs) concept within the EPBD [EPBD, 2017]. As a result, the energy use and GHG emissions that occur during the use phase of new buildings is decreasing. This study shows that GHG emissions from the use phase of typical new standard residential buildings can decrease towards levels of 20%-40% when very energy efficient buildings with heat pumps are constructed with mineral materials. This shows that embodied energy for new buildings are very relevant in the overall life cycle of a building, while the challenge is to significantly reduce it.

This study conducts a **life cycle analysis for individual building and construction types**, which determines the total global warming potential in CO_2-equivalent greenhouse gas emissions over the entire life cycle of the building. The life cycle of a building includes the operation and the manufacturing of the materials as well as the construction of the building – and ideally also the later reuse, recycling, and disposal of the materials. Timber construction types such as solid wood and wood frame are considered main construction variants for buildings, whereas brick, sand-limestone, reinforced concrete, and cellular concrete represent alternative mineral constructions. These construction types are typically applied for new buildings of single-family houses, multifamily houses, and office buildings. The main output of the life cycle analysis is that the manufacturing phase of mineral building variants creates significantly more greenhouse gas emissions than it does for wooden building variants (see Figure 1 – where a concrete basement is assumed for all variants). The use-phase of all buildings is the same, therefore it is not considered here. Since the carbon content of wood (storage effect) is also accounted for, there are even negative values for the CO_2-Storage of wooden buildings. Later in the disposal phase the CO_2 is released again (by default thermal usage of wood), if the wood is not reused (which would be the best option). However, also considering the recycling potential,[1] the solid wood variant has the lowest global warming potential with nearly zero (2 t CO_{2_eq}), followed by the wooden frame construction (41 t CO_{2_eq}). If the wood could be reused again and again for a very long period, it would mean long-term carbon storage. This should be the preferred option (see also Figure 21 in chapter 3.3 on the total carbon sink of the forest and its wooden products). The mineral construction variants were much higher and do not differentiate significantly from each other (344 - 390 t CO_{2_eq}).

[1] The recycling potential considers further usage of the material in buildings/products instead of default usage in the disposal phase (thermal combustion for wood or recycled debris for concrete/stone).

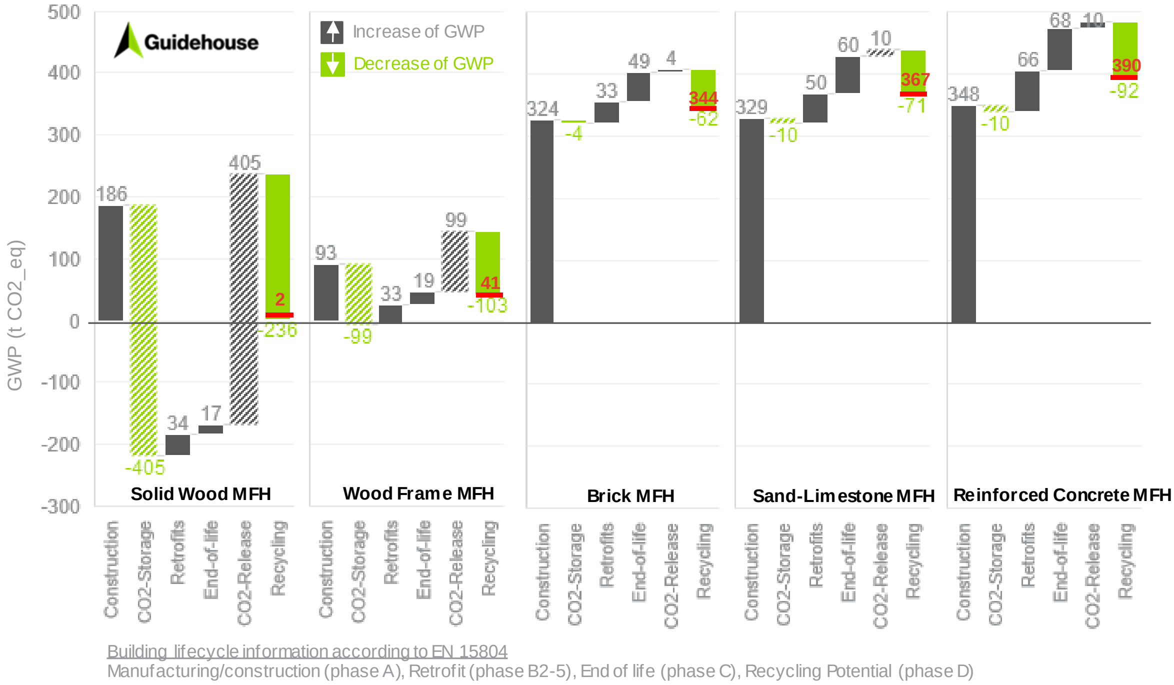


Figure 1: Waterfall Diagram on Global Warming Potential (GWP) over the Life Cycle of MFH Construction Variants without Use Phase (Source: Legep Modelling)

Based on the analysis of individual reference buildings, a **bottom-up analysis** is used in a second step to upscale the effects to the **European building sector** with increasing shares of wooden buildings. For this task, the analysis includes the Built-Environment-Analysis-Model (BEAM²) to determine the total new building activity across Europe in 2020 and in a forecast towards 2050. In this context, the availability of wood from the European Forests is also considered (chapter 3), where at least 60 million m³ are available in addition to the current usage.

Based on a recent Navigant study [Esser et al., 2019] on the new building and renovation activity across the EU, this report uses an average new building rate of 0.7% for residential and 1.1% for non-residential buildings for the analysis. The current wood building market share in the EU can be approximated with 5.5% of all new buildings in 2020. An average growth rate of wooden buildings of 3% p.a. since 2000 leads to the definition of the **baseline** pathway (see *Figure 2*). Thus, a wood market share of 13% for residential and the majority of non-residential buildings[2] can be achieved by 2050. A more ambitious wood market share leads to the **upper limit pathway**. Here the market share is growing steadily towards 15% p.a. and then decreases again when the wood market share reaches its assumed maximum. The yearly increase of the wood market share is ambitious, but also realistic.[3] By this ambitious definition, the wood market share ends up at 75% of all new buildings.

[2] *Only 3/4 of the heated non-residential building stock can be approximated with the office reference building building, the reminding 1/4 of heated floor area in non-residential buildings are not covered.*
[3] *Similar developments have been observed and also assumed for modelling in a study of heat pump potentials with the EU market [Bettgenhäuser et al., 2013].*

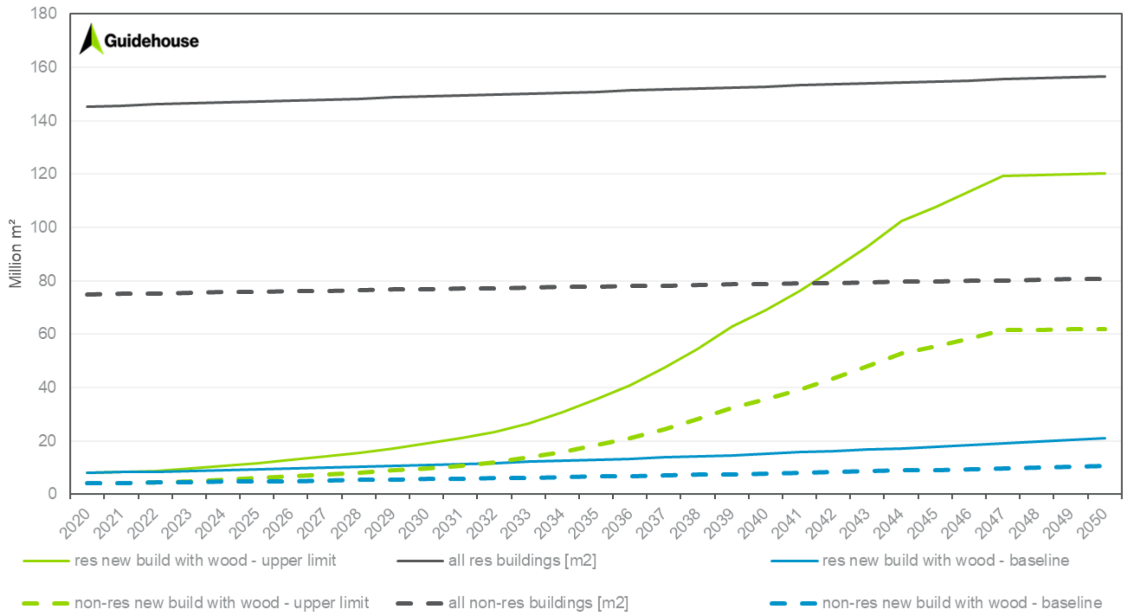


Figure 2: New buildings in the EU (residential and non-residential) and baseline/upper limit for wood market share (Source: BEAM²)

Based on this development for wooden buildings, the savings in greenhouse gas emissions are calculated over the life cycle for the buildings. Figure 3 summarises the greenhouse gas emissions of conventional building materials versus wood over the life cycle (without use phase) for new buildings in the EU28 for the baseline pathways and the upper limit pathway in steps for 2020, 2030, 2040, and 2050.

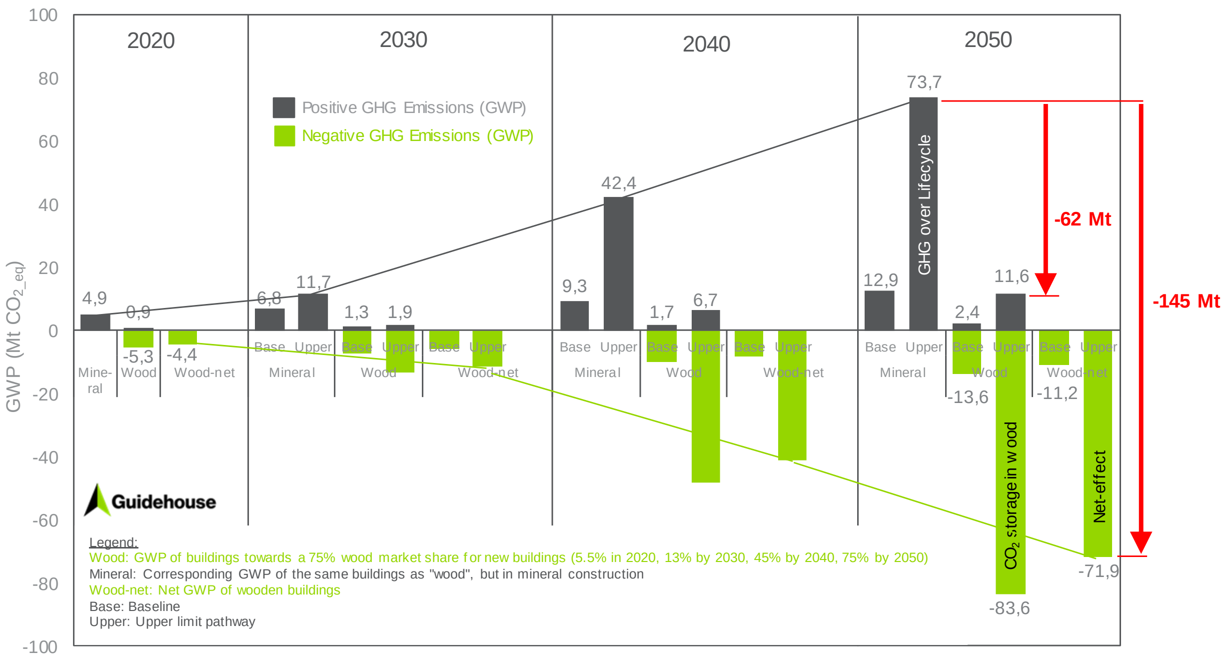


Figure 3: GWP of conventional building materials vs. wood over the Life Cycle for new buildings in the EU (Source: Legep & BEAM² Modelling)

Mineral buildings always end up with a significant positive global warming potential over their lifetime (e.g. 73.7 Mt in 2050 for the upper limit pathway = 75% of new buildings). Wooden buildings show lower positive emissions for manufacturing, retrofitting, disposal, and end-of-life cycle (e.g. 11.6 Mt in 2050), but negative emissions if the CO_2 stored in wood is taken into account (e.g. -83.6 Mt in 2050).

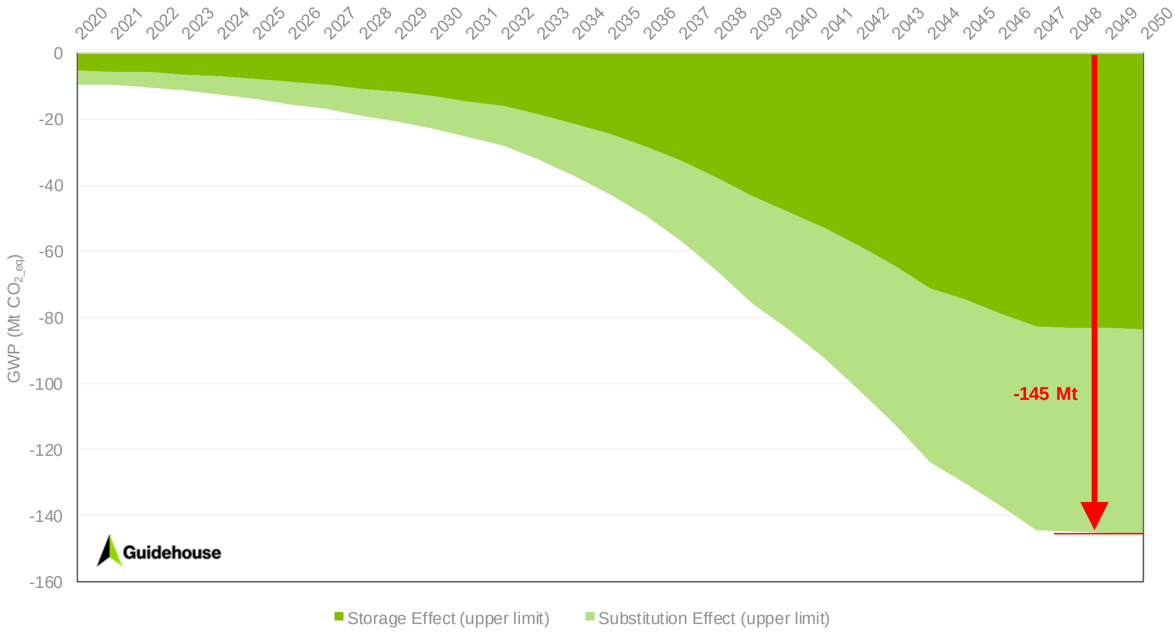


Figure 4: GWP for Substitution and Storage Effect of wood vs. mineral building material for new buildings in the EU28 – upper limit (Source: Legep & BEAM² Modelling)

The overall net-effect of wooden buildings is **62 Mt in 2050 or even 145 Mt** (if the CO_2 stored in wood is accounted for and remains removed from the atmosphere – meaning wood is reused where possible and replaced by fresh wood if reuse is not possible). This is shown in *Figure 4*, which displays the CO_2 storage effect and the substitution effect of wooden buildings for the upper limit pathway (75% wood market share until 2050). These numbers (62 Mt and 145 Mt, respectively) for the life cycle (without use phase) of the building are significant compared to the current GHG emissions for the EU building sector (use phase of buildings only), at approximately 650 Mt p.a. A "shifting baseline" for mineral and wooden buildings (e.g. decreasing carbon footprint of electricity and energy supply) would affect the mineral construction variants more than the wooden construction variants due to a higher energy demand in the production process for mineral variants.

Approximately **90 Mm³ of additional wood resources** would be required for the upper limit pathways by 2050 for solid wooden constructions (using mainly cross-laminated timber [CLT]), WF constructions (using mainly glulam and oriented strand boards [OSB]) and wooden insulation (wood fibre insulation boards ([WFIB] and medium density fibre [MDF]), see *Figure 5*. This amount is reasonable as studies show the upper limit of additional sustainable wood resources from EU forests with a range of **60–235 Mm³** per year by 2030 (see chapter 3), and more wood could be made available for saw-wood and use as glulam or cross-laminated timber from the existing use-cascade.

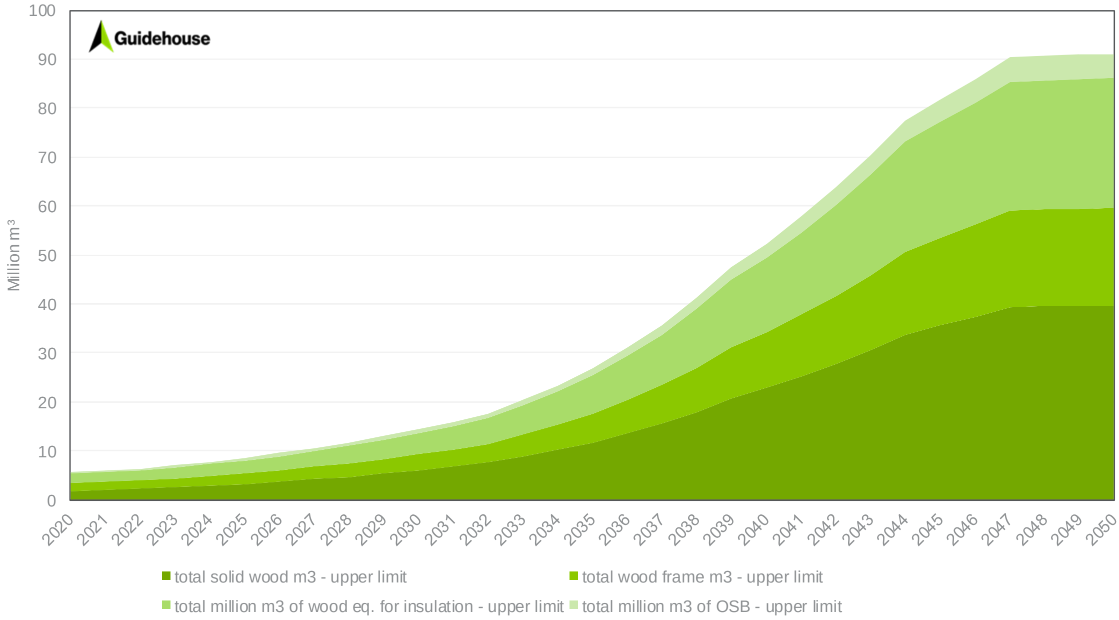


Figure 5: Total demand of wood for buildings (solid wood, wood frame, wood fibre insulation and OSB/MDF boards) for new buildings in the EU – upper limit (Source: Legep & BEAM² Modelling)

The use of wood – as well as the global warming savings potential – could be increased by applying wood products to building renovations. This would mainly affect wooden insulation such as wood fibre insulation board and medium density fibre board. However, it bears significant potential since energy efficient renovations need to take place across Europe and wood could very well replace most of the conventional insulation materials like mineral wool or EPS/XPS. Thus, including **wood as a key material** in the **EU "renovation wave"** and other activities would be very beneficial.

Introduction

Background

Building operations are becoming more and more efficient during their use phase, and the share of energy and greenhouse gas (GHG) emissions resulting from manufacturing of materials and construction processes are becoming more dominant in the building life cycle. As the legislation (primarily the Energy Performance of Buildings Directive - EPBD) focuses on the operation phase of buildings only, this aspect is not yet covered from a building's perspective. For this reason, the overall GHG footprint of buildings must be assessed and systematically reduced to align the building sector with the long-term target of a net-zero emissions system in Europe by 2050, as laid down in the European Commission's A Clean Planet for All Strategy [European Commission (EC), 2018] and supported by the EU Green Deal [European Commission (EC), 2019].

Depending on the impacts and advantages of using wood instead of mineral materials, promoting wood in the building sector can be useful to reach long-term energy and climate targets. In this case, life cycle assessment (LCA) methods would need to be further specified to quantify the embodied energy and GHG emissions of building materials and production processes, along with additional research on how to implement the life cycle perspective into regulatory law (e.g. phasing out of fossil energy subsidies and introduction of environmentally friendly taxes and emission trading systems, see chapter 4).

Goal of the Study

This study intends to (i) give an overview of the embodied GHG emissions of different building construction concepts (mineral vs. wooden constructions) and (ii) highlight the GHG reduction potential of using wood instead of mineral construction materials. The analysis over the entire life cycle covers the operation and the manufacturing of the materials and the construction of the building – and ideally the eventual reuse, recycling, and disposal of the materials.

This approach is in line with the priorities of the new EU Green Deal [European Commission (EC), 2019] where sustainable construction methods and a circular economy are key policy areas towards 2050. The European Commission's in-depth analysis regarding a net-zero emissions society by 2050 in the "Clean Planet for All" package [European Commission, 2018;] shows that circular economy and sustainable building concepts are required.

Since the availability of wood as material is a necessary precondition, the additional availability of solid wood from EU forests is also considered in the analysis. In addition to the technical impacts of wooden buildings, the EU policy framework is assessed with regard to options for improvement. Recommendations are also provided for adapting EU policies.

Overview of Methodology

This chapter summarises the methodology for the analysis within the project (see *Figure 6*). Since the GHG emission reduction potential of wooden buildings and construction elements within the EU building sector is determined by a bottom-up approach, the first step of the methodology is to conduct a life cycle analysis (LCA) of representative individual buildings in **work package 1** (chapter 2). Different building construction types like concrete, brick, stone, and wood are modelled and compared in detail with an LCA software. The full life cycle of buildings is considered, from construction via use phase until demolition/ dismantling.

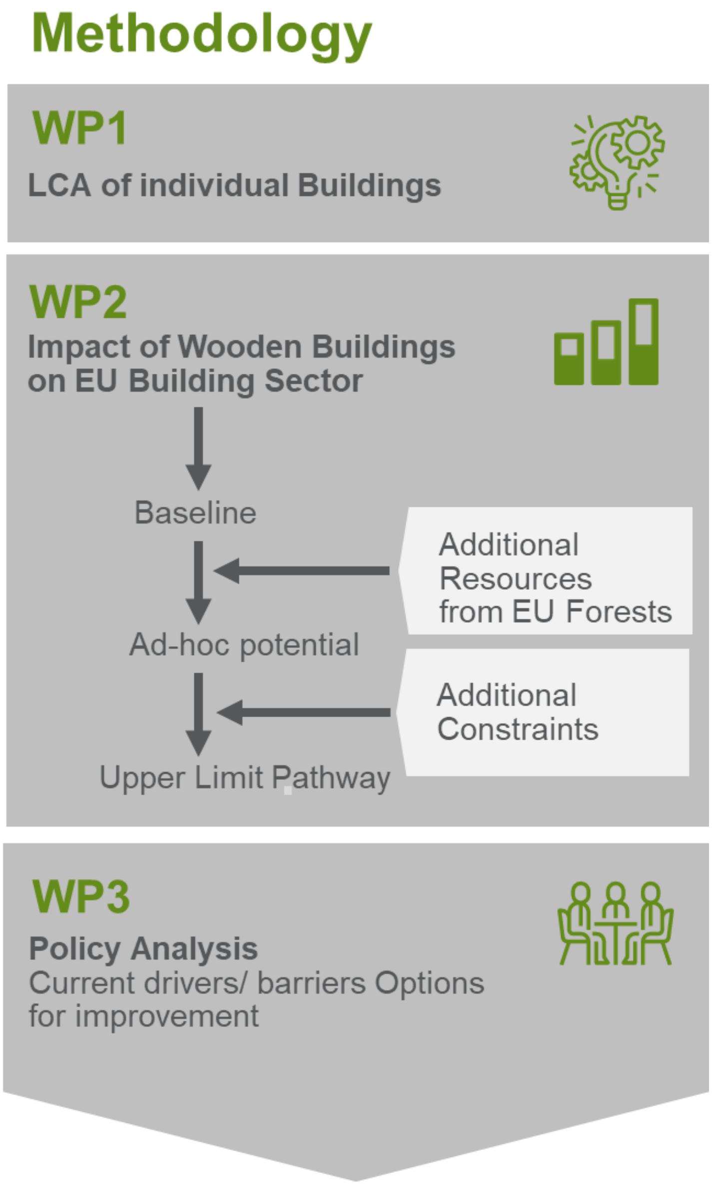


Figure 6: Overview of Methodology

Based on material mass balances, a series of environmental indicators are calculated, where the GWP in CO_2-equivalent units is the most relevant for this study.

To determine a possible uptake of wooden construction elements used for new buildings and retrofits, a baseline development of using wood in the EU building sector is defined in **work package 2** (chapter 3). Since more timber would need to be supplied from the forest sector to increase the wood market shares for new buildings, the additional available potential of wood from EU forests is analysed. Based on this analysis, the theoretical ad hoc potential of wooden buildings is derived. Additional constraints can lead to a realistic pathway and bandwidth for the uptake of wooden buildings and building elements in the EU until 2050. Examples of such constraints include the following:

- Current new building and renovation rates

- Real availability of m^3 of wood from the forest sector (includes the ramping up of capacities over the supply chain)
- Availability of craftsmen and professional planners
- The effects of a changing policy environment towards climate change

The pathways are described in detail regarding the volumes of wood used, replacement of other building materials, and the GHG savings effects for the carbon content captured within the wood itself and the GHG emissions saved by replacing other materials.

The policy framework (with regard to wooden elements and buildings) is briefly addressed in **work package 3**. In a first step, current incentives and barriers are analysed on the EU level. Based on this setup, improvement options are discussed, and recommendations are formulated towards an enabling framework.

LIFE CYCLE ASSESSMENT OF INDIVIDUAL BUILDINGS

This study analyses the climate impact of wooden buildings and building elements over the whole life cycle in terms of GHG emission reductions. The methodology and general framework of LCAs are explained in Chapter 1, while the following Chapters 2.2 – 2.5 are oriented along the stages I-IV of LCAs according to [EN ISO 14040]. *Figure 7* also depicts this framework. **Stage I** defines the overarching goal of the LCA and sets the scope of the analysis. The underlying reference buildings and constructions variants are also defined in stage I. **Stage II** represents the life cycle inventory, which consists of the mass and material balancing for all variants. This step is the basis for the impact assessment of the LCA in **stage III**. Here, the main results are calculated regarding the embodied energy and GHG emissions (GWP) of the variants. Finally, **stage IV** evaluates and interprets the results.

Key Findings of LCA on individual Building Level

- In general, a life cycle analysis consists of (i) a definition of objective and scope, (ii) life cycle inventory, (iii) impact assessment and (iv) evaluation/interpretation.
- Building life cycles are categorised in (A) product/construction stage, (B) use stage, (C) disposal/end-of life stage and (D) recycling potential stage.
- As life cycle inventories show, mineral buildings have significantly higher material and mass streams than wooden buildings (which impact the global warming potential of the construction).
- The impact assessment shows, that the global warming potential over the life cycle for wooden buildings with minimal 2 kg CO_{2_eq}/m2 compared to mineral buildings with up to 500 kg CO_{2_eq}/m2 is marginal.
- Apart from the temporary CO_2-saving effect (carbon storage) of wood the substitution effect of mineral materials accounts for the largest part of the overall global warming potential.
- For an average wooden single-family house this means 0.3 tonnes CO_{2_eq} emissions for the construction process and at the same time 42.8 tonnes of CO_{2_eq} stored in the wood itself over the lifetime, while an average mineral single-family house accounts for 73.5 tonnes of CO_{2_eq} emissions for the construction process. This seems quite a lot compared to an average CO_2-footprint of 7 tonnes for an average European citizen in 2018 according to Eurostat greenhouse gas statistics.

Methodology - Introduction to LCA

Based on the general definitions of LCA from [EN ISO 14040, 2009], the full life cycle of buildings is considered in multiple phases according to building-specific definitions in [EN 15804, 2014] from construction via use phase until dismantling, demolition, and reuse. The individual analysis determines the GHG savings for wooden buildings compared to brick, stone, and concrete concepts. The substitution effect (producing wooden building elements instead of alternatives) and the CO_2-storage within the material wood are analysed. This chapter focuses on LCA of individual buildings. A scaling up of the GHG-saving effect towards higher wooden buildings market share for new construction – also considering the available resources from the forestry sector – is elaborated on in chapter 3.

Five reference buildings for the LCA calculation provide guidance on how to determine what sustainable building material will cut GHG emissions. These variants consist of frequently used wall structures with different core elements. Two of these variants focus on timber construction (solid wood and wooden frame) and the other three on mineral construction (vertically perforated/honeycomb bricks, sand-lime stones, and reinforced concrete/cellular concrete). These variants serve as basis for the definition of energy balances, mass balances, and the calculation of the GWP saving potential.

The analysis is based on the modelling of different building construction types for multiple reference building types with the LCA software LEGEP.[4] This LCA tool is used to evaluate the GWP calculations for each of the variants. It is in line with the definitions of [EN ISO 14040, 2009] and [EN 15804, 2014]. The main result of this calculation is the GWP in terms of CO_2-equivalent GHG emissions. Finally, a basic comparison to the LEVEL(S) framework is conducted.

General Concept of LCA

LCA is a compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle [EN ISO 14040, 2009]. Therefore, it considers all product phases from mining, manufacturing, production, usage, end-of-life, recycling, and disposal. There are two main principles to be followed when conducting LCAs.

- Cross-media consideration: All potentially relevant harmful effects on environmental media (soil, air, and water) must be taken into account.
- Material flow consideration: All material flows associated with the system (raw material inputs and emissions from preliminary and disposal processes, from energy generation, transport, and other processes) must be taken into account.

According to [EN ISO 14040, 2009], an LCA can assist in:

- Identifying opportunities to improve the environmental performance of products at various points in their life cycle
- Informing decision makers in industry, government or nongovernment organisations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign)
- Selecting relevant indicators of environmental performance, including measurement techniques
- Marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration)

An LCA consists of the following four stages (see Figure 7): **(i) definition of objective and scope, (ii) life cycle inventory, (iii) impact assessment, and (iv) evaluation/interpretation**. This study is conducted along the ISO 14040 standard. It defines the objective and scope of the analysis (GHG emissions and global warming as a main indicator over the entire building life cycle), defines a life cycle inventory (mass balances and material flows), conducts the impact assessment (combination of material flows and impact categories/indicators in LEGEP), and evaluates the results of the analysis.

[4] See www.legep.de for technical details.

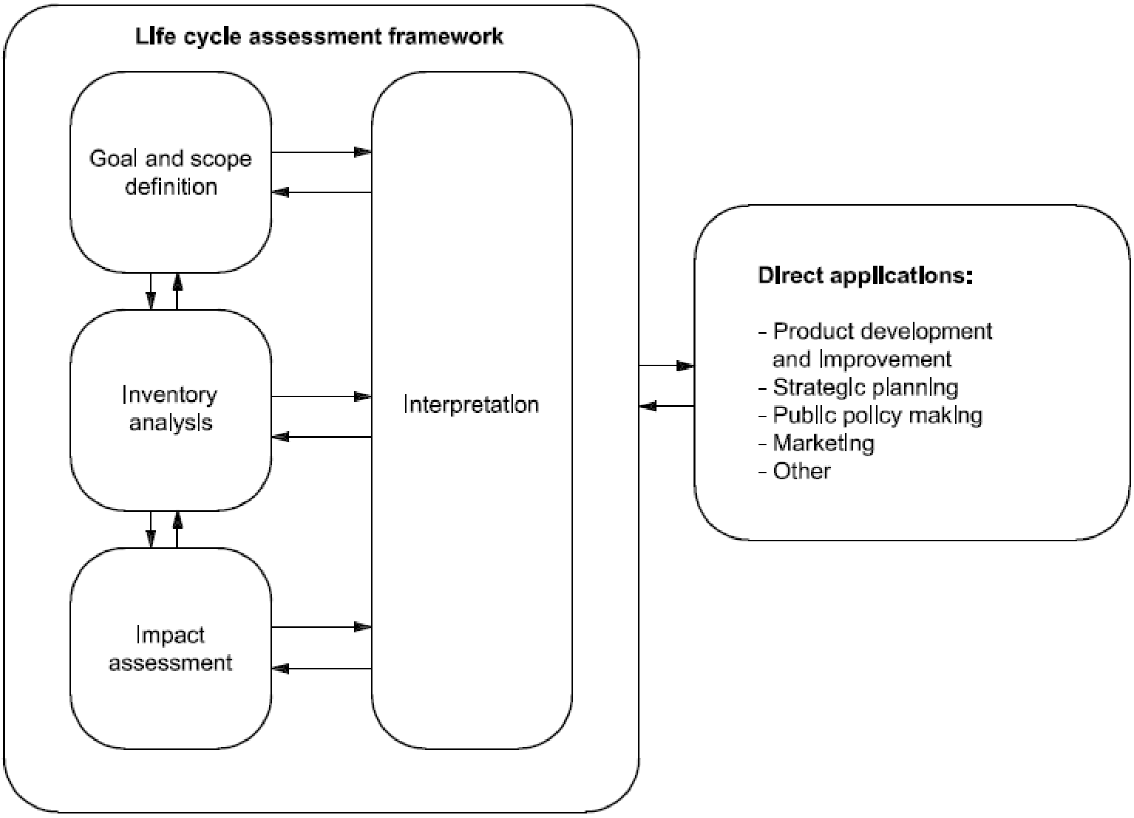


Figure 7: Stages of an LCA [EN ISO 14040, 2009]

Relevant Standards

In that framework, a range of European standards are relevant for LCAs. ISO 14040 and 14044 define general principles, a framework, requirements, and guidelines for LCAs (of all product categories in general), while EN 15804 and EN 15978 focus on the construction sector and spefify EPDs (Environmental Product Declarations) and calculation methods for constructions works:

- ISO 14040: Life Cycle Assessment – Principles and Framework
- ISO 14044: Life Cycle Assessment – Requirements and Guidelines
- EN 15804: Sustainability of Construction Works – EPDs – Core Rules for the Product Category of Construction Products
- EN 15978: Sustainability of Construction Works – Assessment of Environmental Performance of Buildings – Calculation Method

ISO 14040: Life Cycle Assessment – Principles and Framework

Since there is growing importance of environmental protection and the need to understand possible impacts of products on the environment, the interest in understanding and addressing these impacts has risen. The LCA has been developed as one of the methods to measure these impacts. International rules were created for carrying out LCAs in the ISO standards 14040:2006 and 14044:2006. These standards were then transferred into national standards.

ISO 14040 gives details and definitions on key features, scope, general principles, and phases of an LCA, Life Cycle Inventory Analysis (LCIA), system boundaries, and other relevant aspects (reporting, critical review).

ISO 14044: Life Cycle Assessment – Requirements and Guidelines
Based on the foundation of ISO 14040, the ISO 14044 standards details the methodological framework, reporting, and a critical review of all aspects regarding LCA.

EN 15804: Sustainability of Construction Works – EPDs – Core Rules for the Product Category of Construction Products
The EN 15804 standard provides basic rules for LCA of all construction products and services witin the general framework of ISO 14040. It builds the foundation of all EPDs. Construction products, construction works, and construction processes are verified and presented consistently. An EPD communicates verifiable, accurate, non-deceptive environmental information for products and their application. It supports scientifically based, fair decisions and creates an incentive for a continuous improvement of environmental quality.[5]
This European standard provides basic product category rules for EPDs for construction products and services. EPDs facilitate the selection and documentation of products during construction. They provide the basis for LCAs. The LCA-based information of an EPD typically includes the following, see Figure 8:

- Only the product stage. Such an EPD includes the provision of raw material, transport, manufacture, and related processes. This EPD is called cradle to gate6, and becomes an EPD based on the information modules A1 to A3.
- The product stage and other selected phases of the life cycle. This EPD is called cradle to gate with options and becomes an EPD based on the information modules A1 to A3, plus other selected optional modules, e.g. the disposal describing modules C1 to C4 (if the manufacturer is responsible for it). Information module D can be included in this EPD.
- The life cycle of a product according to the system boundaries. In this case, the EPD includes the product stage, construction process, use stage and inspection incl. maintenance and replacement, disposal (end-of-life) including waste treatment for reuse, recovery and recycling. This EPD is referred to as cradle to grave and is an EPD for construction products based on a LCA, which takes into account all information modules A1-C4. Information module D can be included in this EPD.

[5] *Source: [DIN EN 15804:12 + A1:2013]*
[6] *"exit gate" of the last company involved in the production process is meant.*

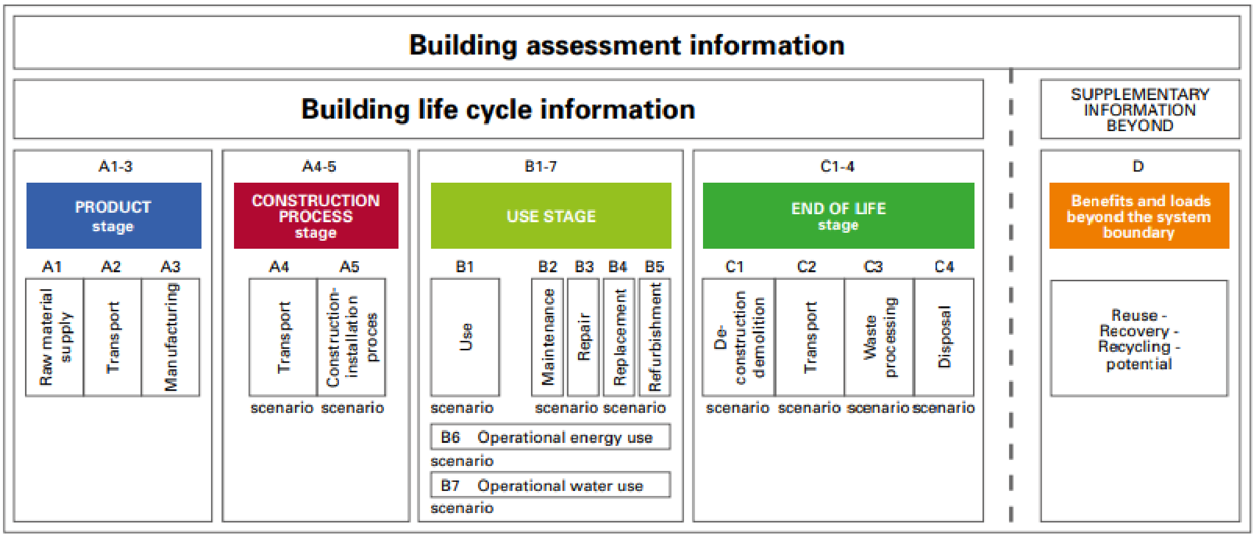


Figure 8: Lifecycle of a building according to EN 15804
(Source: [EN 15804, 2014] by CEI-Bois)

The **disposal** phase of a construction product begins with the replacing, removing, or dismantling materials from the building when they no longer has any further function. This phase can also begin with the disposal phase of the building itself. The total output from the dismantling is not considered as waste if [EN 15804, 2014] …

- …the recovered material, product, or component is commonly used for specific purposes.[7]
- …there is a market characterised by a positive economic value for the recovered material, product, or component, or a demand for it.
- …the recovered material, product, or component fulfils the technical requirements for the specified purposes and complies with existing legislation and standards for products.
- …the use of the recovered material, product, or component does not lead to overall adverse environmental or health impacts.

The disposal phase includes dismantling, transport, waste treatment, and waste disposal. Pollutions (e.g. emissions) from waste disposal are considered to be part of the investigated product system according to the polluter-pays principle. However, if such a process is used to generate energy, such as electricity and heat from waste combustion or landfill gas, then the potential credits from this usable energy are assigned to Module D (Potential after LC, see *Figure 9*). The calculation is based on average substitution processes [EN 15804, 2014]. For wooden construction material the thermal combustion corresponds to the standard scenario. Positive emissions from the CO_2-content of wood are considered, but at the same time some negative emissions from replaced fossil energy carriers for combustion. This means, that the CO_2-emissions captured by wood as material are not released right after harvest, but delayed with the lifetime of the material. If the wood is burned or rotting, the CO_2-emissons are released again. Therefore, it it important to extend the lifetime of wood as recycled material as long as possible in order to delay

[7] The "specific purpose" is not limited to the function of a particular product, but may also apply to a material used as input to the production process of another product or to the production of energy EN 15804, 2014.

the emissions as long as possible. It would make sense to focus on reusing wood as much as possible and ensuring any loss through burning is replaced with new wood. This would maximise the potentials sink. Once saturation is reached, this level of wood product stock would have to be maintained on the long-term, to avoid becoming a source of emissions later.

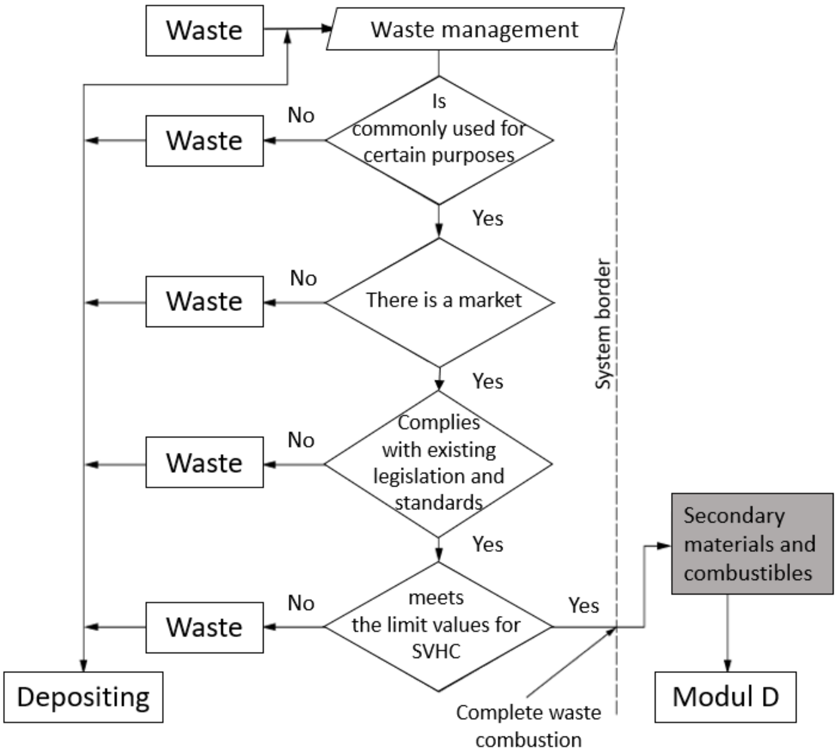


Figure 9: Decision chart for the end of the waste characteristic [EN 15804, 2014]

The **potential after LC** (Modul D) aims to provide transparency on the environmental benefits or impacts caused by recyclable products, recycled materials, or usable energy sources leaving the product system. All declared credits and debits leaving the product system that are not considered co-products and that have reached the end of their waste characteristics must be assigned to module D. Avoided effects of assigned co-products must not be assigned to Module D [EN 15804, 2014].

EN 15978: Sustainability of Construction Works – Assessment of Environmental Performance of Buildings – Calculation Method

The EN 15978 provides calculation rules for the assessment of the environmental quality (environmental performance) of new and existing buildings based on the specific framework of EN 15804 for construction work and the general framework of LCA within ISO 14040. Its calculation method is based on the LCA data, as well as tools for reporting and communicating the outcome of this assessment. It applies to new and existing buildings and to refurbishments.[8]

This standard contains

- The description of the purpose of the assessment
- The system boundaries applicable at the building level

[8] *Source: DIN EN 15978*

- The procedure used for the inventory analysis
- A list of indicators and methods for calculating these indicators
- The requirements for the presentation of results in reporting and communication
- The requirements for the data required for the calculation

This assessment approach covers all phases of the building life cycle and is based on the data taken from the relevant EPDs, their information modules [EN 15804, 2014], and other information necessary and relevant for the performance of the assessment. The assessment includes all building-related construction products, processes, and services used throughout the life cycle of the respective building.

EU Level(s) Framework

Level(s) is a voluntary reporting framework to improve the sustainability of buildings. Using existing standards, Level(s) provides a common EU approach to the assessment of environmental performance in the built environment. The buildings sector is one of the most resource consuming sectors in Europe, accounting for approximately half of all extracted materials, half of total energy consumption, one third of water consumption and one third of waste generation. That's why the buildings sector is a key target in the European Commission's policy for circular economy; a regenerative economic system in which resource and energy consumption are minimised. Level(s) is a sustainability framework of the circular economy, and offers a tiered approach to life cycle assessment. Source of this overview is [EC, 2017].

The Level(s) common framework of core indicators aims at:

- Raising awareness of, and demand for, better buildings - among the general public, developers and public procurement offices;
- Improving knowledge of resource efficiency in the built environment to support better decision making on the part of designers, architects, developers, construction companies, construction product manufacturers, investors, and building owners.

Within the framework, each indicator is designed to link the individual building's impact with the priorities for sustainability at the European level. These priorities are:

- Greenhouse gas emissions throughout the building's life cycle with a focus on production/construction phase as well as on removal/disposal/recycling phase.
- Resource efficient and circular material life cycles
- Efficient use of water resources
- Healthy and comfortable spaces
- Adaptation and resilience to climate change
- Life cycle cost and value

Each indicator within Level(s) can be used for different types of performance assessment, from a basic level through to a full Life Cycle Assessment (LCA). The entry point to Level(s) is through the common performance metrics: the simplest and most accessible use of each indicator. Level(s) sets out common units of measurement and basic calculation methodologies, which can be used by building professionals, building assessment schemes, investor reporting tools and public sector initiatives. To compare the environmental performance of buildings, at a portfolio or national level, Level(s) offers the option of comparative performance assessment. This option is suited to building professionals and owner of property portfolios. For building professionals working at a more detailed level to improve performance and optimise design and as-built performance, the design performance optimisation represents the most sophisticated use of each indicator. To minimise the gap between design, as-built and occupied performance, users can report on the indicators at different project stages: design stage (based on calculations), completion stage (based on as-built drawings), post-completion (based on commissioning and testing), and post-occupancy (based on measured performance).

A report of JRC on Level(s) explains the structure and objectives [JRC, 2017]. The Level(s) framework consists of six macro-objectives, which set goals for the contribution of buildings across the EU to environmental, health and comfort, and cost, value and risk objectives. Based on these goals, building specific indicators have been developed. In this way, users can be sure that by using the Level(s) framework, or schemes or tools that are aligned with the framework, they are contributing to meeting these goals. An overview of the indicators, scenarios and LCA tools that form part of the Level(s) framework is presented in *Figure 10*.

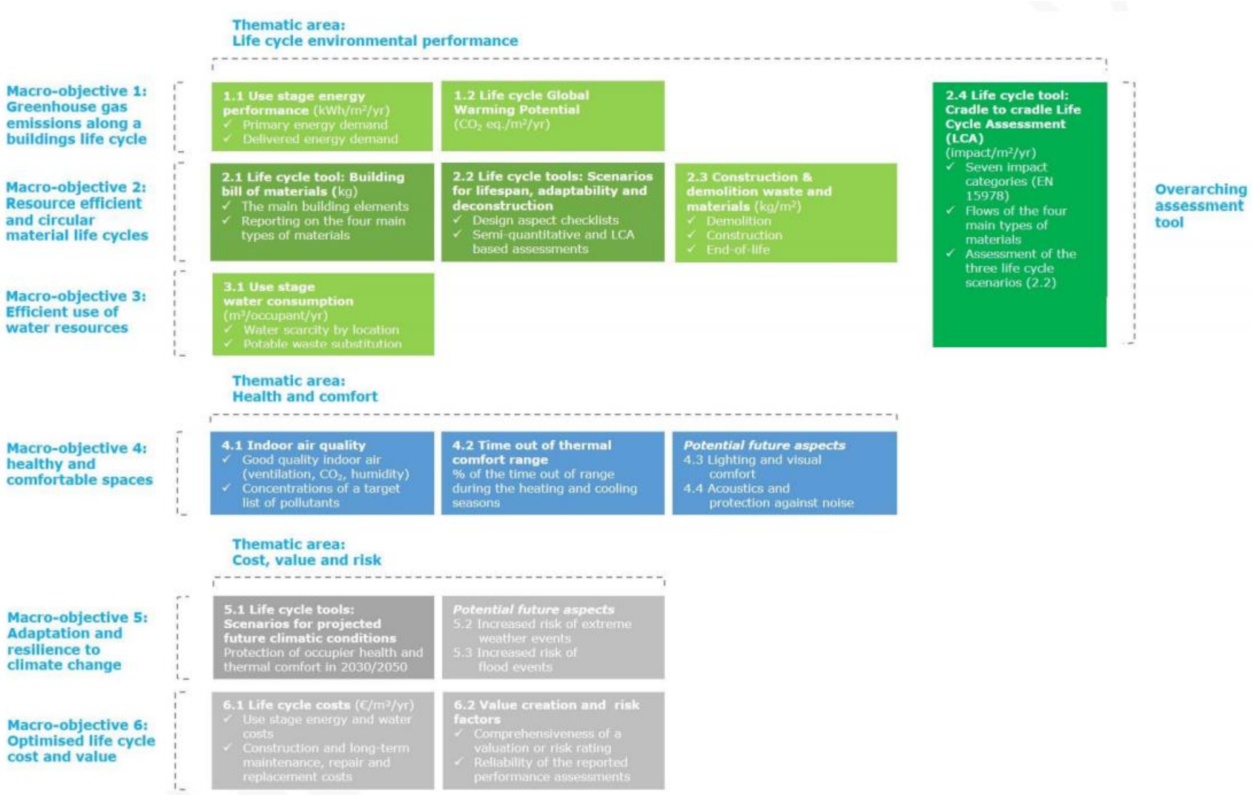


Figure 10: Overview of the Level(s) framework. Source: [JRC, 2017]

Before Level(s) can be launched on the market and start constituting a basis for different policy and business initiatives, it has to be thoroughly tested by building professionals across Europe. For this purpose, the European Commission opened a two-year testing phase for Level(s) in spring 2018. During the testing phase, stakeholders across the construction and real estate value chain, from investors, to developers, designers and manufacturers, are supported in testing the Level(s) indicators on their respective building projects. The feedback from the testing phase will inform the final version of the Level(s) framework – to be launched around summer 2020. Level(s) is being tested in more than 130 building projects in 21 countries. [JRC, 2017]

Stage I: Goal and Scope of LCA

In the first step, the goal and scope of the LCA is defined. As stated, the overarching goal is to calculate the overall impacts of the category GHG emissions for different building types over the entire life cycle. A comparison between different construction variants gives then insights on the environmental performance of these variants.
The scope of the analysis is set to three reference building types and five constructions variants. They are analysed within the general scope of EN ISO 14040 and the specific life cycle phases for buildings according to EN 15804. The following chapters summarise the reference buildings and constructions variants as well as the energy performance.

Reference Buildings and Construction Variants

Since the aim of the analysis is to determine the overall GHG reduction potential for wooden buildings and construction elements in Europe with a bottom-up approach, individual reference building cases need to be defined. In this project's framework, we use the following three reference building geometries:

- Single-family house (SFH) with 147 m^2 floor area
- Multifamily house (MFH) with 1,290 m^2 floor area
- Office building (OFB) with 6,998 m^2 gross floor area

The SFH and MFH are based on reference buildings of [Dietmar Walberg et al., 2015], while the OFB is based on a building on typical reference buildings from [Klauß and Kirchhof, 2010]. These reference buildings do not represent example buildings based on individual evaluations, but rather reflect the current construction practise across Germany and Europe. Detailed definitions of the reference buildings can be in Annex I.

As part of this study, the reference buildings are organised in the following five construction variants to analyse and compare their GHG balances:

- Vertically perforated/honeycomb bricks
- Sand-lime stones
- Reinforced concrete/cellular concrete as mineral materials
- Wooden frame constructions
- Solid wooden elements

Different thicknesses of the load-bearing layers have been defined in consultation with experts on buildings structural analysis to meet the statics requirements. The detailed definitions of foundations, basement, walls, ceilings, and roofs for the different construction variants can be found in Annex I. Since reinforced concrete is unusual for SFHs, this variant is not considered, whereas bricks and wood frame constructions are not considered as typical variants for office buildings.

The primary building materials for mineral constructions are sand-lime stones, bricks, and reinforced/cellular concrete. Regarding wooden building variants, the following wooden or wood-based construction materials are used:

- Sawn-wood: Massive wooden beams and planks, technically dried with dimensional stable properties.

- Glulam: Glued laminated timber in form of beams and sometimes also boards, which are composed of single planks.
- CLT: Cross-laminated timber elements consists of different oriented layers of wooden planks and/or beams, which are glued or dowelled together to a massive panels.
- OSB: Oriented strand boards consist of compressed layers of wood strands (flakes) in specific orientations glued together with adhesives.
- MDF: Medium density fibre boards are used similar to OSB for construction purposes.
- WFIB: Wood fibre insulation boards consist mainly of wood fibres and are used for insulation purposes.

Energy Balances

This chapter details the building energy demand for heating (energy balances) for the combinations of reference building and construction variant. The variants of a reference building are defined in a such way that the final and primary energy demand for heating is the same. This allows for a direct comparison of the construction variants and differences in GHG emissions for manufacturing and construction of the building.
The final and primary energy demand for the SFH construction variants are shown in *Table 1* with the heat transmission coefficient (u-value) of walls, windows, and roofs. They are in line with requirements for new buildings in nZEB standard. The corresponding structures and thicknesses of the components are shown in Annex I.

Table 1: Annual primary energy demand and u-values of all SFH variants

Energy	u-value wall	u-value roof	u-value win	final energy	primary energy
	W/(m²K)	W/(m²K)	W/(m²K)	kWh/(m²a)	kWh/(m²a)
Solid Wood (SW)	0,17	0,17	0,67	15,9	28,7
Wood Frame (WF)	0,17	0,17	0,67	15,9	28,7
Brick (BR)	0,17	0,17	0,67	16,0	28,7
Sand-Limestone (SL)	0,18	0,17	0,67	16,1	28,9
Cellular Concrete (CC)	0,18	0,17	0,67	16,1	28,9

Energy balances for the MFH and the office building are also be found in Annex I. While the final and primary energy per m^2 are comparable between the SFH and MFH, the office buildings values are significantly lower due to a more compact A/V ratio. Since the variants per building do not differ with regard to final and primary energy demand for the operation phase, the focus lies on a comparison between the embodied energy and GHG emissions for manufacturing and construction and on a comparison to the use phase.

Stage II: Lifecycle Inventory - Mass and Material Balances

The LCIA involves data collection and the calculation procedures to quantify relevant inputs and outputs of the system within the boundary conditions/scope of step I. For this study, the data collection done within the LEGEP software and based on the databases "Ecoinvent" and "Ökobau.dat". They provide the necessary environmental impact indicators on European level for all relevant materials within the scope of the analysis (e.g. the GWP of 1 m^3 of concrete). Furthermore, the mass and material balances per reference building type and construction variant are calculated in this step. They are the key input to the impact assessment in stage III.

The mass balance of the variants strongly depends on the material used for the construction. Since wood has a lower density than mineral construction material, the mass of the two timber variants is lower than the mass of the two mineral variants. Table 2 and the following tables and graphs provide example for SFHs.

Table 2: Comparison of the mass of the SFH variants

Material	Mass total	Mass basement	Mass above basement
	t	t	t
Solid Wood (SW)	197	127	70
Wood Frame (WF)	194	127	67
Brick (BR)	335	127	208
Sand-Limestone (SL)	349	127	222

Table 3 details the individual materials and their mass and volume per variant. Since these variants are all defined with a concrete basement, most of the mass is assigned here. The solid wood variant shows the highest amount of wood, while the wood frame variant has demand for OSB panels. For brick and sand-limestone, the respective category gives the amount of material involved.

Table 3: Masses and Volumes for main Construction Materials for the SFH variants

Material	Wood		Concrete		Bricks, Stones		Insulation		Steel		OSB	
	t	m3	t	m3	t	m3	t	m3	t	m3	t	m3
Solid Wood (SW)	40	88	136	59	-	-	5	71	6	1		
Wood Frame (WF)	16	33	136	59	11	7	7	126	6	1	6	10
Brick (BR)	5	9	195	84	102	124	3	65	8	1		
Sand-Limestone (SL)	5	9	196	85	85	61	13	101	8	1		

Since a basement is included in all variants, the overall mass is mainly determined by the amount of reinforced concrete for the basement. However, the mass-related share of renewable raw material (wood in this case) for the solid wood and wooden frame variants are with 22%-14% significantly higher than for the mineral materials brick and sand-limestone (see Figure 11).

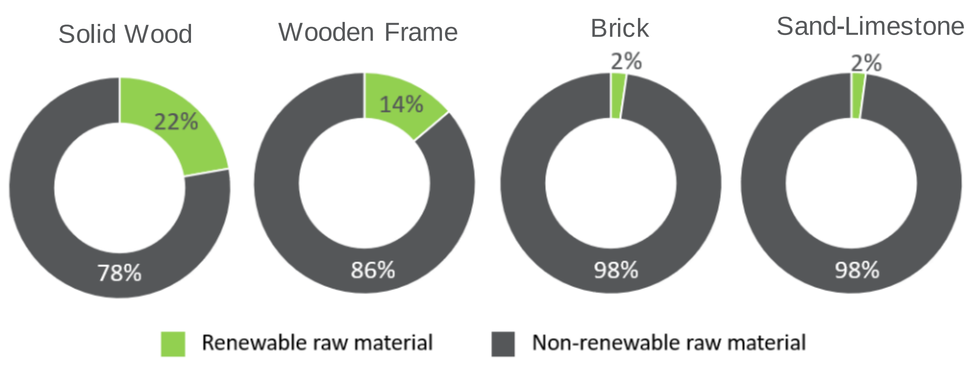


Figure 11: Mass-Ratio of renewable and non-renewable raw material of each variant related to the mass of the SFH with basement

If the basement is not considered, the material percentages shift significantly, as noted in *Figure 12*. Here the mass of wood accounts for 63% of the total mass for the solid wood variant and for 40% at the wood frame variant, whereas almost no changes occur for the mineral construction variants.

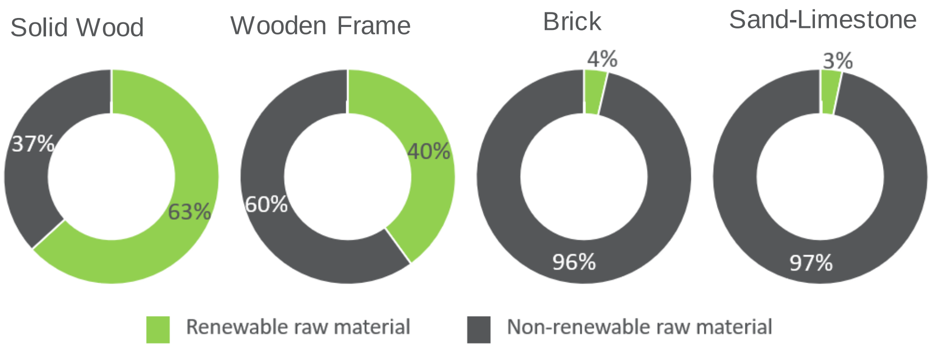


Figure 12: Mass-Ratio of renewable and non-renewable raw material of each variant related to the mass of the SFH without basement

Additional details and all data regarding the mass and material balances on the MFH and office building can be found in Annex I.

Stage III: Impact Assessment

Based on the life cycle inventory, the environmental impact assessment is the core element of any LCA. The following sub-chapters give an overview on the impact assessment results for the reference building variants. In general, the IA approach consists of a variety of environmental indicators and impact categories, but this analysis focuses on the GWP in CO_{2_eq} GHG emissions as a main indicator.
LCAs for buildings are generally structured in four phases according to EN 15804. While all process and energy-related GHG emissions during the production of components and construction activities onsite are covered be the phases A1 through A3 (including the credits for the CO_2 stored in wood), retrofits during the operation phase of the building are covered in phases B2 and B4, see *Figure 4*. In in disposal phase (C3-C4) the GHG emissions involved for the deconstruction of the building are assigned and benefits if the material can be recycled (e.g. concrete can be recycled to road base construction material) or used in processes (e.g. wood as fuel for thermal powerplants).
Overall, negative emissions can occur (i) in case of wood as building material for the temporary CO_2-storage effect (where the CO_2 is stored in the construction phase and released again during the disposal phase) and (ii) for end-of-life credits (which can cover a further usage as material - alternatively to the default usage covered in the disposal phase - and avoids new material resources).

Single-Family House

The GWP in terms of corresponding CO_{2_eq} emissions related to the different phases for SFH between the construction variants are compared in *Table 4*.

Table 4: GWP for the four SFH variants

GWP (EU Data)	Manufacturing A1-A3	Retrofit B2+B4	Dsiposal C3-C4	End of LC D
	t CO_{2eq}	t CO_{2eq}	t CO_{2eq}	t CO_{2eq}
Solid Wood (SW)	-33,2	7,50	84,80	-46,20
Wood Frame (WF)	6,2	7,50	36,80	-23,80
Brick (BR)	72,5	7,50	17,70	-16,70
Sand-Limestone (SL)	67,9	7,90	18,90	-16,40
Delta btw. SW and BR	*105,7*	*0,00*	*-67,10*	*29,50*

GWP (EU Data)	total	total	only Manu-facturing	only Manu-facturing
	t CO_{2eq}	kg CO_{2eq}/m2	t CO_{2eq}	kg CO_{2eq}/m2
Solid Wood (SW)	12,9	75,69	-33,2	-193,90
Wood Frame (WF)	26,7	156,11	6,2	36,23
Brick (BR)	81,0	473,74	72,5	424,03
Sand-Limestone (SL)	78,3	458,14	67,9	397,32
Delta btw. SW and BR	*68,1*	*398,05*	*105,7*	*617,93*

Solid wood and wood frame emit a relatively small amount of GHG emissions over the whole life cycle in the range of 75 – 150 kg CO_{2_eq}/m^2. This is compared to the mineral variants, bricks and sand-limestone, which emit around 450 kg CO_{2_eq}/m^2. The main reason for the difference is the realtively small amout of energy demand for manufacturing, transportantion, and constriction of wooden building elements and non-existent process emissions (like for cement production) in comparison to mineral construction materials and variants. The CO_2-storage effect of wood is only partly considered in the overall balance over the life cycle since the CO_2 absorbed in phase A (manufacturing) is by default released again in phase C (disposal) and only shares of the wood are assumed to go into phase D (where a material reuse is assumed as end-of-life and the corresponding CO_2 emissions are not released in the atmosphere again).
However, this changes if only the GWP for manufacturing is analysed. Since the CO_2 storage of wood is considered with 917 kg of CO_2 per m^2 of wood [Wegener et al., 2010], but not the release of stored carbon into the athmosphere, the solid wooden variant (with its high volume of wood) concludes with -193 kg CO_{2_eq}/m^2 and the wood frame variant with 36 kg CO_{2_eq}/m^2. In comparison, the mineral variants rank around 400 kg CO_{2_eq}/m^2 of of GHG emissions for manufacturing only.
Generally, the differences in CO_2-emissions of the four variants mainly depend on the ratio of renewable to non-renewable raw material. Even wooden buildings do not consist entirely of wood. For example, windows are always made of glass, floor slabs are always made of reinforced concrete, staircases are often made of reinforced concrete for fire protection reasons, and the building technology mainly consists of metal and plastics.

Multi-Family House

Table 5 shows the results for the impact assessment on MFH in terms of corresponding CO_{2_eq} emissions related to the different phases.

Table 5: GWP of the five MFH variants

GWP (EU Data)	Manufacturing A1-A3	Retrofit B2+B4	Dsiposal C3-C4	End of LC D
	t CO_{2eq}	t CO_{2eq}	t CO_{2eq}	t CO_{2eq}
Solid Wood (SW)	-218,7	34,40	422,00	-235,50
Wood Frame (WF)	-6,5	32,90	118,00	-102,70
Brick (BR)	320,6	32,60	53,10	-61,90
Sand-Limestone (SL)	318,9	49,60	70,30	-71,40
Reinforced Concrete (RC)	337,7	66,30	78,40	-92,20
GWP (EU Data)	**total**	**total**	**only Manu-facturing**	**only Manu-facturing**
	t CO_{2eq}	kg CO_{2eq}/m2	t CO_{2eq}	kg CO_{2eq}/m2
Solid Wood (SW)	2,2	2,85	-218,7	-286,29
Wood Frame (WF)	41,7	54,62	-6,5	-8,47
Brick (BR)	344,4	450,77	320,6	419,62
Sand-Limestone (SL)	367,4	480,85	318,9	417,37
Reinforced Concrete (RC)	390,2	510,74	337,7	442,03

Comparabe to the SFH results, the construction variants solid wood and wood frame for MFH emit a relatively small amount of GHG emissions over the whole life cycle, in the range of 0–55 kg CO_{2_eq}/m^2 compared to the mineral variants with bricks and sand-limestone with around 450–510 kg CO_{2_eq}/m^2. The spread between the wooden variants in relation to the mineral variants is even larger than for SFH, since for structural reasons (statics), more material is needed in the lower levels for the MFH with its five storeys above basement.

The big differences between wooden and mineral buildings mirrors SFH. The realtively small amout of energy demand for manufacturing, transportantion, and constriction of wooden building elements and non-existent process emissions (like for cement production) in comparison to mineral construction materials and variants is relevant here.

When only focusing on the manufacturing GHG emissions, the solid wooden variant shows more extreme values compared to the wood frame and the mineral variants per m². For solid wood, the manufacturing phase concludes with a negative GHG value of -286 kg CO_{2_eq}/m^2, while the wood frame variant is almost carbon neutral with -8 kg CO_{2_eq}/m^2. The mineral variants show slightly higher GHG emissions with 417–442 kg CO_{2_eq}/m^2 compared to the SFH.

Office Building

Table 6 shows the impact assessment results for the office building variants in the same way as for SFH and MFH in terms of corresponding CO_{2_eq} emissions related to the different phases.

Table 6: GWP of the three Office variants

GWP (EU Data)	Manufacturing A1-A3	Retrofit B2+B4	Dsiposal C3-C4	End of LC D
	t CO_{2eq}	t CO_{2eq}	t CO_{2eq}	t CO_{2eq}
Solid Wood (SW)	-1.631,8	256,64	3.148,31	-1.756,94
Sand-Limestone (SL)	1.710,9	266,12	377,18	-383,09
Reinforced Concrete (RC)	1.745,9	342,76	405,32	-476,66
GWP (EU Data)	**total**	**total**	**only Manu-facturing**	**only Manu-facturing**
	t CO_{2eq}	kg CO_{2eq}/m2	t CO_{2eq}	kg CO_{2eq}/m2
Solid Wood (SW)	16,2	2,60	-1.631,8	-261,46
Sand-Limestone (SL)	1.971,1	315,83	1.710,9	274,13
Reinforced Concrete (RC)	2.017,3	323,24	1.745,9	279,75

Since the wood frame and brick construction variant have not been assesst for the office building, the overview gives only results for solid wood, sand-limestone, and reinforced concrete constructions.
In contrast to the the results of SFH and MFH, the office buildings GHG emissions per m² and construction variant are not as differentiated. This is primarily due to the different design and load-bearing concept for the office building. Since the loads are centrally bundled in pillars, the outside and inside walls do not have to be desined as strong as for the other concepts, especially the five-storey multifamily building. This leads to lower materials demands on average and to a smaller GHG footprint per m² of floor area.
The GWP for the solid wood variant is near 0 kg CO_{2_eq}/m^2 while the sand-limestone and reinforced concrete variants rangk around 315–323 kg CO_{2_eq}/m^2 for the whole LCA. When focusing only on the manufacturing GHG emissions, the solid wooden variant shows negative values around -260 kg CO_{2_eq}/m^2, while the mineral variants

show significant positive emissions aground 275 kg CO_{2_eq}/m^2 for the same reasons as elaborated above.

Stage IV: Evaluation and Interpretation

The impact assessment of individual buildings is conducted for the scope of SFHs, MFHs, and office buildings with the construction variants solid wood, wood framed, bricks, sand-limestones, and reinforced/cellular concrete. Overall the goal is to compare the impact category GWP in terms of GHG emissions over the life cycle. The building shell of each variant has been defined so that the energy demand for different construction variants per building type is the same. The differences in embodied GHG emissions are directly comparable.

The main differences between the construction variants are compared in Figure 13. The columns per variant show the GHG emissions for manufacturing and construction (phase A), retrofit (phase B), disposal (phase C), end-of-life (phase D), and the total. The manufacturing GHG emissions for wooden buildings (and especially the solid wood concept with a high amount of wood) are negative compared to significant positive GHG emissions for phase A for the mineral variants. This is because the CO_2 stored in wood is included here as credit. It is fully released in the disposal phase (phase C). Here, the columns show significantly higher values for the wooden building concepts. Finally, the end-of-life GHG emissions (phase D) are accounted for and they are negative for all variants, but are significantly larger for the solid wood case. This step accounts for the use of materials, and there is more potential for solid wooden elements in comparison to wood frame buildings (with less amount of wood) or mineral buildings (where typically only the recycling of concrete and stones for road base material is an option).

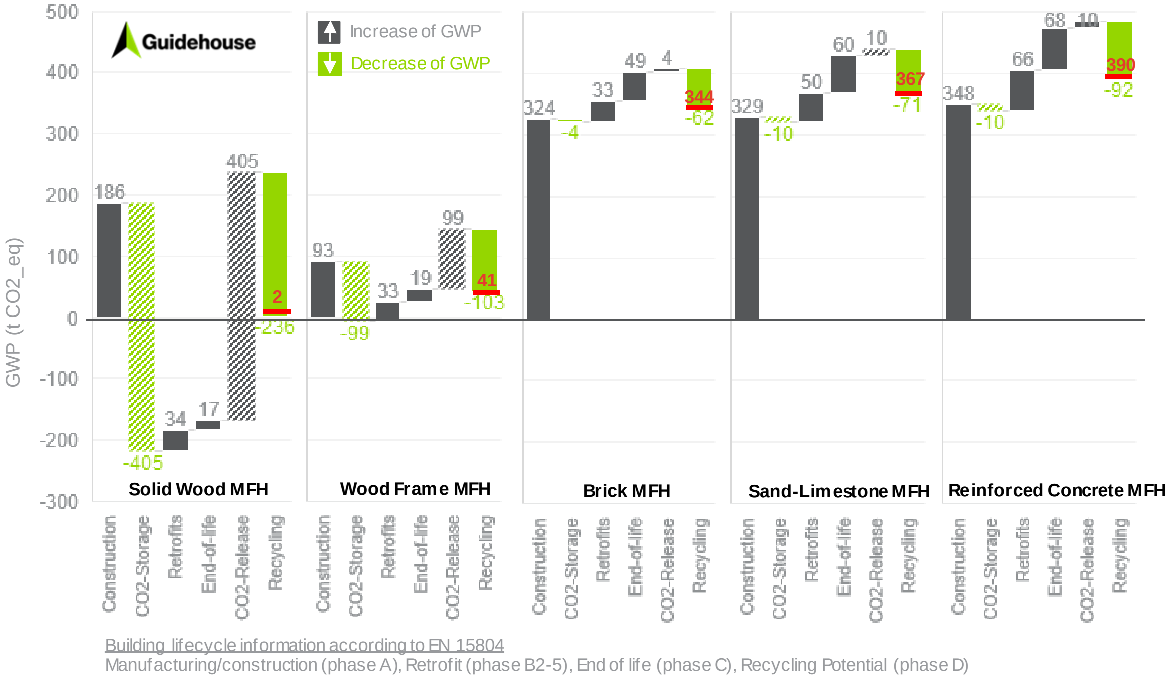


Figure 13: Global Warming Potential (GWP) over the Life Cycle of MFH Construction Variants without Use Phase (Source: Legep Modelling)

In relation to the EU Level(s) framework, the LCA of individual buildings in this chapter corresponds to the first macro-objective "GHG emission along a buildings life cycle". The overarching indicator is the GWP over the life cycle of the building, together with the use stage energy consumption. In Level(s), further objectives like resource efficient and circular material life cycles and efficient use of water resources play a role in the overall LCA context. They are also part of the full LCA within the Legep software that is used for the analysis, but they are not focus areas of the study.

Impact of Wooden Buildings on the EU Building Sector

This chapter is based on the individual building LCA from chapter 2. It shows the impact of higher wood market shares for new buildings across the EU by aggregating the individual LCA results with a bottom-up approach. Section 1 includes a baseline pathway developed based on trends regarding wood as a construction material. An upper limit pathway is developed in section 2 to show the full impact of higher wood market shares for new buildings. This step involves an analysis of EU forests (in section 3) to determine the additional amount of wood available for the construction sector as well as additional constraints for the uptake of the wood market shares across Europe. Overall, the aim of this chapter is to show the potential GHG emission savings of wooden buildings over the full life cycle of buildings.

Key Findings on EU Building Sector Level

- Currently, approx. 5.5% of the new buildings in Europe are constructed with wood as main material (with significant differences between MS)
- Main types of wooden products used for new buildings are sawn-wood, glulam, CFL, OSB and WIFB.
- In the baseline pathways, the wood quota keeps growing with 3% p.a., which leads to a quota of 13% by 2050 for residential and non-residential buildings
- This leads 2.4 Mt GHG-emissions in 2050 over the LC for a 13% wood quota, while the same buildings in mineral construction would have GHG-emissions of 24 Mt in 2050 (substitution effect).
- The potential of wood from EU forests is not deployed yet (more m³ are re-growing each year than is extracted). Depending on the study and approach 60 Mm² - 235 Mm³ of additional wood is available within the EU.
- Taking further constraints into account, the maximum realistic uptake of the wood quota is seen at 75% of the new building rate.
- The GHG for wooden buildings at that level would be 11.6 Mt GHG-emissions, while the same share of buildings in mineral construction would add up to 73 Mt GHG emissions (substitution effect).
- Together with the CO2-storage in wood, 145 Mt GHG emissions can be saved in comparison to typical mineral buildings.
- For the upper limit pathway 90 Mm³ of additional wood resources would be needed – which is a realistic scale of additional wood from EU forests.

Methodology for EU Building Sector Scenarios

This chapter determines the building sector activities and corresponding GHG emissions in the building sector. Based on new building rates, wood market shares, and definition of replaced building construction types, the GHG emissions savings are calculated for wooden buildings in the baseline. This step of scaling up results to the EU building sector is done with the Navigant BEAM² Model, which is an integrated

assessment model for the European buildings sector (see details in Annex II) and has been used from many impact assessments of the EU building sector (e.g. in the framework of the EPBD or the Smart Readiness indicator for buildings).
The overall aim of the methodology is to scale up the results from the individual LCA in chapter 2 to the European building sector and to differentiate between the **substitution effect of wood** (replacing minerals materials) in terms of GHG savings and the **CO_2 storage effect of wood** (since each m³ of wood stores 917 kg of CO_2 as long as it is in use and not burned or rotting). This is done for all new buildings in a baseline pathway with BAU trend-assumptions on the wood market shares and an upper limit pathway with high shares of wood in new buildings.

Determination of the Baseline

To determine the baseline for new buildings and the effect of wood market shares, the current picture and recent trends need to be analysed. Therefore, new building rates since 2012 are analysed based on a recent Navigant study for the EC on renovation and new building rates. Furthermore, the replacement mix of mineral buildings is determined, which can be partly replaced by wooden buildings in the future pathways. Finally, the baseline GHG emission savings are shown with the necessary (additional) wood demand for this pathway.

New Building Rates and Wood Market Shares

Based on the recent Navigant study [Esser et al., 2019], an average new building rate of 0.7% for residential and 1.1% for non-residential buildings has been observed (see details in Annex II). These figures are used as new building rates in this study (see Figure 14).

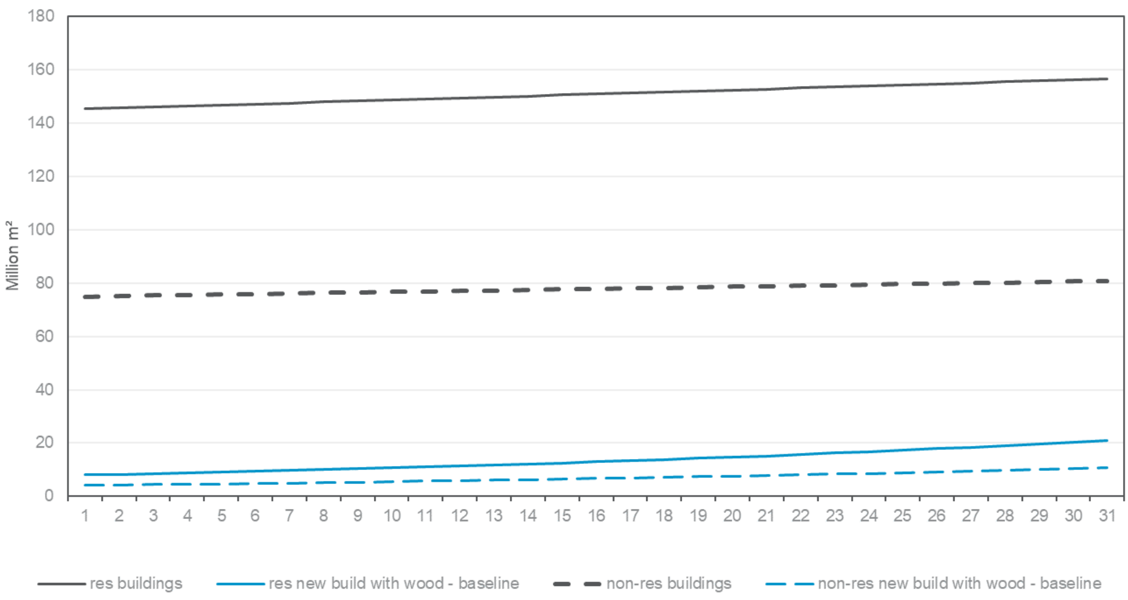


Figure 14: New buildings in the EU (residential and non-residential) and baseline for wood market share (Source: BEAM²)

The wood building market share (defined as share of all new buildings) in the EU can be approximated with 5.5% [Jakob Hildebrandt et al., 2017] of all new buildings in 2020. The average growth rate of this wood market shares of 3% p.a. [Jakob Hildebrandt et al., 2017] since 2000 leads to the definition of the baseline pathway, as shown in Figure 14. A total wood market share of 13% for residential and non-residential buildings can be achieved by 2050. The current share of wood frame buildings within the wood market share is approximately 75% across the EU, while the remainder (25%) can be assumed with solid wood buildings as the main type of construction. In the baseline pathways this share stays constant until 2050.

Replaced Building Construction Types

To determine the substitution effect of wooden buildings properly, the mix of replaced construction types must be determined. Since there is no European statistic about the primary construction materials of new buildings (on average), the German situation has been used to define the average replaced building types for wooden buildings, based on 2018 statistical values for new building permits [DESTATIS, 2019]. This leads to an average use of 40% brick, 25% sand-limestones, and 35% reinforced concrete/cellular concrete for the residential sector. While the proportion for sand-limestone is the same for non-residential buildings, a large share shifts to reinforced concrete (60% in total) and only 15% remain for bricks, as shown in *Figure 15*.

Assumption RESIDENTIAL EU	
Replaced construction mix	2018
Brick (BR)	**40%**
Sand-Limestone (SL)	**25%**
Reinf. Concr. (RC) + (CC)	**35%**

Assumption Office NON-RESIDENTIAL EU	
Replaced construction mix	2018
Brick (BR)	**15%**
Sand-Limestone (SL)	**25%**
Reinf. Concr. (RC)	**60%**

Figure 15: Replaced construction mix by new wooden buildings (Own calculations based on Destatis)

Baseline GHG Emissions

The GHG emissions from new buildings are calculated based on the new building activities for residential and non-residential buildings, the wood market share and the replaced building construction types. *Figure 16* shows the GWP over time for new wooden buildings, with a wood market share of 5.5% in 2020 and increasing towards 13% by 2050, which grows towards 2.4 Mt of CO_{2_eq} emissions.
If these buildings were built with the average mineral construction mix from above (replaced building constructions), a significantly higher share of GHG emissions would have been emitted, see *Figure 17*.

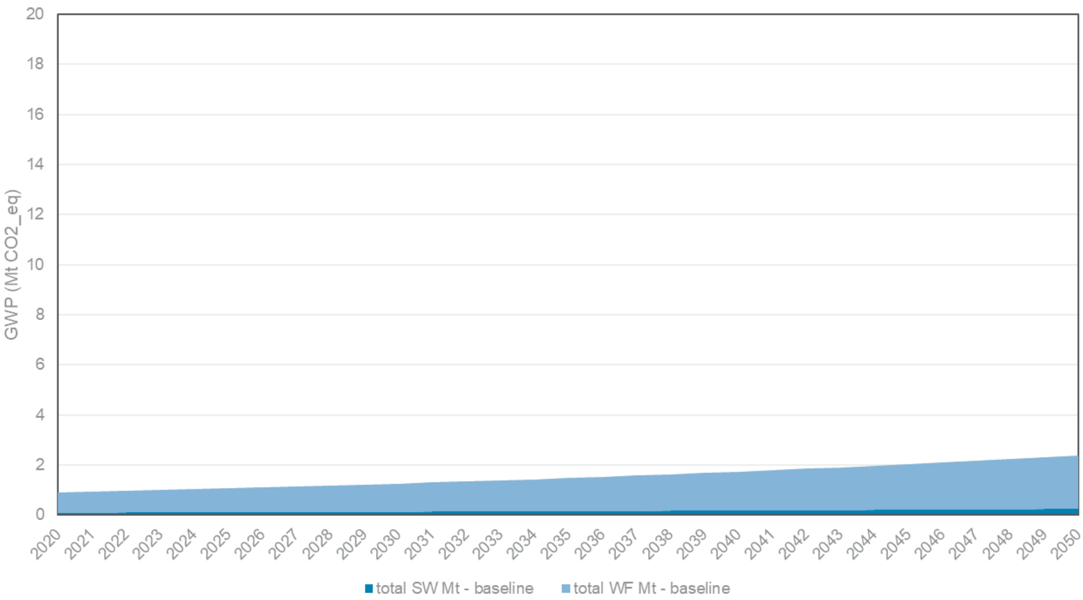


Figure 16: GHG emissions (GWP) for new wooden buildings – baseline (Source: Legep & BEAM² Modelling)

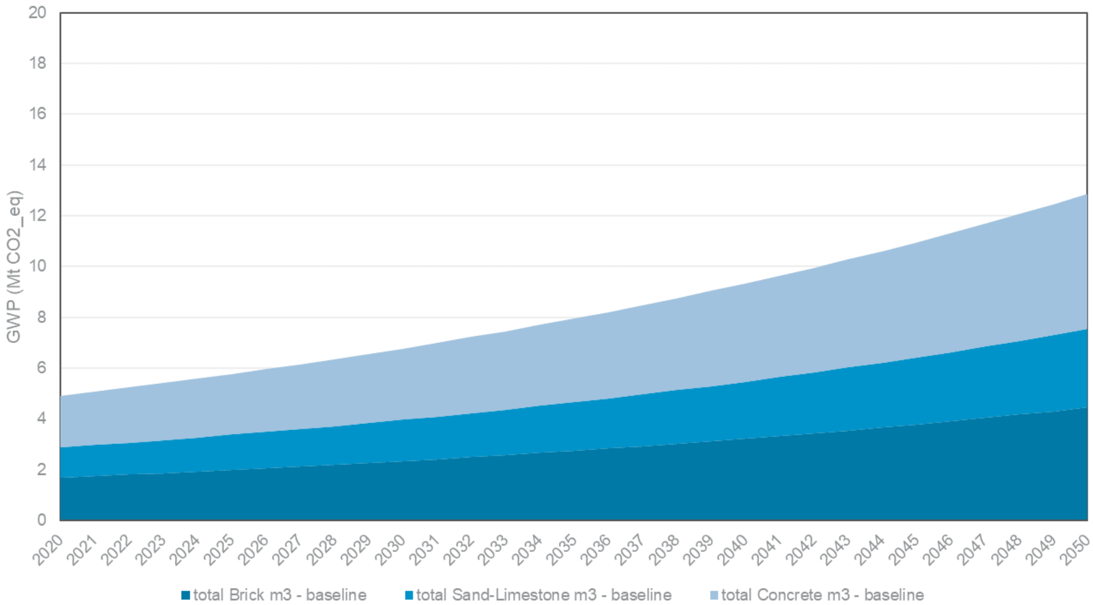


Figure 17: GHG emissions (GWP) for new mineral buildings (as alternative to wooden buildings) – baseline (Source: Legep & BEAM² Modelling)

The difference between these GHG emissions is the substitution effect of wooden buildings. It is shown in *Figure 18* with the CO_2-storage effect of wood (carbon content of wood). In the baseline, these effects add up to a total saving of about 24 Mt CO_2-eq GHG emissions by 2050.

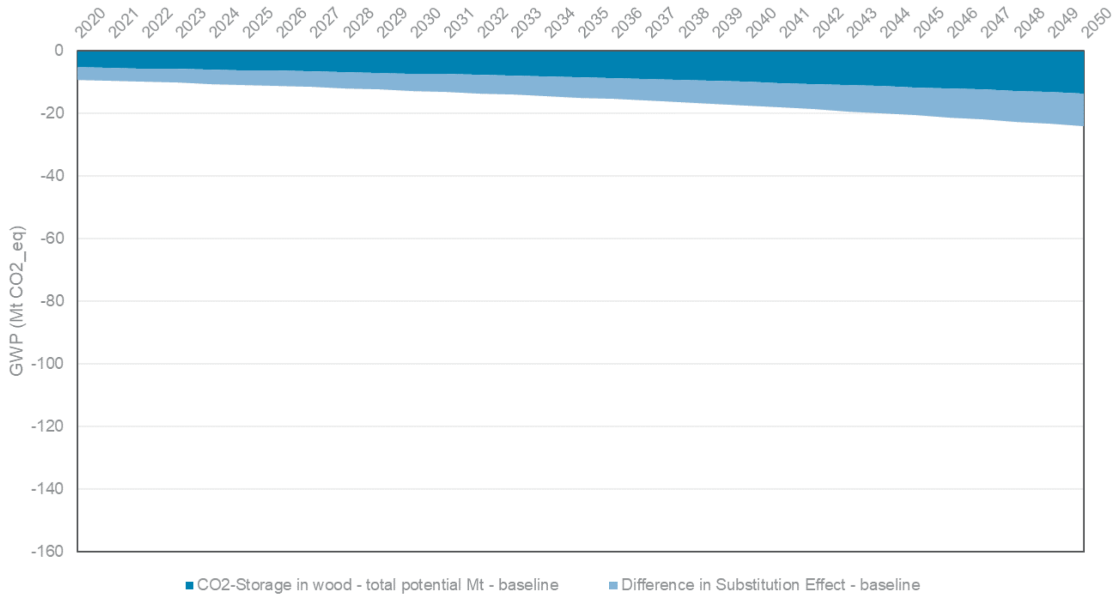


Figure 18: GHG emissions (GWP) SAVINGS for CO2-storage in wood and substitution effect due to new wooden buildings – baseline (Source: Legep & BEAM² Modelling)

To put this number into context, the overall GHG emissions of the European Building sector for the use phase of the buildings (EPBD scope) are shown in *Figure 19*. Target scenarios and shallow renovation scenarios are shown based on 2015 numbers. While the two target scenarios reach approximately 90% reduction of GHG emissions, the shallow renovation scenarios levels off at approximately 500 Mt GHG emissions. However, this figure shows that the saving potential about 24 Mt GHG emissions from the wooden buildings in the baseline scenario have a certain effect, but are not significant compared with the current emissions from usage of the buildings.

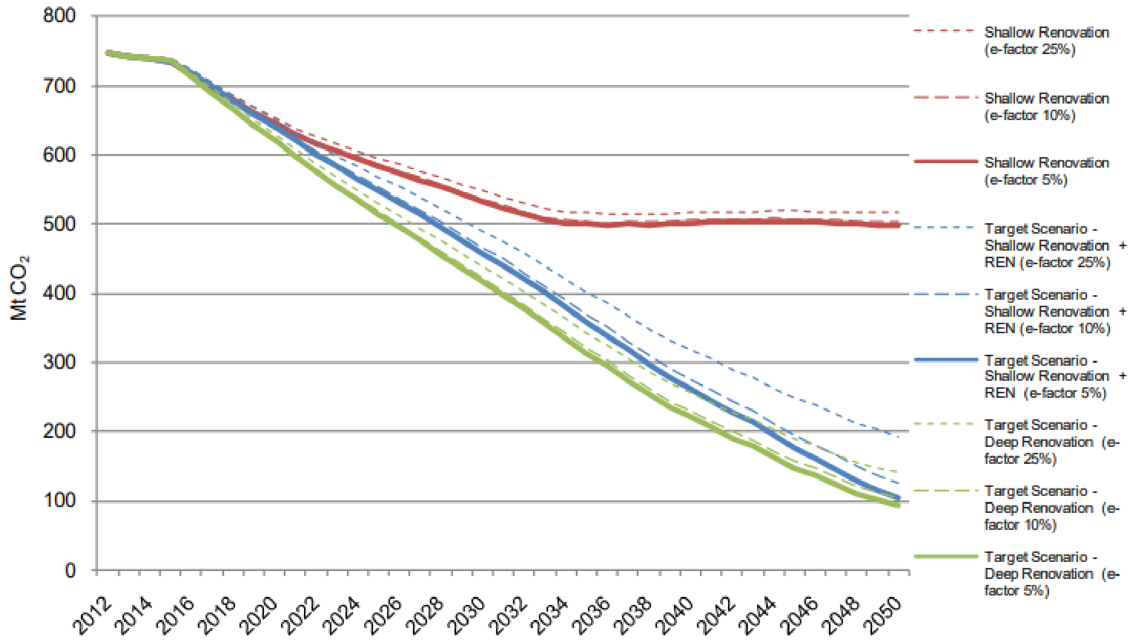


Figure 19: Total CO2-Emission of EU27 building sector, Navigant 2015

Baseline Wood Demand

Taking the baseline development into account, the overall wood demand for solid wood and wood frame buildings (which would be glulam and CLT products) and for OSB/MDF and WFIB (wood fibre insulation boards) grows towards 14.8 Mm³ by 2050. Since the EU forest can supply at least an additional 60 Mm³, the baseline increase of 3% wooden buildings per year can easily be covered.
However, a higher demand for wood and wood products is given in the upper limit pathways, as noted in the next chapter.

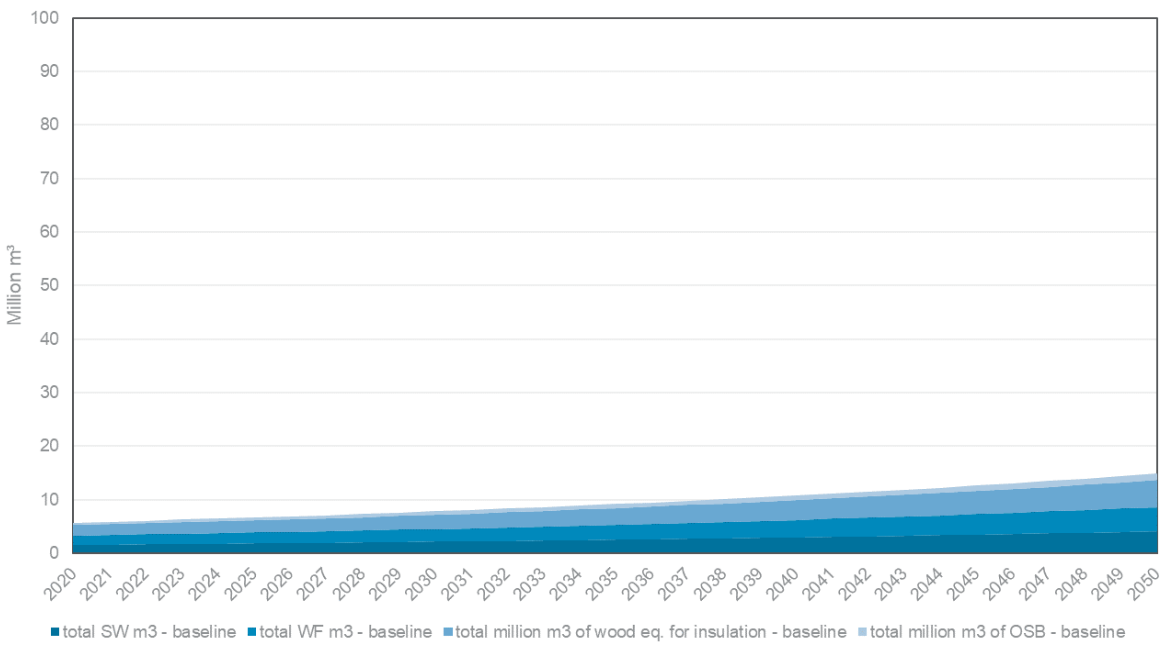


Figure 20: Total demand of wood for buildings (solid wood, wood frame, wood fibre insulation and OSB/MDF boards) for new buildings in the EU – baseline (Source: Legep & BEAM² Modelling)

Quantification of the Potential of EU's Forests

This chapter aims to answer how much timber can be extracted from the EU's forests up to 2050 for the purpose of building construction, and how much of a carbon sink this represents. Carbon sequestration in wooden products with a long lifetime, such as wooden building frames, delays the release of carbon into the atmosphere and allows the regrowth of new forests that can then again absorb CO_2. The dynamics of carbon sequestration in forests and products are explained and how the effects are measured. Subsequently, we discuss the structure and development of EU forests to 2030 and 2050 under different scenarios. Finally, we discuss the conversion and end-use sector, focusing on how much of the wood could be used for the production of end-products like sawn-wood, CLT, glulam, OSB, WFIBs, or medium density fibre board (MDF). This chapter summarises the findings, while the detailed analysis and figures on the EU forest sector potential can be found in Annex II.

Carbon Sequestration in Forests and Wood Products

Before discussing the potential of the EU's forests to supply wood for the construction sector, a common understanding of the dynamics of carbon sequestration in forests and products is necessary. Forests effect GHG balances in two ways:

- Forests absorb CO_2 from the atmosphere and sequester this in biomass, which acts as a carbon stock.
- A share of this sequestered carbon is transferred to soils through litterfall from trees or turned into wood products through harvesting.

Only a share of the harvested wood ends up in long-lived wood products, the largest part is used for bioenergy and paper and pulp. Besides the sequestration effect, wood products can use emissions savings by substituting fossil alternatives further down the value chain.

Figure 21 shows an example of the total carbon stock for a managed forest and it´s wood products. In the first period (60 year) the forest is mainly growing and the forest carbon increasing. After the first clear-cut, a significant amount of carbon is stored in the wood products produced from the forest, mainly for buildings. Therefore, also the avoided emissions by wood substitution of cement and steel are increasing. This cycle goes further on and captures more and more Carbon. However, it is most important that the wood products remain as long as possible in the building sector/ products, since a burning or rotting of these products would release the Carbon again. Wood in buildings and products that needs to be replaced and burned should be replaced by fresh wood from the forest in order to keep the carbon sink.

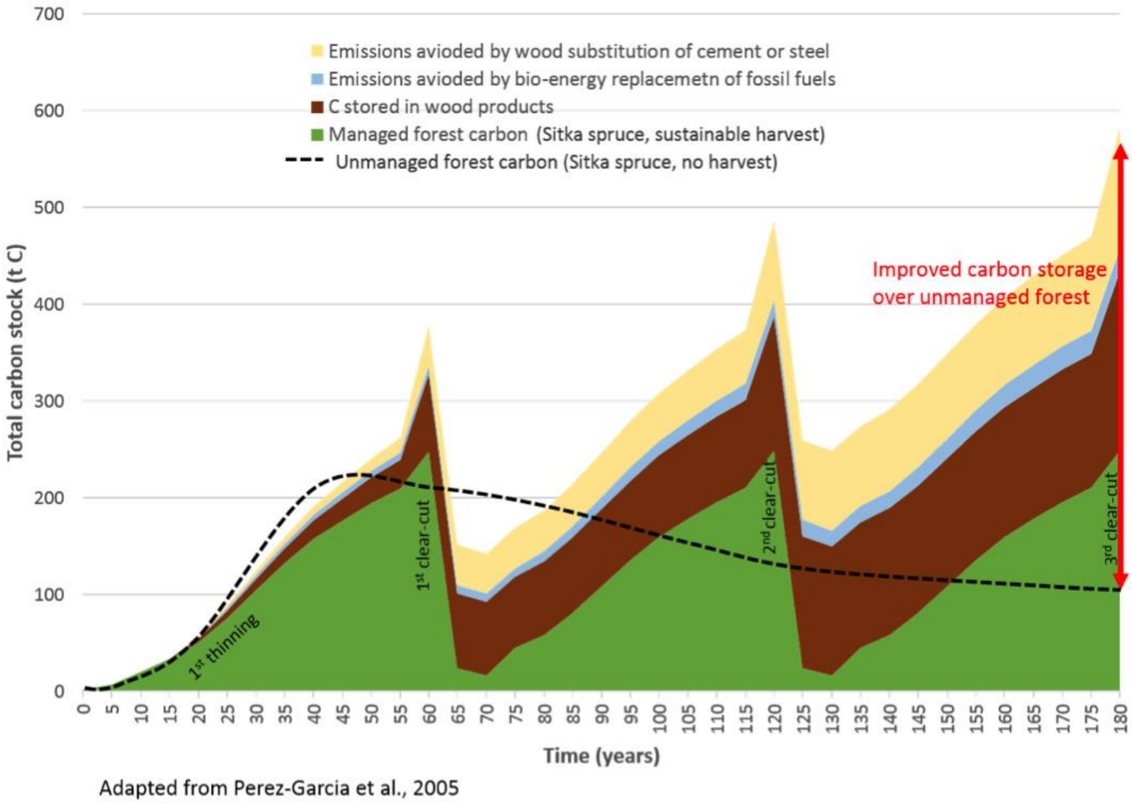


Figure 21: Total carbon stock of forest and wood products from it (Source: Forest, Environmental Research & Services (FERS)[9])

Wood Harvesting Scenarios

Various models exist that project the growth and availability of wood from EU forests, and scenario outcomes are dependent on parameters such as the assumed age structure of existing forests, harvesting intensity, rotation period of to be planted forest, forest management intensity, and climatological conditions. In Annex II a baseline is laid out for the net annual increment of wood and different scenarios for the extraction of wood from the forest. Summarising and reviewing a variety of studies (such as [G.J. Nabuurs et al., 2018; Ragnar Jonsson et al., 2018], [UNECE, 2011] , [Ragnar Jonsson et al., 2018]), we conclude that estimates vary widely depending on the assumptions and boundary conditions that need to be met, e.g. existing policies (LULUCF Regulation), demand for bioenergy, and forest management practices:

- Bottom-up studies show that an additional **60 Mm³** may become available compared to the 2015 level of harvesting at 420 Mm³.
- Studies that respect the limitations stipulated by the LULUCF Regulation show that an additional **0–140 Mm3** can be harvested towards 2050.
- Studies that explore the upper limit of wood mobilisation in EU forests, while not letting harvests exceeding the net annual increment, show an additional potential of **97–235 Mm³** by 2030.

[9] Source: https://www.fers.ie/forest-carbon-basic-facts/

Forestry Sector Impacts

This chapter explores how much wood can be made available for the construction of wooden frames and building elements, its impacts on the forestry sector, and how much carbon the wood can store. The forestry sector is relatively complex economically, with various residue streams and recovered products that need to be taken into account in the balance. *Figure 22* illustrates the flows of woody biomass and wood products for 2015 in the EU.

Construction wood mainly relies on large diameter logs, meaning the sawn-wood/sawmill subsector. Of the harvested wood entering that sector, around half ends up as a residue going to the pulp or panel industry. Wood-based construction is an important driver for raw material availability for pulp and paper and for emerging industries (such as the production WFIB for insulation purposes or wood-based packaging solutions), as sawmilling generates raw materials for these industries (wood chips, bark, sawdust, and forest residues).

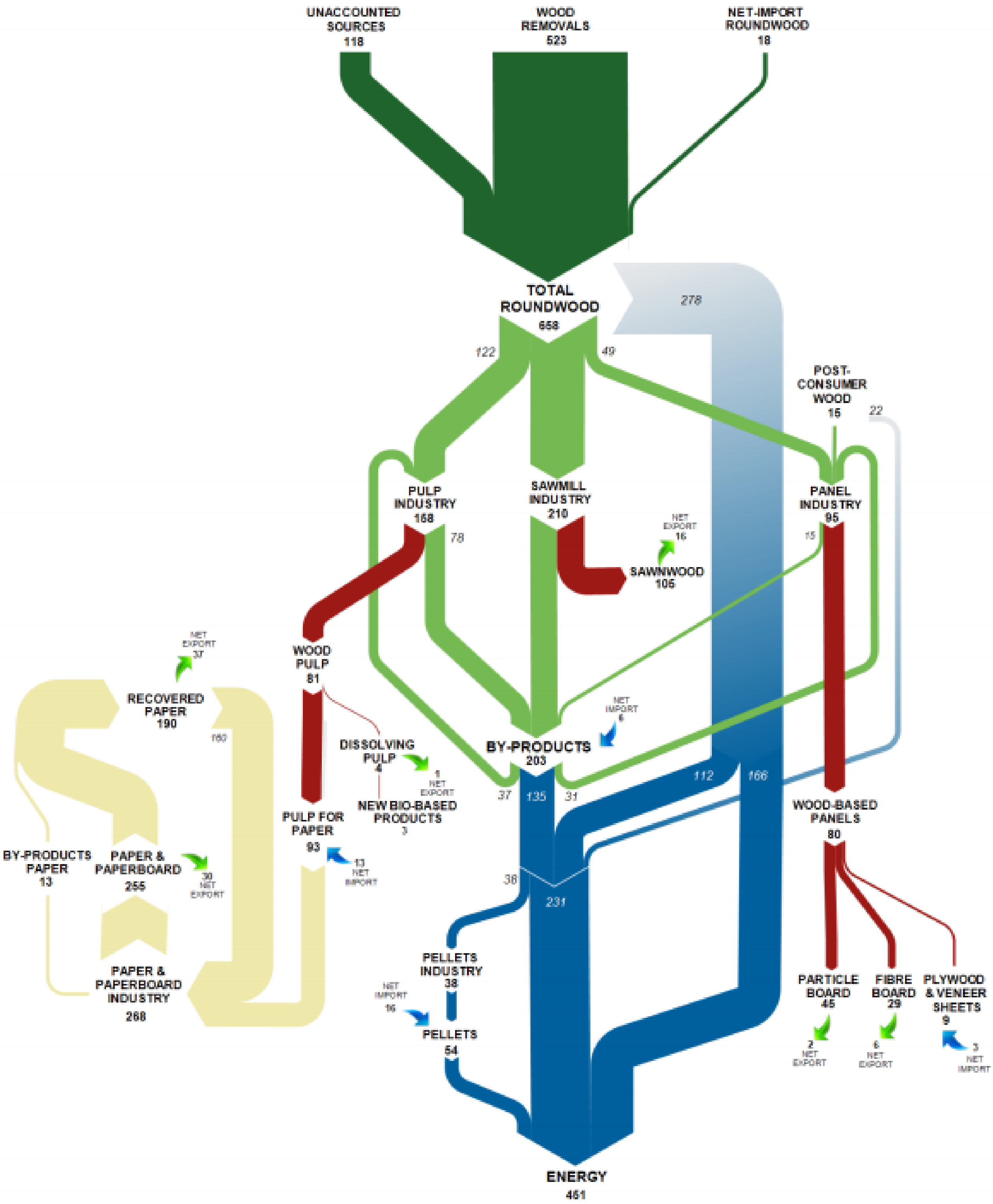


Figure 22: Sankey diagram of the EU's woody biomass balance in 2015 (units in Mm3). Source: [Noemi Emanuela Cazzaniga et al., 2019]

Wood Demand vs. Mobilisation Potential

The raw material impact of an increase in wood construction can be estimated as follows: A 100% market share of wood construction of all buildings in Europe would translate to a maximum direct annual demand of around 45–145 million m^3 of wood products, which then translates into around 100-400 million m^3 of raw wood, strongly depending on the raw material, species, production technique, and product (sawn-wood needs to be produced from log-wood, while glulam or CLT, OSB, MDF, and WIFB can also be produced from smaller logs and thinning) [Elias Hurmekoski, 2017][10].

Cross-Laminated Timber

CLT, glulam, OSB, and WFIB are the primary wood products used for modern wood construction . A CLT panel consists of several layers of dried lumber boards stacked in alternating directions, bonded with adhesives and pressed to form a solid, straight, rectangular panel. An advantage of using CLT is that the large diameter logs can be used, as well as the thinnings. Pre-commercial and regular thinning are forest management activities aimed at maintaining forest health, and the harvested wood is generally used for bioenergy purposes. However, using thinnings as a resource for CLT production can increase revenue from thinnings and improve the economic feasibility of forest management. CLT is typically made from Norway spruce. However, there is growing interest in and research on use of locally abundant, under-utilised timber resources for which there are no established structural properties as feedstocks for CLT. Examples include the use of Sitka spruce in Scotland and Ireland; Italian marine pine in Sardinia; and European beech in Germany and Switzerland [Colin M. Rose et al., 2018].

Wooden Buildings as a Carbon Sink

Wood weighs 500 kg/m^3 on average and is made up of close to 50% carbon.[11] This implies that 1 m^3 of wood contains around 250 kg C, or 917 kg CO_2. If we assume that wooden construction reaches a market volume of 50 million Mm [proHolz Austria, 2019] of long-lived wooden products, 4.6 MtCO_2 would be locked into wooden construction elements annually. This is a figure for all of Europe; however, market potential varies per region. *Table 7* illustrates that Northern Europe has the highest market potential for additional wood construction, whereas Southern and Eastern Europe have the lowest potential. This potential is based on local culture and structure of the construction sector and aligns well with the relative amount of harvests foreseen in e.g. the EFSOS study elaborated in the chapter on Wood Harvesting Scenarios.

[10] The EU building stock is renewed at a 1% annual rate – an area of 240 million m2 is built annually1 . The wood use intensity of wood construction can be assumed to vary from 0.2 m3 /m2 (light frame) to 0.6 m3 /m2 (massive frame). Thus, a simple calculation suggests that 100% of the European construction markets could be covered with 45–145 million m3 of wood products, translating to around 100-400 million m3 of raw wood (the conversion factor to roundwood equivalent (RWE) ranging from 2.0 for sawnwood to 2.8 for cross-laminated timber (CLT)). As the increment in forests available for wood supply was 769 million m3 in 2010 in EU27 (Eurostat), a 100% market share of wood construction in Europe would require a maximum of 53% of the annual growth of European forests.

Table 7: Market potential of wood construction in selected regions in Europe[12]

Region	Northern Europe	Central Europe and the UK	Western Europe	Southern and Eastern Europe
Market potential by 2030	High	Intermediate	Low to intermediate	Low
Countries	Finland, Norway, Sweden	Austria, Northern Italy, Southern Germany, Switzerland, the UK	France, Ireland, The Netherlands, Northern Germany	Czech Republic, Hungary, Poland, Southern Italy, Spain

Upper limit and bandwidth of GHG Emission Reduction

This chapter shows the impact of higher wooden building market shares (within the new building rate of the European Buildings sector) that go beyond of an 3% increase per year as defined in the baseline scenario. A theoretical ad hoc potential is described in a first step. It answers the question, *"What would happen if the wooden buildings market share would increase to 100% next year"?* Since this is not possible in practice, additional boundary conditions, constraints, and elements are discussed in a second step that brings down a possible increase of the wooden building's quota. Finally, step three defines a realistic upper limit for the development of wooden buildings and the bandwidth of possible GHG emission reductions by wooden buildings.

Ad Hoc GHG Savings Potential

To quantify the ad hoc potential of wooden buildings, the wood market share for new residential and non-residential buildings is set from 5.5% in 2020 to 100% in 2021. The effect would be 94 Mt of CO_2 stored in wood products (CO_2 storage or sequestration effect), where 55 Mt would be created by sawn-wood (as glulam or CLT), 32 Mt by insulation material (mainly WFIB and MDF), and 7 Mt by OSB boards for wood frame constructions (see *Figure 23*). The positive GHG emissions from the production of wooden buildings account for 16.6 Mt, but at the same time the and the substitution of mineral construction variants saves of 89.4 Mt. Therefore, the substitution effect accounts to 73 Mt. Together with the CO_2-sequestraton, the total net-effect for wooden buildings sums up to 167 Mt of GHG emissions.

[12] *Adapted from Elias Hurmekoski, 2017*

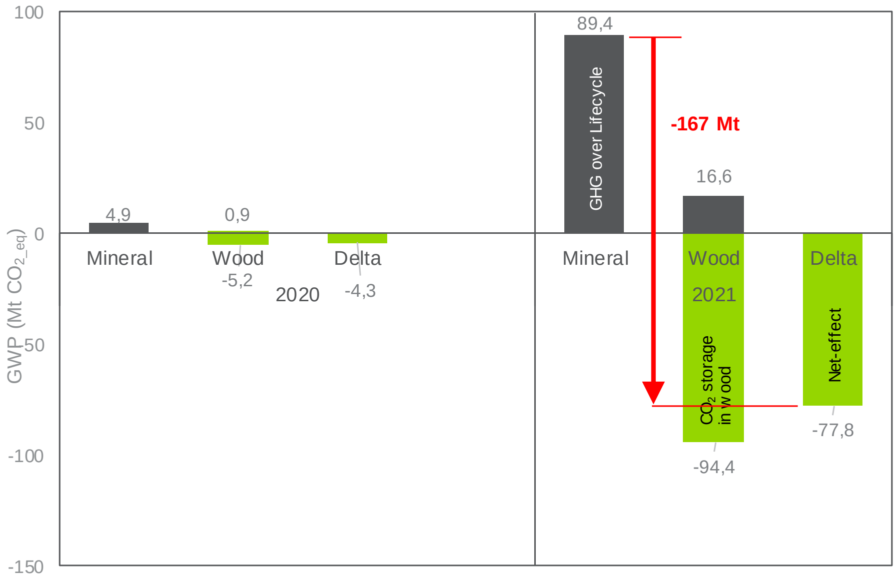


Figure 23: GWP SAVINGS of wooden building material vs. conventional for new buildings in the EU – AD HOC POTENTIAL (Source: Legep & BEAM² Modelling)

For this theoretical ad hoc potential, a significant amount of wood would be needed. Apart from 60 Mm³ for sawn-wood (glulam and CLT), 35 Mm³ would be needed for wooden insulation material (WFIB and MDF) and in addition also 8 Mm³ for OSB boards. All in all, approx. 103 Mm³ of wood. Since this is a theoretical potential, this amount is not discussed any further. The final demand for the upper limit in the realistic pathway is discussed in a later section.

Additional Constraints and Boundary Conditions for the uptake of Wooden Buildings

To define a realistic uptake of wooden buildings and the wood market share for new buildings across the EU, the following constraints and boundary conditions need to be considered. Based on this element, the upper limit of a realistic pathway is defined in the following chapter.

Availability of Resources and Production Capacities

The availability of resources from the forest sector is the key criterium of using more wood in the building sector. However, the material must be supplied on time and in the appropriate quality to replace more traditional, mineral construction types of buildings. Chapter 3 concludes that the estimates of additional available wood resources vary widely depending on the assumptions and boundary conditions that need to be met in the underlying studies. The following additional capacity is mentioned:

- Bottom-up studies show that an additional 60 Mm3 may become available compared to the 2015 level of harvesting at 420 Mm3.
- Studies that respect the limitations stipulated by the LULUCF[13] regulation show that an additional 0–140 Mm3 can be harvested towards 2050.
- Studies that explore the upper limit of wood mobilisation in EU forests, while not letting harvests exceeding the net annual increment, show an additional potential of 97–235 Mm3 by 2030.

[13] *Land Use, Land Use Change and Forestry*

- At least 60 Mm³ can be assumed available, but there may be as much as 97-235 Mm³ by 2030.

Apart from the resources, capacities and processes (e.g. manufacturing processes for CLT, WFIB and OSB) for harvesting and producing timber (sawmills etc.) need to ramp-up to increase the output of the products. Ramp-up times and capacities need to be considered, as well as the capacity in the construction sector (craftsman) and the availability of planners for wooden buildings.

Cost

Apart from technical aspects and the availability of the construction material, manufacturing costs play an important role for the attractivity and possible uptake of wooden buildings. A construction costs analysis with the LEGEP[14] software tool shows that manufacturing costs for wood building constructions are not more expensive than for traditional mineral constructions (see *Figure 24*). Prefabrication and efficiency improvements in manufacturing processes may also have an impact to bringing down cost.

However, some external costs are not included in the alternative mineral construction types (brick, stone, concrete), since carbon emissions are only factored into a small extent (via the EU-ETS). If carbon prices are increasing, prices of mineral construction types will grow faster than the prices of wooden buildings.

Manufactoring Costs SFH	manufact. costs	manufact. costs
	€/m2	€/NGF
Solid Wood (SW)	2.101	359.199
Wood Frame (WF)	2.170	371.121
Brick (BR)	2.076	355.048
Sand-Limestone (SL)	2.111	361.034
Cellular Concrete (CC)	2.322	397.137

Manufactoring Costs MFH	manufact. costs	manufact. costs
	€/m2	€/NGF
Solid Wood (SW)	1.130	863.018
Wood Frame (WF)	1.165	890.193
Brick (BR)	1.133	865.391
Sand-Limestone (SL)	1.087	830.658
Reinforced Concrete (RC)	1.290	985.632

Manufactoring Costs Office	manufact. costs	manufact. costs
	€/m2	€/NGF
Solid Wood (SW)	1.550	9.671.000
Sand-Limestone (SL)	1.547	9.656.000
Reinforced Concrete (RC)	1.639	10.229.000

Figure 24: Manufacturing costs for SFH, MFH and Office building (Source: Legep Modelling)

Regulatory Policy and Fire Safety

Regulatory policy is another criterium for realising more buildings with wooden constructions. The areas of fire safety regulation and federal building regulation define which type of construction material is allowed for what purpose in what kind of buildings. For example, it may not be allowed to use combustible materials in multifamily buildings or high-rise buildings for the facade cladding (or at least, not only this material). Whether wood as structural material or cladding is allowed to be used is dependent on the local and federal building regulations. Since these regulations are updated on a regular basis and research findings with regard to wood as construction material are also input to these processes, the potential for large and tall buildings made of wood is growing.

Acceptance and Individual Preferences

In addition to the availability of wood as material, the availability of planners and craftsman is an important driver or barrier for wooden buildings. The individual preferences of building owners and acceptance aspects are also relevant to the uptake of the wood quota.

---

[14] Construction cost are calculated and shown for Germany, based on real project costs over the years (Legep approach).

Since the discussion about environmental impacts and climate change is accelerating more and more in society, sustainable construction methods and materials with little (or even negative) GHG footprints will attract more and more people in the future. In the in-depth analysis of the [European Commission, 2018;], the EC sees circular economy as essential, enabling us to reach net-zero GHG by 2050. Wood as a construction material can be used in a circular economy, while most of the mineral and traditional building materials are not able do so (since often recycling in the sense of downcycling is possible only). This factor has significant potential to accelerate the use of wood as construction material.

Construction Time and Potential of Prefabrication
The ability for prefabrication of wooden building elements is an advantage compared to traditional onsite mineral building constructions (such as concrete or stone/brick). The construction time is much shorter due to pre-manufacturing offsite (and therefore the building is ready much earlier) and the quality is typically higher or easier to reach with manufacturing indoors in the industry environment. Furthermore, cost decrease effects due to economy of scale are likely to happen if the wood market share keeps increasing.

Limits of Conventional Mineral Construction Types and Materials and Climate Targets
There is no way to stick to the mineral construction methods of today (and the past) if the construction sector is going reach climate targets. The main reason for this is that during the manufacturing of cement (as part of concrete and mortar), more than 50% of the GHG emissions do not occur due to the energy input to the process, but due to chemical processes in the materials production.

Realistic Pathway: Additional GHG Savings Through an Uptake of Wooden Buildings

Based on the theoretical potential of wooden buildings for new residential and non-residential houses across the EU and the additional constraints and boundary conditions to increase the wood quota, a realistic pathway is developed to show the bandwidth of possible uptakes and their impacts with regard to the GWP in terms of GHG emissions. The realistic pathways is defined by the baseline as lower limit and the upper limit as maximum realistic uptake.

The GHG emissions savings for wooden buildings in the upper limit pathway are calculated based on the new building rates and assumptions for the upper limit of the wood quotas. They consist of the substitution effect of wooden buildings (replacing mineral building constructions) and the CO_2 storage effect of wood.

New Building Rates and Wood Quota
The new building rate is considered the same as for the baseline scenario, based on a recent Navigant study, [Esser et al., 2019] which is 0.7% in average for residential buildings and 1.1% for non-residential buildings.

The wood building market share in the EU can be approximated with 5.5% of all new buildings in 2020 and a growth rate of wooden buildings of 3% p.a. since 2000. Compared to the baseline, where the same growth rate is assumed until 2020, a more ambitious definition the wood market share leads to the upper limit pathway. Here the market share is increased steadily towards 75% by 2050, based on a growth rate that is increasing towards 15% p.a. by 2031 and then falls again (see *Figure 25*). Only 75% of the heated new non-residential buildings are covered in the calculation, since they can be approximated with the office reference buildings. The remaining 25% of heated non-residential and all non-heated non-residential buildings are not covered by the calculation. The yearly increase of the wood market share is ambitious, but also realistic. The additional constraints and boundary conditions allow for such a growth rate as upper limit, and similar developments have been observed and assumed for modelling in a study of heat pump potentials with the EU market [Bettgenhäuser et al., 2013]. These assumptions lead to the new building rates and wood quotas, shown in *Figure 26*.

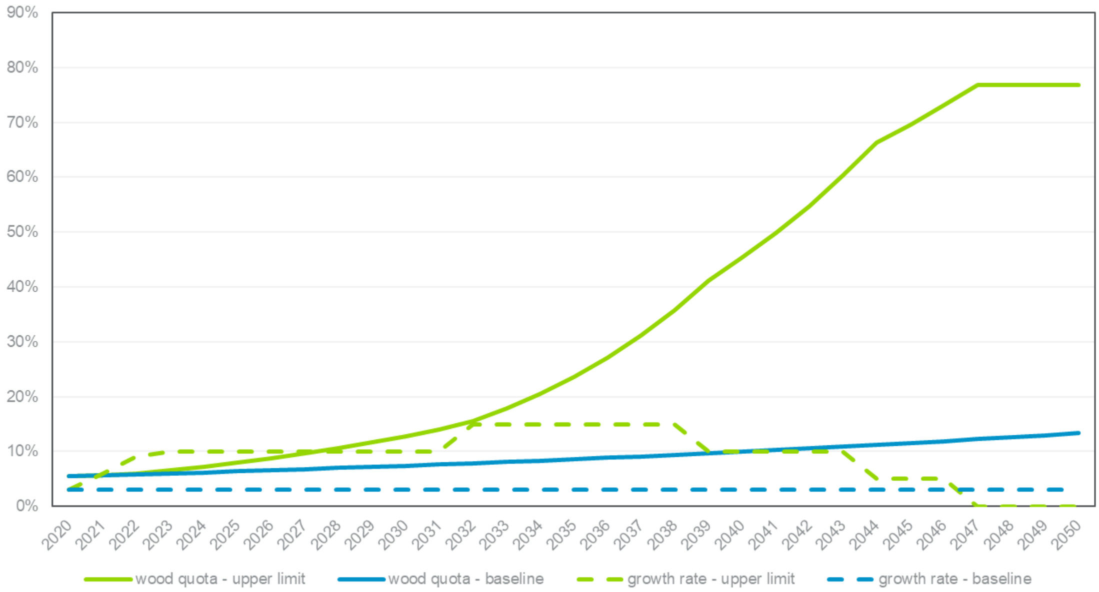


Figure 25: Wood market share for new buildings and it´s growth rate – baseline and upper limit pathway (Source: BEAM² Modelling)

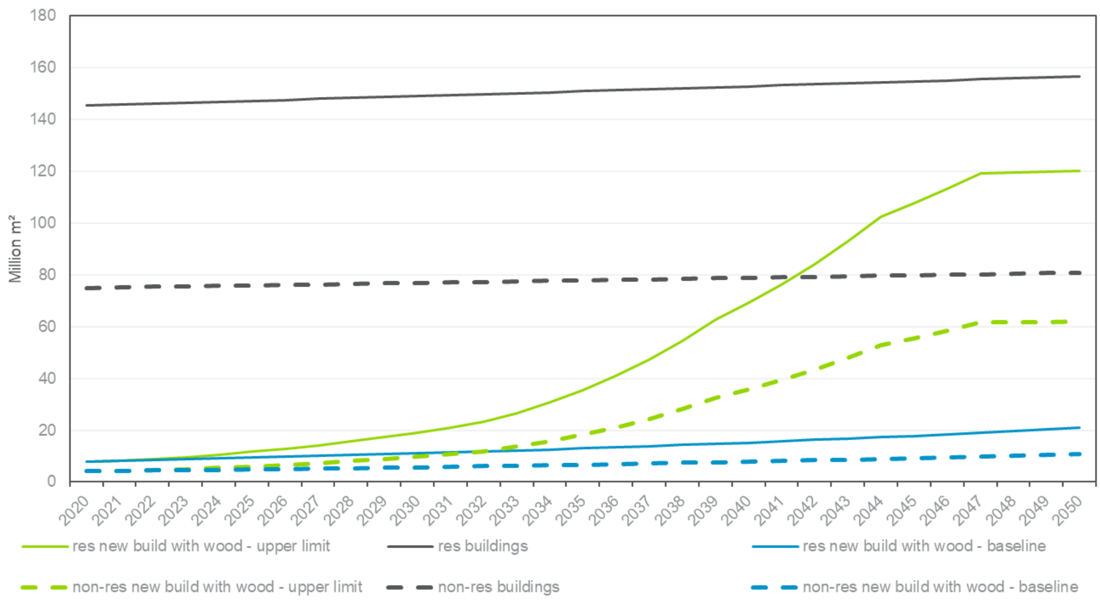


Figure 26: New building rates for residential and non-residential buildings in the EU and corresponding wood market shares – baseline and upper limit pathway (Source: BEAM² Modelling)

While the share of wood frame buildings is constant in the baseline with 75% within all wooden buildings, it decreases by 2.5% p.a. in the upper limit pathway until it reaches 50% for wood frame constructions and 50% for solid wood construction types. The assumption of the replaced building types (mix of mineral building constructions) is the same as for the baseline.

GHG Emissions for Upper Limit Pathway

Based on the new building activities for residential and non-residential buildings, the wood market share and the replaced building construction types, the GHG emissions from new buildings in the upper limit pathway are calculated. *Figure 27* shows the GWP over time for the upper limit pathway. The underlaying wood market share starts with 5.5% in 2020 and increases up to 75% by 2050. By than year 11.6 Mt of CO_{2_eq} emissions would be emitted for the wooden buildings.

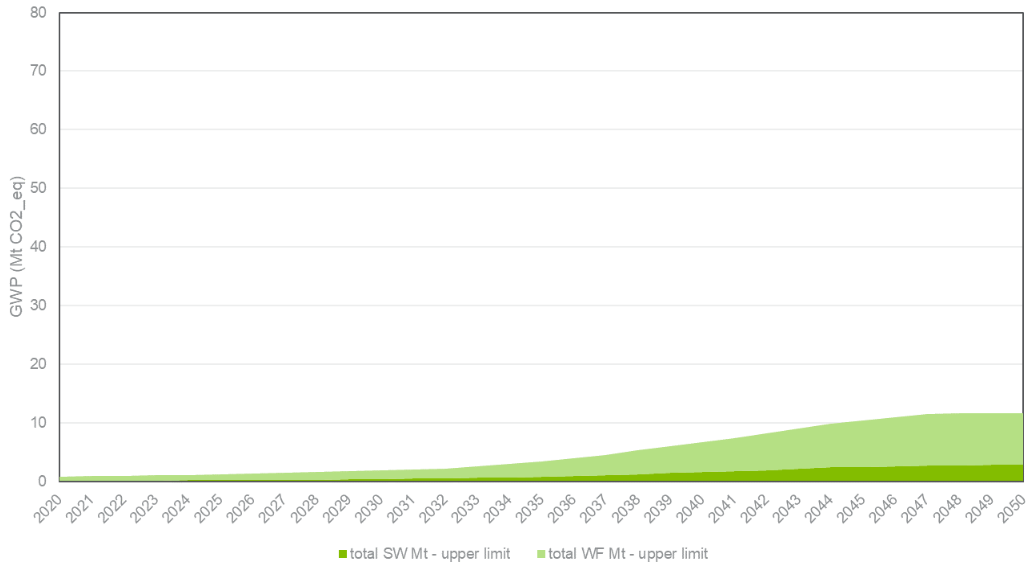


Figure 27: GWP for new wooden buildings in the EU – upper limit (Source: Legep & BEAM² Modelling)

If the same share of buildings were realised as traditional, mineral buildings as defined before, significantly more GHG would be emitted (see *Figure 28*). Here the brick, stone, and concrete construction materials account for 73 Mt of CO_{2_eq} emissions by 2050.

The difference from the CO_{2_eq} emissions for wooden buildings and the replaced construction types (mix of mineral constructions) is the substitution effect of wood. *Figure 29* shows this effect and the corresponding savings over time for the baseline and upper limit scenarios, where the 10 Mt CO_{2_eq} emissions can be saved in the baseline and 62 Mt CO_{2_eq} emissions in the upper limit pathway. The area in between is considered to be the realistic bandwidth of future development for wooden buildings.

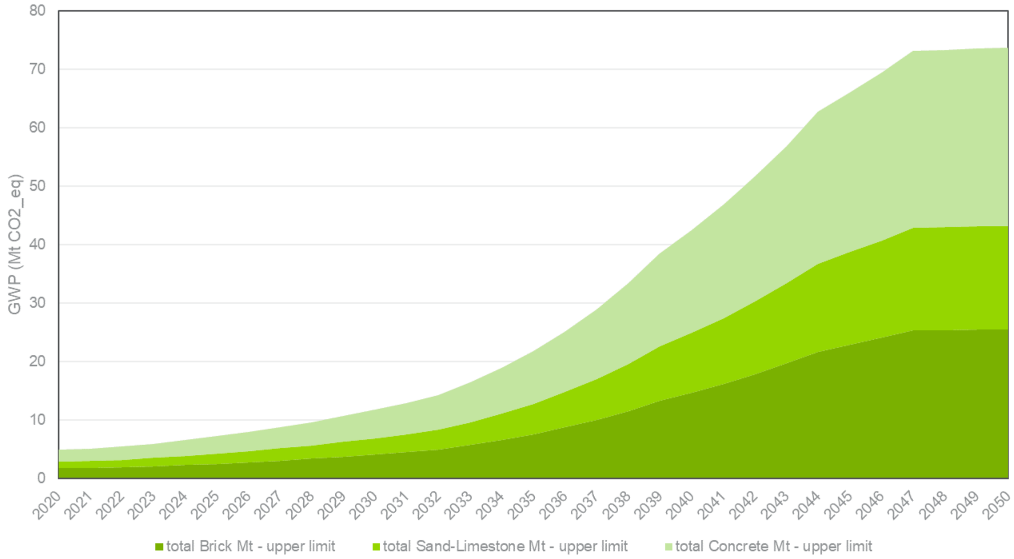


Figure 28: GWP for new mineral buildings (replacement) in the EU – upper limit (Source: Legep & BEAM² Modelling)

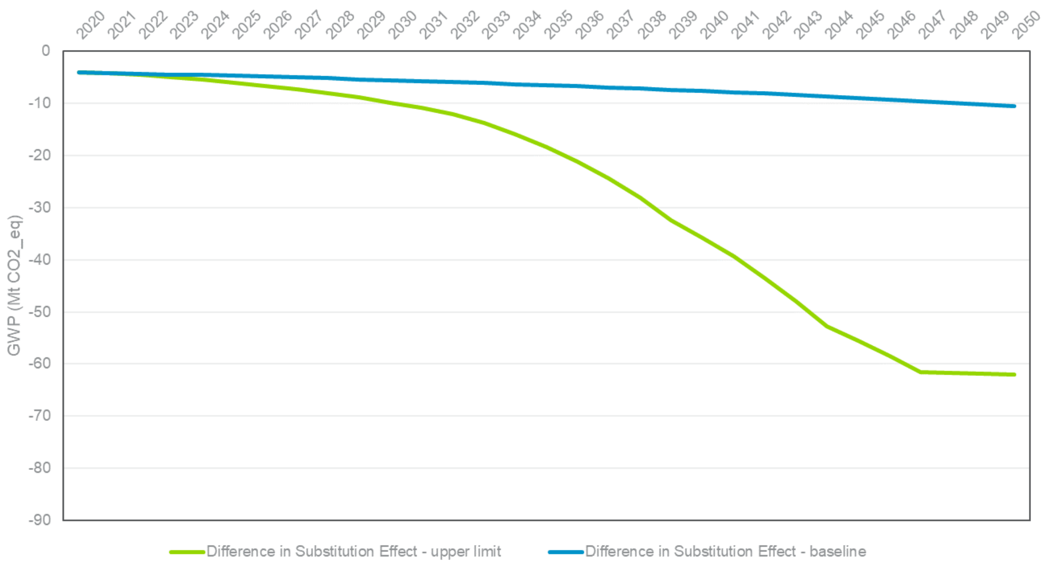


Figure 29: GWP SAVINGS by substitution effect of new wooden buildings in the EU – baseline and upper limit (Source: Legep & BEAM² Modelling)

In addition to the substitution effect, the CO_2 storage effect of wood is also very relevant. *Figure 30* shows the CO_2 savings due to the carbon capture and storage (CCS) in wooden buildings over time.

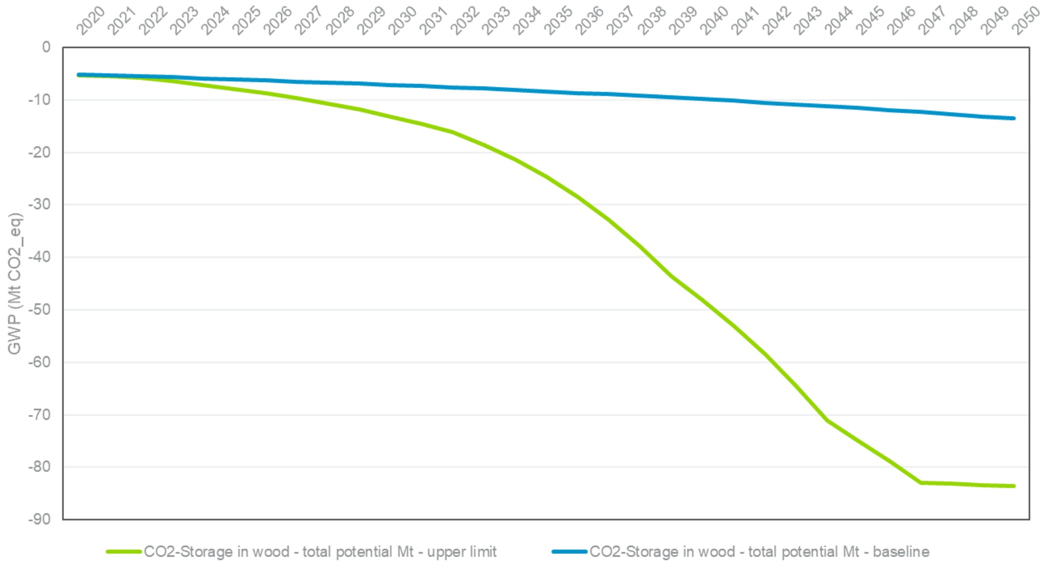


Figure 30: GWP (only CO2) SAVINGS by storage effect of new wooden buildings in the EU – baseline and upper limit (Source: Legep & BEAM² Modelling)

The order of magnitude of effect is comparable with the substitution effect. The wood must be conserved as material as long as possible, since the thermal usage or rotting of it would release the CO_2 back into the atmosphere. However, since the substitution effect alone is significant, wooden buildings would be very useful even without any savings in the material.

Adding up both effects leads to *Figure 31*. By substituting mineral construction materials and storing CO_2 in the wooden structure of the buildings, 145 Mt of CO_{2_eq} can be saved by 2050.

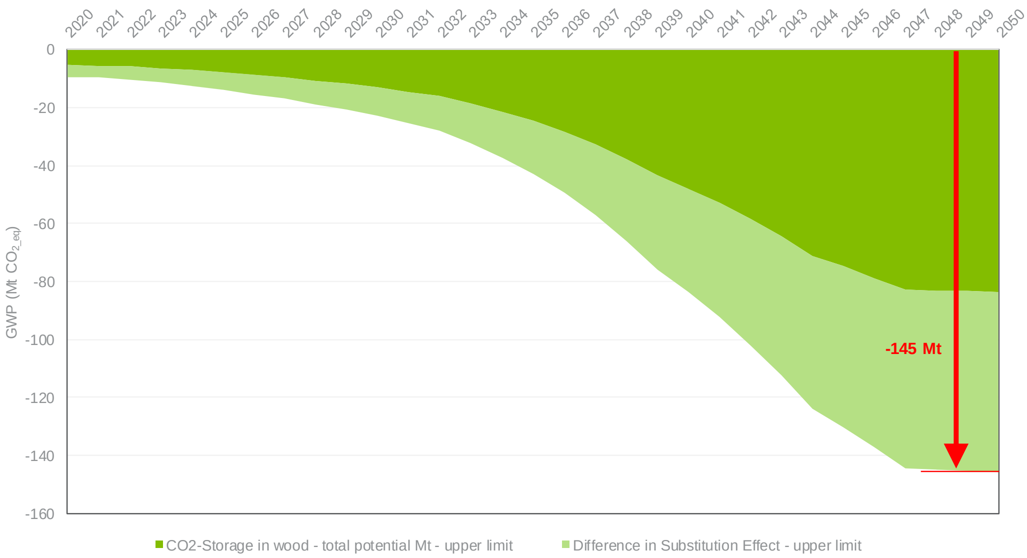


Figure 31: GWP for Substitution and Storage Effect of wood vs. mineral building material for new buildings in the EU – upper limit (Source: Legep & BEAM² Modelling)

The same development is shown in *Figure 32*, but in another visualisation. For the years 2020, 2030, 2040, and 2050, the baseline and upper limit GHG emissions are shown for both mineral buildings materials (to be replaced) and wooden buildings materials. The delta between the two variants is shown in each last column. The picture for 2050 shows, that in the upper limit pathway 73.7 Mt CO_{2_eq} emissions would be created by mineral construction types (for 75% of the new building rate, which is considered as realistic upper limit for the wood buildings market share by 2050), while by that time the wooden buildings mix would only emit 11.6 Mt CO_{2_eq} emissions. This leads to a difference of 62.1 Mt CO_{2_eq} emissions between the two options (substitution effect), which is significant. If the CO_2 storage in wood is also considered, additional savings of 83.6 Mt CO_{2_eq} occur (storage effect). Both effects sum up to overall savings of about 145.7 Mt CO_{2_eq} by 2050. Compared against the current GHG emissions in the EU buildings sector without construction activities (see chapter 2.3.3) of about 650 Mt CO_{2_eq}, the 145 Mt represent approximately 20%, a significant number.

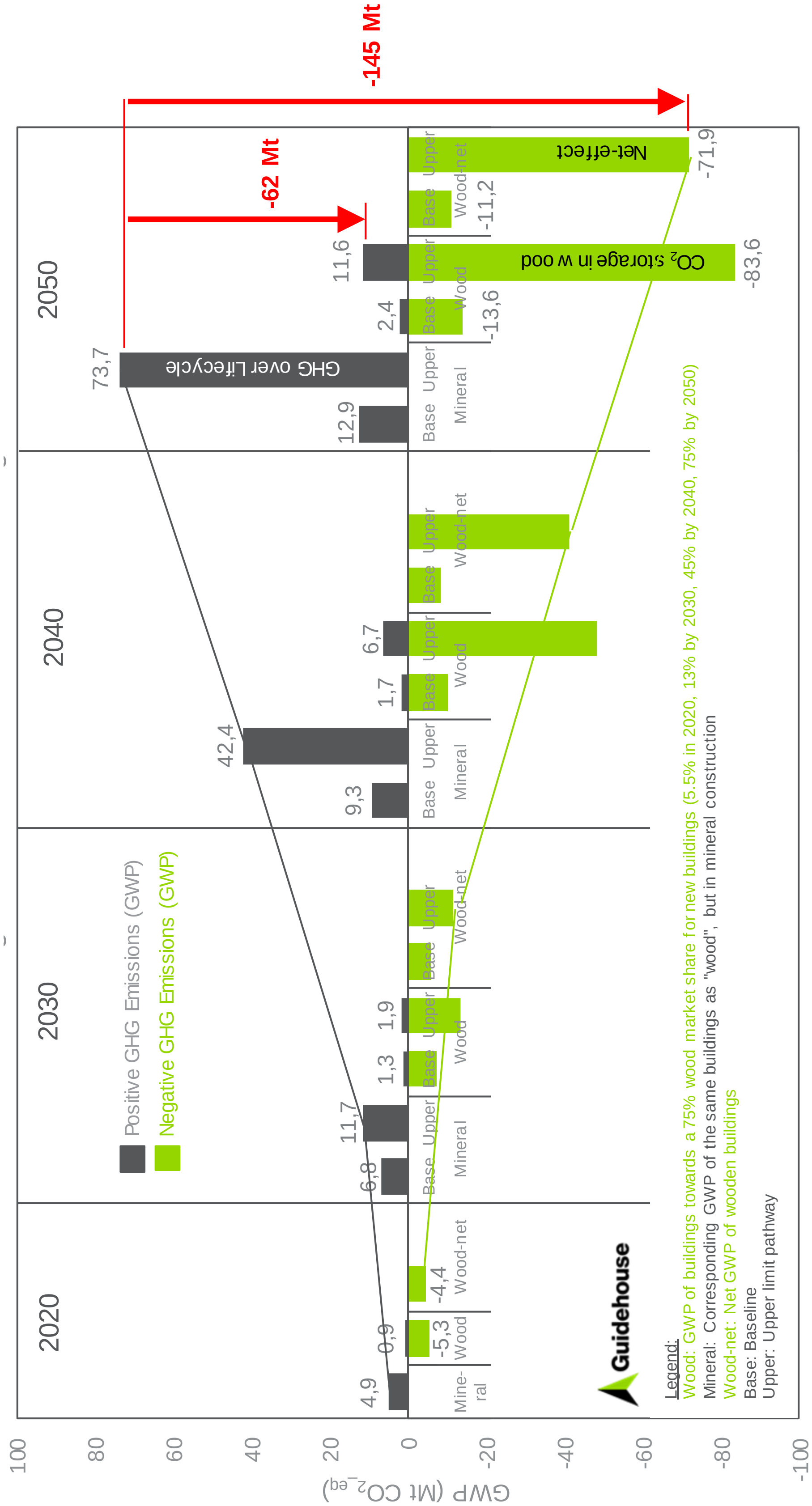


Figure 32: GWP of conventional building materials vs. wood over the Life Cycle for new buildings in the EU (Source: Legep & BEAM² Modelling)

Wood Demand for upper limit pathway
To enable the uptake of wooden buildings to a market share of 75% for new buildings by 2050, a significant amount of additional resources is requited, as shown in *Figure 33*. The demand increases from current levels around 5 Mm³ p.a. towards approximately **90 Mm³ of addition wood resources** in the upper limit pathway by 2050. This overall number contains solid wood constructions (using mainly CLT), wood frame constructions (using mainly glulam and OSB) and wooden insulation (WFIB and MDF). This amount seems reasonable, since studies show the upper limit of additional sustainable wood resources from EU forests with a range of **60–235 Mm³** by 2030 (see chapter 3), and more wood could be made available for saw-wood and further on usage as glulam or CLT from the existing use-cascade.

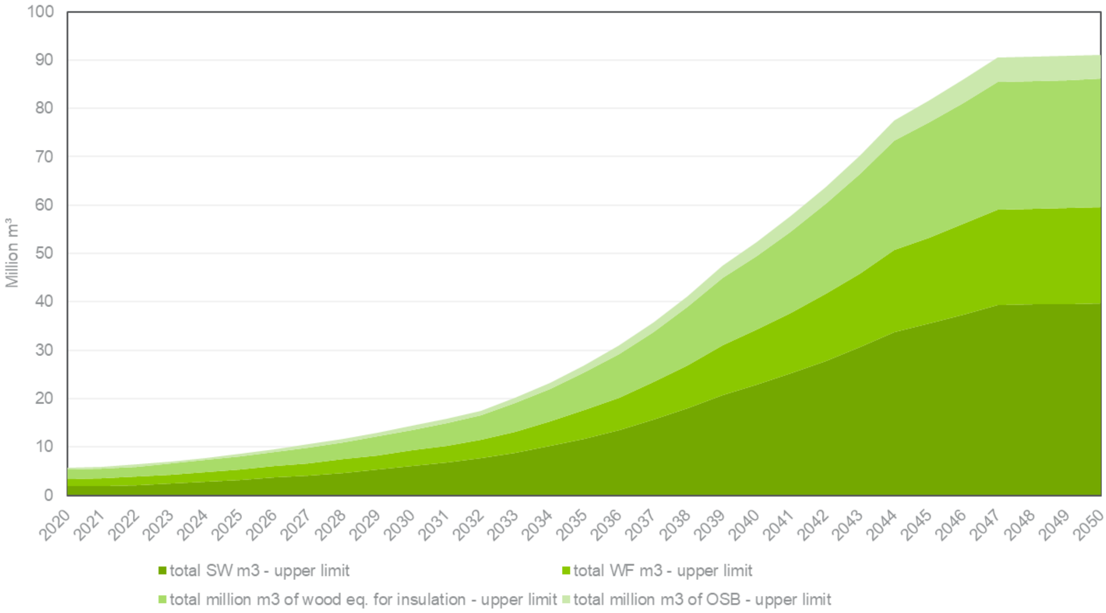


Figure 33: Total demand of wood for buildings (solid wood, wood frame, wood fibre insulation and OSB/MDF boards) for new buildings in the EU – upper limit (Source: Legep & BEAM² Modelling)

Depending on the type of wood product, manufacturing technique, and wood-input, a conversion factor to roundwood equivalent (RWE) ranging from 1.5. to 2.8 for different wooden products (such as CLT, OSB, glulam, WFIB) is assumed, see [Elias Hurmekoski, 2017]. This market share could be brought further down, since CLT and glulam can also be assembled by smaller log-wood pieces and many of the remaining parts (thinning) can be processed to WFIB or OSB, which are also needed in wooden buildings.

Discussion

The current new building rate across Europe is about 0.7% for residential and 1.1% for non-residential buildings, while the wood market share is approx. 5.5% in average (with significant differences between MS), where wood is the main construction material (main products are sawn-wood, glulam, CFL, OSB and WIFB).
The historic growth rate of wooden buildings is with 3% p.a. quite moderate and therefore assumed for the baseline pathway with a final market share of 13% by 2050. This is conservative assumption, but in line with the definition of a baseline. The impact with these amounts of wood is GHG savings of about 21.6 Mt in 2050 compared to the current mineral building construction mix. In relation to the current

GHG emissions for the use phase of buildings with approx. 650 Mt CO_2 across the EU, these savings are important – but not large.

Since the additional potential of the EU forest sector for wood is quantified in a range of 60 Mm² - 235 Mm³, there is sufficient room for additional wooden building constructions. Furthermore, the relatively large share of wood going into thermal usage needs to be reviewed, since a long-term material use of it is from a climate perspective much more favourable.

In order to significantly increase the share of wooden buildings, a development such as the upper limit pathway would be required. Here the wood market share is increased towards 75% of the new building rate by 2050. This leads to GHG savings of about 61.4 Mt GHG emissions for the substitution effect (replacing mineral materials with wood) and 84 Mt of CO_2 that is in addition stored in wood. In total 145 CO_{2_eq} can be saved by 2050 in the upper limit pathway compared to mineral building constructions. To support this development, 90 Mm³ of wood resource would be needed in 2050. In light of the additional resources from EU forests, this amount seems to be reasonable if the forest and wood industry as sufficient time and a planning horizon to manage growing material flows year by year.

The substitution effect of wood is modelled for 2020. It is not taken into account, that energy mix etc. decarbonize over the coming decades. Therefore, the impact of wood as material will become smaller in the future. However, energy supply is only one component within the GHG emissions of mineral buildings construction. Other components such as process emissions cannot be avoided for current processes (such as cement production). If alternative materials are developed and partly could replace the traditional mineral materials, the impact of wood as substitute is decreasing.

Apart from the substitution and storage effect of wood, also the forest sector can have an impact. If wood demand is increasing, the rather mature European forests stock is used as material step by step and old/mature trees are replaced by new, fast growing trees which absorb more CO_2 than the mature trees would do. As effect, the overall carbon stock in the forest sector can be increased. However, cutting down old trees and forests needs to be done in a careful manner, since they also have a function to stabilize the climate. In hot summers, old trees vaporize a lot of water, which leads to a significant cooling effect not only in the local context, but also to the overall mean temperature. Cutting down old forest to substitute mineral buildings in large quantities therefore is not recommended, but rather finding a balance between what is the best way for the overall ecosystem. Furthermore, the species of trees will change due to climate change and long dry periods during summertime. This also needs to be considered in the overall approach.

Not only solid wood, but also wood fibre insulation boards (WFIB) could be used to replace conventional materials (such as mineral wool, EPS or XPS). For new buildings it is considered in the analysis above, but for renovation activities there is a huge additional potential. This makes also sense from the resource perspective, since wood fibre insulation can also be produced from small pieces of wood – while sawn-wood only can be produced from larger logs. But also, glulam or CLT products help to use more of the resource wood in wooden products, since smaller pieces can be put together into larger elements.

Finally, there are a couple of advantages of wooden buildings in contrast to conventional construction types. As wooden elements are prefabricated in an industry environment, quality assurance and dimensional accuracy are typically higher or easier to archive in comparison to on-site constructions with stones or concrete. Since the construction times are minimal on site for wooden constructions, the building can be occupied earlier. In case of retrofits, large-scale renovations with prefabricated elements can be conducted with using wood in structure and for insulation to replace conventional mineral retrofits.

EU Policy Analysis and Recommendations

In order to be able to deploy the potential of sustainable and renewable materials (such as wood) in the construction sector, the policy framework needs to be aligned with the overall targets of a net-zero economy in the long-term perspective. Therefore, this chapter gives a brief overview on the EU building sector regulation and policy framework with a focus of wood as construction material. Based on this, direct and indirect wood construction policies are identified and further improvement steps towards a fair evaluation of the entire lifecycle for buildings are discussed.

Key Policy Recommendations

- The EU policy framework does only consider the use phase of buildings, but not the manufacturing/construction an disposal/reuse phase.
- Therefore, the major advantages of wood as construction material are not considered.
- Environmental taxes or emission trading schemes as indirect policies can help to stimulate the market for sustainable construction material.
- Phasing out of subsidies for fossil fuel and resources would accelerate alternative materials.
- Prohibition of certain substances or byproducts have the potential to increase the uptake of wooden buildings.
- Market incentives but also mental models towards wooden products is important.
- Subsidies and persuasion are important for countries with low wooden quotas.
- The encouragement of reliable and international certification schemes to reduce quality and sustainability concerns is key.
- Education and knowledge transfer about wood use in construction is key to overcoming path dependencies, which are especially strong in the building sector where the market is dominated by stone materials.
- R&D support for innovations is a key element of a more sustainable economy; resource efficiency gains in Europe are mainly driven by changing technology.

Overview of the current EU Building Regulation

The current EU policy framework for the building sector is mainly based on the Energy Performance of Buildings Directive (EPBD). But also other directives, guidance documents and schemes are relevant and have impact on buildings, such as the Energy Efficiency Directive (EED), the Ecodesign Directive, the Renewable Energy Directive (RED) and the EU-ETS.

As central policy instrument, the EPBD [EPBD, 2017] sets a number of requirements for new buildings and (major) renovations across the EU. Minimum performance requirements are established on component level for new buildings and renovations, while cost-optimality is the leading principle to set overall minimum performance levels for new buildings and renovations. Furthermore, new buildings need to comply with the nearly Zero Energy Building (nZEB) definition. While minimal component performance requirements are set on EU level, nZEB definitions and cost-optimality requirements are assessed and defined on member state (MS) level. In addition, MS are also obliged to develop long-term renovation strategies for their buildings stocks that comply with the long-term energy and climate targets.

However, all requirements within the EPBD address the use phase of buildings, excluding the manufacturing/construction and disposal/reuse phases of building elements. Therefore, the major benefits of wood as construction material – as discussed above – are not covered by this piece of legislation.

The Ecodesign Directive [EC, 2015] covers more than 40 product groups and sets mandatory ecological requirements for energy-using and energy-related products, including construction materials and technical building systems (TBS). The directive aims at reducing the energy consumption and other negative environmental impacts of products during their use phase. Manufacturers have to take mandatory requirements in the design stage of products into account. While the Directive's primary aim is to reduce energy use, it is also aimed at enforcing other environmental considerations including materials use; water use; polluting emissions; waste issues and recyclability. However, also the Ecodesign Directive focuses on the energy consumption in the use phase of produces, but does not include the manufacturing phase. Since some preparatory studies for Ecodesign also include an LCA already, further steps towards a full life cycle approach should be possible, especially in view of TBS (which are not considered in the analysis above).

The amended Energy Efficiency Directive [European Parliament and the Council of the European Union (EU) 2018] is also relevant for the building sector. It updates the policy framework to 2030 and beyond and sets an overall mandatory energy efficiency target for 2030 of at least 32.5%. Thereby it sets indirect incentives to reduce energy consumption (and GHG emissions) during the manufacturing and construction process of buildings outside the building sector.

Also, the EU Emission Trading System (EU-ETS) has an impact of the construction sector across Europe. The total amount of certain greenhouse gases to be emitted is limited by a cap, while the emission allowances within the system can be traded between companies. Since the price of GHG emissions is expected to grow and energy intense industries (such as cement) receive free allocations at the moment, the impact on industry processes can potentially grow.

Finally, the review of the Construction Product Regulation (CPR) and the published Circular Economy Action Plan of the European Commission aim for a strategy of a sustainable built environment. The sustainability performance of construction products is addressed in the context of the revision of the CRP , including the possible introduction of recycled content requirements for certain construction products.

Identify Options to Promote Wood Construction

Based on the current EU building regulations the following chapter focuses on the identification of options to promote wood as construction material within the EU policy framework. The analysis is based on [Jakob Hildebrandt et al., 2017] to a large extent, since the authors worked on a comprehensive summary of EU policies regarding wooden buildings. The focus is on the identification of possibilities for the consideration of wood construction EU building sector regulation. In this regard, three trends in development can potentially lead to a higher share of wood construction in the future:

- Technical progress towards high performing load-bearing wood constructions
- Progress in the harmonization of fire protection and environmental regulations
- Constant growth in the capacity to produce ecological construction materials

Against this background, it can be distinguished between indirect and direct wood construction policies (see *Figure 34*). The following chapters elaborate on the possibilities how to align the policy framework to promote wood construction.

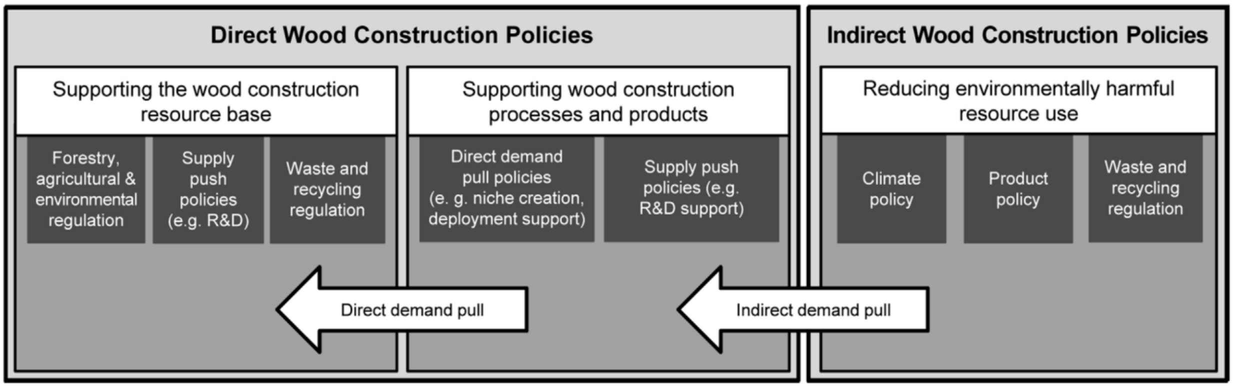


Figure 34 Categorisation of wood construction policies.
Source: [Jakob Hildebrandt et al., 2017].

Indirect wood construction policies

In contrast to direct policies, the indirect wood construction policies address the framework and boundary conditions around the construction sector. One the one hand side instruments can indirectly influence rates of new construction or retrofitting by increasing costs for consumption of environmentally harmful products. Promotion of fiscal reforms, development of environmental taxes, and development of emission trading schemes are instruments that restrict carbon-intense products and production processes—supporting ecological construction products. It is debatable whether current carbon pricing schemes are effective at reducing carbon emissions because the increasing efficiency in the manufacturing sector is mainly driven by energy costs and less by policies. Under Europe's current legislation, the cement sector – a high carbon emission sector – will not have to buy carbon certificates until 2043 (and, as such, the amount of carbon produced by the sector will probably not decrease).

On the other hand phasing out of subsidies that support fossil resources can in addition can foster a sustainable building sector as well. Finally, command and control instruments (such as prohibiting the use of certain substances or byproducts) have the potential to increase the uptake of wooden building materials.

In this framework, one the one hand side subsidies and other support for the use of fossil energy and materials should be phased out, while at the same time environmentally friendly taxes and emission trading systems should be established on the other hand to support an increase of wooden building constrictions on the mid- and long-term.

Direct Wood Construction Policies

On the other hand, policy instruments can directly influence rates of new construction or retrofitting by enhancing wood construction processes and products as well as supporting the wood construction resource base. In this filed also overcoming prejudices is quite important: "People generally regard wood as less fire resistant, less durable, less dimensionally stable, less resistant to decay and insects, and more expensive to maintain, than other materials." As these arguments are generally not valid and a closer look is needed to take specific parameters of individual materials into account, the public should be informed about it. Furthermore, experiences with building standards and tradition have a great influence on the willingness to take up alternative materials such as wood components (wooden window frames).

In countries with low wooden construction rates, also subsidies and persuasion are suitable instruments to familiarize consumers to these new products. On the one hand knowledge transfer from producer and politics to consumer through labelling or information campaigns is important, but on the other hand also between producers.

The encouragement of reliable and international certification schemes to reduce quality and sustainability concerns regarding the increased use of wood (demands of different groups such as architects, designers, building owners) also should be addressed. Certification often includes compatibility with strict fire regulation standards. Education and knowledge transfer about wood use in construction is key to overcoming path dependencies, which are especially strong in the building sector where the market is dominated by stone materials. The uptake of innovative wooden construction components depends not only on market incentives but also on the mental models towards wooden products in the construction sector. R&D support for innovations is a key element of a more sustainable economy; resource efficiency gains in Europe are mainly driven by changing technology. Support can be public and private through innovative financing instruments, such as revolving funds, preferential interest rates, guarantee schemes, risk-sharing facilities, blending mechanisms. Finally, the public procurement can be designed in such way, that sustainable materials are supported or at least all external effects (such as environmental impacts) are considered.

All in all, direct wood construction policies need to enable higher wooden market shares for new buildings and renovations. Prejudices must be overcome, and positive examples and experience need to be spread. Non the less international (mandatory) certification schemes help to clearly shown the benefits of sustainable materials over the entire life cycle. Regulatory policy can also help to support this development, if not only the use phase of buildings would be covered by building sector specific regulation, but the entire life cycle of a buildings including manufacturing, construction, disposal and recycling.

Discussion

The current building and construction policies on EU level do cover the use phase of buildings very well, while the manufacturing and construction phase on the one hand and the disposal and recycling phase on the other hand are not covered. Therefore, the major advantages of wooden constructions and building elements are not considered in this scope. Environmental taxes or emission trading schemes as indirect policies can help to stimulate the market for sustainable construction material, supported by a phasing out of subsidies for fossil fuel and resources. In addition, the prohibition of certain substances or byproducts have the potential to increase the uptake of wooden buildings further. Education and knowledge transfer about wood as well as showing positive examples and focusing on R&D are key elements for the success of wooden buildings.

The way forward form a policy perspective should be focused on creating a level playing field for all buildings materials, also including TBS. If impact assessments are done over the full life cycle, a fair comparison between alternatives is possible with regard to energy and climate targets. Once the individual footprints are clear, instruments like environmental taxes and emission trading systems with fair boundary conditions can significantly help to bring sustainable building materials forwards. In addition to that, direct subsidy measures can help in markets with very low wood shares to reach a critical mass and to accelerate the system.

Conclusions

The scope of the building sector typically only covers the use stage (B) of the building, while the product/construction stage (A), disposal/end-of life stage (C) and recycling potential stage (D) are also important from a lifecycle perspective. In this regard, the LCA of individual buildings highlights, that mineral buildings have significantly higher material stream with higher mass streams than wooden buildings - which impact the GWP of the construction. The impact assessment shows, that the GWP over the for the manufacturing and construction for wooden buildings with minimal 2 kg CO_{2_eq}/m^2 compared to mineral buildings with up to 500 kg CO_{2_eq}/m^2 is marginal. Apart from the temporary CO_2-saving effect (CCS) of wood (917 kg CO_2/m^3) – which is not included in the numbers above - the substitution effect of mineral materials accounts for the largest part of the overall GWP.

The current wood market share for new residential and non-residential buildings is approx. 5.5%, while the new building rate for residential buildings is about 0.7% and 1.1% for non-residential buildings. Where wood is the main construction material, sawn-wood, glulam, CFL, OSB and WIFB are mostly used as products. The **baseline** pathway builds on a future growth rate for wooden buildings of 3% p.a. as it has been observed in the past decade. The impact with these amounts of wood is GHG savings of about 21.6 Mt in 2050 (assuming todays energy mix and processes) compared to the current mineral building construction mix. In relation to the current GHG emissions for the use phase of buildings with approx. 650 Mt CO_2 across the EU, these savings are important – but not large. An ambitious pathway towards using wood in the EU building sector is described in the **upper limit pathway**. Here the wood market share is increased towards 75% of the new building rate by 2050. This leads to GHG savings of about 61.4 Mt GHG emissions for the substitution effect (replacing mineral materials with wood) and 84 Mt of CO_2 that is in addition stored in wood. In total 145 CO_{2_eq} can be saved by 2050 in the upper limit pathway compared to mineral building constructions. To support this development, 90 Mm³ of wood resource would be needed in 2050. In light of the additional resources from EU forests, this amount seems to be reasonable if the forest and wood industry as sufficient time and a planning horizon to manage growing material flows year by year. If wood would be reused as often as possible and - if not – replaced by fresh wood from the forest, the net-sink and carbon stock of wooden building would remain over time.

In the area of EU policy framework, the current building and construction policies on EU level do cover the use phase of buildings very well, while the manufacturing and construction phase on the one hand and the disposal and recycling phase on the other hand are not covered. In this setting, the benefits of wooden buildings are not accounted for in the current system. From the policy side, emission trading schemes or environmental taxes can help to establish a level playing field when externalities are considered over the whole life cycle of a product. Furthermore, the phasing out of fossil subsidies is an important element to remove market distortion. In order to support this process, direct subsidy measures can help in markets with very low wood shares to reach a critical mass and to move the market forward.

Since there is sufficient evidence about the positive impacts of wooden buildings in the EU building sector, the next steps need to be prepared now. Fair market conditions, a level playing field and assessments over the total lifecycle of products – also considering the ability to work into a circular economy – need to be implemented. This also includes a definition of the buildings sector that goes beyond the current scope.

Further Research Questions

In order to further specify the findings and add elements to them, the following further research questions (nonexclusive) arise from the study. In the authors view they should be addressed by further research.

Methodology

- Dynamic calculations with regard to a dynamic/shifting baseline can help to further specify the findings. The GHG emissions of replaced materials is decreasing over time due to decreasing carbon content in electricity mix and process improvements over time. This is an important element that should be considered.
- How could a methodology look like that includes LCA /embodied carbon into cost-optimality calculations and minimum performance requirements for buildings?
- What is the potential of the growing insulation market for energetic retrofits of buildings and the possible role of wooden insulation (WFIB)?`

Forest

- What impacts does a shift in tree-species due to climate change have on the availability of resources from the forest (growth time until maturity) and on the carbon content captured by the trees over time?
- How does the cooling effect of old/mature forests change if mature trees cut down and replaced by young, fast growing trees? What is a reasonable balance to not eliminate the cooling effect of forests on the climate, especially during summertime?

Policy and Co-Benefits

- What changes in regulations are needed to remove barriers for wooden buildings (especially MFH, office)?
- What would be the price impact of increasing carbon tax on conventional construction methods versus wooden constructions?
- What would be the options for introducing "emission certificates" for wooden buildings to create additional financial market incentives?
- What is the impact of wooden buildings on health compared to "conventional" buildings?
- How should a policy setup look like that supports sustainable materials?

Market and Costs

- What would be the potential of cost-reductions in case of upscaling of industrial built wooden buildings?

A more detailed analyses of necessary changes to the market could help to better understand the next steps (industrial capacity, workforce in forestry, industry, construction site, designers, planners etc.)

Abbreviations

BR	Brick
cbm	cubic meter
CO_2	Carbon dioxide
CO_{2_eq}	Carbon dioxide equivalent
CC	Cellular Concrete
CCS	Carbon Capture and Storage
CLT	Cross-laminated Timber
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
EPD	Environmental Product Declaration
EU-ETS	EU Emission Trading System
GHG	Greenhous-Gas
GWP	Global Warming Potential
IA	Impact Assessment
LULUCF	Land Use, Land Use Change and Forestry
MDF	Medium Density Fibre Board
MFH	Multifamily House
MS	Member State (of the EU)
OSB	Oriented Strand Board
RED	Renewable Energy Directive
RC	Reinforced Concrete
SFH	Single-Family House
SL	Sand-Limestone
SW	Solid Wood
TBS	Technical Building Systems
WF	Wood Frame
WFIB	Wood Fibre Insulation Board

References

Altenbach, Holm (2018): *Holzmann/Meyer/Schumpich Technische Mechanik. Festigkeitslehre*. 13th ed.: Springer Vieweg.

Bettgenhäuser, Kjell; Offermann, Markus; Boermans, Thomas; Bosquet, Michelle; Grözinger, Jan; Manteuffel, Bernhard von; Surmeli, Nesen (2013): *Heat Pump Implementation Scenarios until 2030. An analysis of the technology's potential in the building sector of Austria, Belgium, Germany, Spain, France, Italy, Sweden and the United Kingdom*. By order of European Heat Pump Association (EHPA). ECOFYS. Berlin, Cologne (BUIDE12080)Bettgenhäuser, Kjell; Offermann, Markus; Boermans, Thomas; Bosquet, Michelle; Grözinger, Jan; Manteuffel, Bernhard von; Surmeli, Nesen.

Colin M. Rose; Dan Bergsagel; Thibault Dufresne; Evi Unubreme; Tianyao Lyu; Philippe Duffour; Julia A. Stegemann (2018): *Cross-Laminated Secondary Timber: Experimental Testing and Modelling the Effect of Defects and Reduced Feedstock Properties* Colin M. Rose; Dan Bergsagel; Thibault Dufresne; Evi Unubreme; Tianyao Lyu; Philippe Duffour; Julia A. Stegemann.

DESTATIS (2019): *Baugenehmigungen von Wohn- und Nichtwohngebäuden nach überwiegend verwendetem Baustoff - Lange Reihen z. T. ab 1980* DESTATIS.

Dietmar Walberg; Oliver Brosius; Thorsten Schulze; Antja Cramer (2015): *Massiv- und Holzbau bei Wohngbäuden. Vergleich von massiven Bauweisen mit Holzfertigbauten aus konstenseitiger, bautechnischer und nachhaltiger Sicht*. Arge Kiel Dietmar Walberg; Oliver Brosius; Thorsten Schulze; Antja Cramer.

EC (Ed.) (2015): *Ecodesign - Energy efficient products*. European Commission (EC). Available online at http://ec.europa.eu/energy/efficiency/ecodesign/eco_design_en.htm, accessed 8/24/2015.

EC (2017): *Level(s) Factsheet*. EC, DG Env EC.

Elias Hurmekoski (2017): *How can wood construction reduce environmental degradation?* European Forest Institute Elias Hurmekoski.

EN 15804 (2014): *EN 15804 - Sustainability of construction works - Environmental product declarations* EN 15804.

2014: *EN 15804 - Sustainability of construction works - Environmental product declarations*.

EN ISO 14040 (2009): *EN ISO 14040 Environmental management - LCA - Principles and framework* EN ISO 14040.

2009: *EN ISO 14040 Environmental management - LCA - Principles and framework*.

DIN EN ISO 14040, November 2009: *Environmental management - Life cycle assessment - Principles and framwork*.

EPBD (2017): *AMENDMENT PROPOSALS. On the proposal for a Directive of the European Parliament and of the Council amending Directive 2010/31/EU on the energy performance of buildings - Proposal for a Directive (COM(201 6) 765 final – 2016/0381 (COD))*.

Esser, Anne; Dunne, Allison; Meeusen, Tim; Quaschning, Simon; Wegge, Denis; Hermelink, Andreas et al. (2019): *Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU. Final report - Infographics*. Research report prepared for European Commission, DG Energy. Ipsos; Navigant Esser, Anne; Dunne, Allison; Meeusen, Tim; Quaschning, Simon; Wegge, Denis; Hermelink, Andreas; Schimschar, Sven; Offermann, Markus; John, Ashok; Reiser, Marco; Pohl, Alexander; Grözinger, Jan.

European Commission (2018;): *Our Vision for A Clean Planet for All: Social Transition* European Commission.

European Commission (EC) (2018): *A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. Communication from the Commission to the European Parliament, the European Council, The Council, The European Economic and Social Committee, the Committee of the Regions and the European Investment Bank*. COM(2018) 773 final.

European Commission (EC) (2019): *The European Green Deal - Building and renovating*. European Commission (EC) European Commission (EC).

European Parliament and the Council of the European Union (EU) (2018): *Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency. EED*. In: Official Journal of the European Union, vol. 61 (L 328), pp. 210–230.

G.J. Nabuurs; E.J.M.M. Arets; J.-P. Lesschen; M.J. Schelhaas (2018): *Effects of the EU-LULUCF regulation on the use of biomass for bio-energy* G.J. Nabuurs; E.J.M.M. Arets; J.-P. Lesschen; M.J. Schelhaas.

Jakob Hildebrandt; Nina Hagemann; Daniela Thrän (2017): *The contribution of wood-based construction materials for leveraging a low carbon building sector in europe* Jakob Hildebrandt; Nina Hagemann; Daniela Thrän.

JRC (2017): *Level(s) – A common EU framework of core sustainability indicators for office and residential buildings. Parts 1 and 2: Introduction to Level(s) and how it works*. JRC JRC.

Klauß, Swen; Kirchhof, Wiebke (2010): *Entwicklung einer Datenbank mit Modellgebäuden für energiebezogene Untersuchungen, insbesondere der Wirtschaftlichkeit*. Report by order of the German Federal Ministry of Transport, Building and Urban Development (BMVBS) and the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR). Edited by Zentrum für Umweltbewusstes Bauen e.V. Kassel Klauß, Swen; Kirchhof, Wiebke.

Maschinenbau-Wissen.de: *Biegewiderstandsmoment für einfache Querschnittformen berechnen* Maschinenbau-Wissen.de. Available online at http://www.maschinenbau-wissen.de/skript3/mechanik/balken-biegung/210-biegewiderstandsmoment1, accessed 10/4/2019.

DIN EN 15804:12 + A1:2013, Julie 2014: *Nachhaltigkeit von Bauwerken - Umweltproduktdeklarationen - Grundregeln für die Produktkategorie Bauprodukte;*

Noemi Emanuela Cazzaniga; Ragnar Jonsson; Daniele Palermo; Andrea Camia (2019): *Sankey diagrams of woody biomass flows in the EU-28*. JRC Noemi Emanuela Cazzaniga; Ragnar Jonsson; Daniele Palermo; Andrea Camia.

proHolz Austria (2019): *WOOD AND CLIMATE*. pro Holz Austria proHolz Austria.

Ragnar Jonsson; Viorel NB Blujdea; Giulia Fiorese; Roberto Pilli; Francesca Rinaldi; Claudia Baranzelli; Andrea Camia (2018): *Outlook of the European forest-based sector: forest growth, harvest demand, wood-product ,markets, and forest carbon dynamics implications* Ragnar Jonsson; Viorel NB Blujdea; Giulia Fiorese; Roberto Pilli; Francesca Rinaldi; Claudia Baranzelli; Andrea Camia.

DIN EN 15978: *Sustainability of construction works - Assessment of environmental perfomance of buildings - Calculation method,* accessed 7/25/2019.

The European Parliament and the Council of the European Union (2018): *European Parliament legislative resolution of 17 April 2018 on the proposal for a directive of the European Parliament and of the Council amending directive 2010/31/EU on the energy performance of buildings (COM(2016)0765 – C8-0499/2016 – 2016/0381(COD)). EPBD*.

UNECE (2011): *European Forest Sector Outlook Study II*. UNECE UNECE.

Wegener, Gerd; Pahler, Andreas; Tratzmiller, Michael (2010): *Bauen mit Holz = aktiver Klimaschutz*. Technische Universität München Wegener, Gerd; Pahler, Andreas; Tratzmiller, Michael.

Annex I - Analysis of individual Buildings: Detailed Input and Outputs

Reference Buildings (LCA stage I)

The follwing chapters give an overview on the geometries of the reference buildings

Reference Building "Single-Family House"

The SFH reference building is a detached, rectangular shaped building with a pitched roof oriented to the south. The area of the pitched roof can be used to collect the solar irradiation via solar panels to substitute parts of the primary energy demand with renewable energy. The building has 2+1 storeys, a basement, a ground floor and a top floor (see Figure 35 and Figure 36). The basement is excluded from the thermal envelope. The living area adds up to 147m². The building is designed for a four-person household and has 3 bedrooms.

Key facts		
Location	Cologne, Germany	
Type	Detached SFH	
Roof	Pitch roof	
Number of floors	2+1 (basement)	
Residents	4	
Orientation	South	
Number of apartments	1	
Average apartment size	147	m²
Gross floor area	233	m²
Gross Volume	788	m³

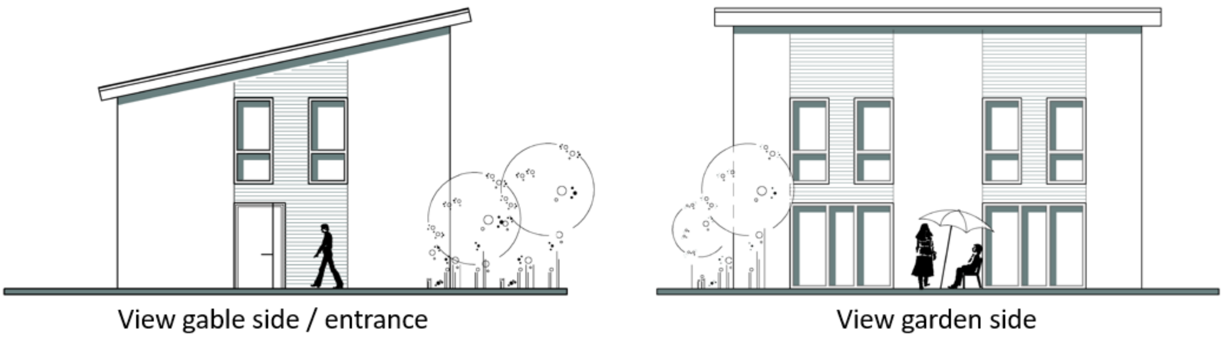
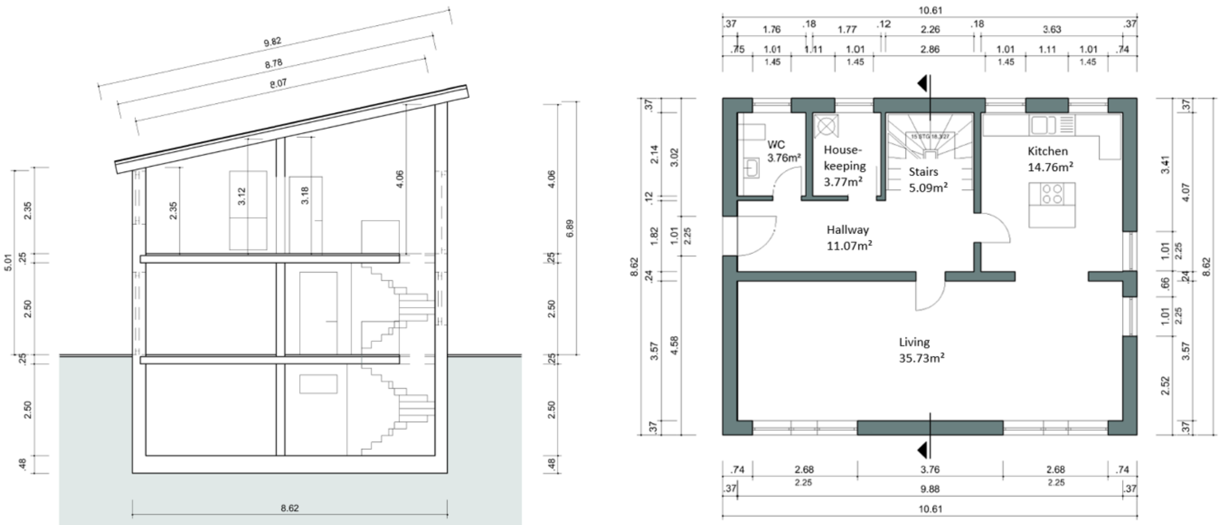


Figure 35: Side and front view of the SFH model building



View Section Ground floor plan

Figure 36: View on chapter and ground floor plan of the SFH model building

Furthermore, the building is equipped with an air-to-water heat pump for space heating and hot tap water.

Reference Building "Multi-Family House"

The MFH reference building is a detached, rectangular shaped building with a flat roof and south orientation. The area of the flat roof can be used for the installation of a PV-system. The building has 5+1 storeys and can accommodate 25 residents in 12 apartments. The basement is excluded from the thermal envelope and is about two-thirds of the size of each of the other floors. The living area amounts to 880 m^2, see Figure 37 and Figure 38.

Key facts		
Location	Cologne	
Type	Detached	
Roof	Flat roof	
Number of floors	5+1(basement)	
Residents	25	
Orientation	South	
Number of apartments	12	
Average apartment size	73	m^2
Gross floor area	1.290	m^2
Gross Volume	3.663	m^3

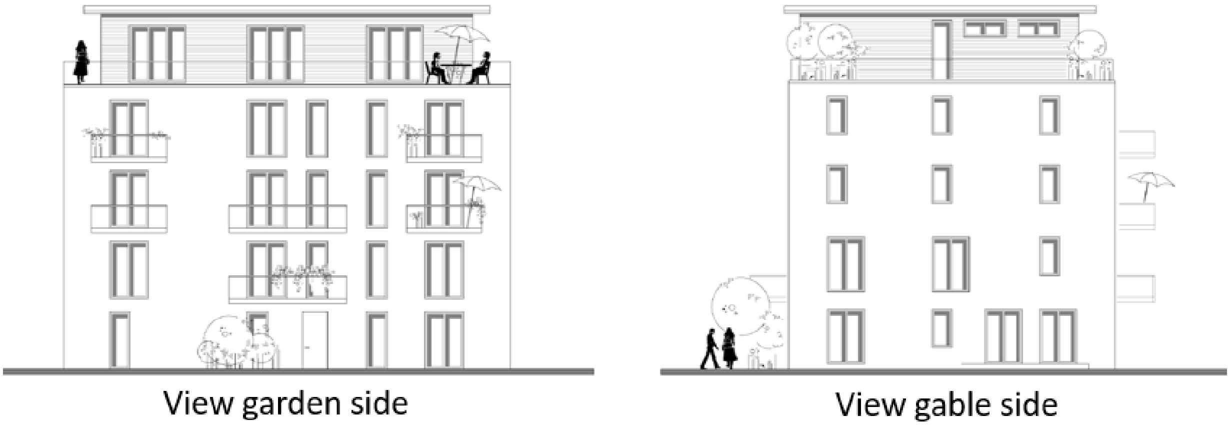


Figure 37: Side and front view of the MFH model building

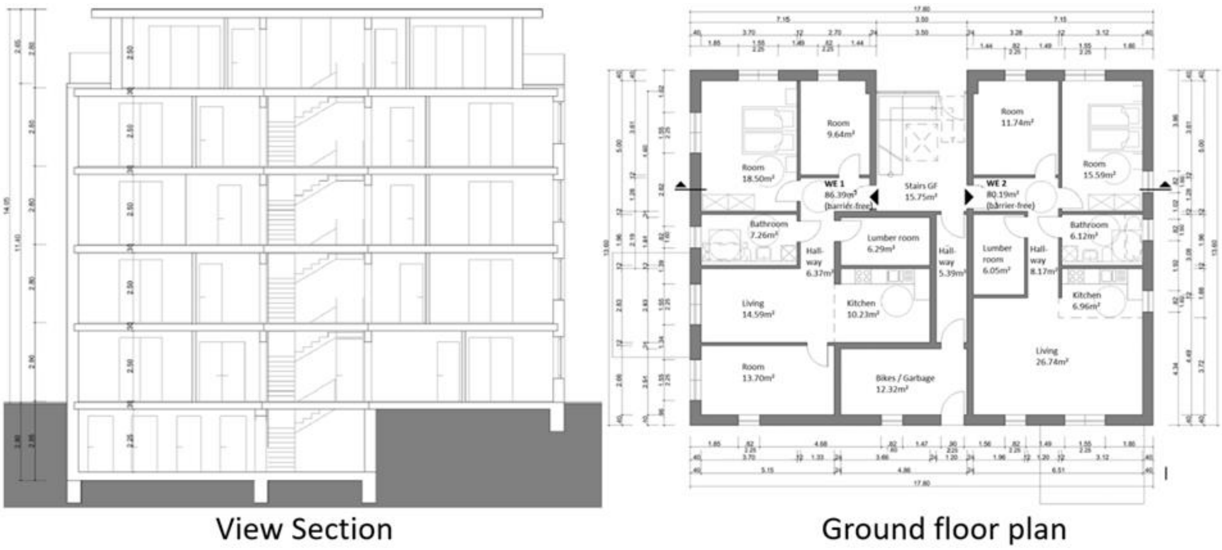


Figure 38: View on chapter and ground floor plan of the MFH model building

The MFH building is also equipped with a air-water heat pump for space heating and hot tap water.

Reference Building "Office"

The office building is a detached, u-shaped building with a flat roof, see Figure 39. The builing has no basement (other than the residential reference buildings) and each of the three storeys has the same structure, see Figure 40: Group offices (zone 2), open-plan office (zone 3), meeting and seminar rooms (zone 4), WC and snitary facilities (zone 16), common area (zone 17) and hallways (zone 19).

Key facts		
Location	Cologne	
Type	Detached	
Roof	Flat roof	
Number of floors	3	
Orientation	South	
Gross floor area	6998	m²
Gross Volume	24146	m³

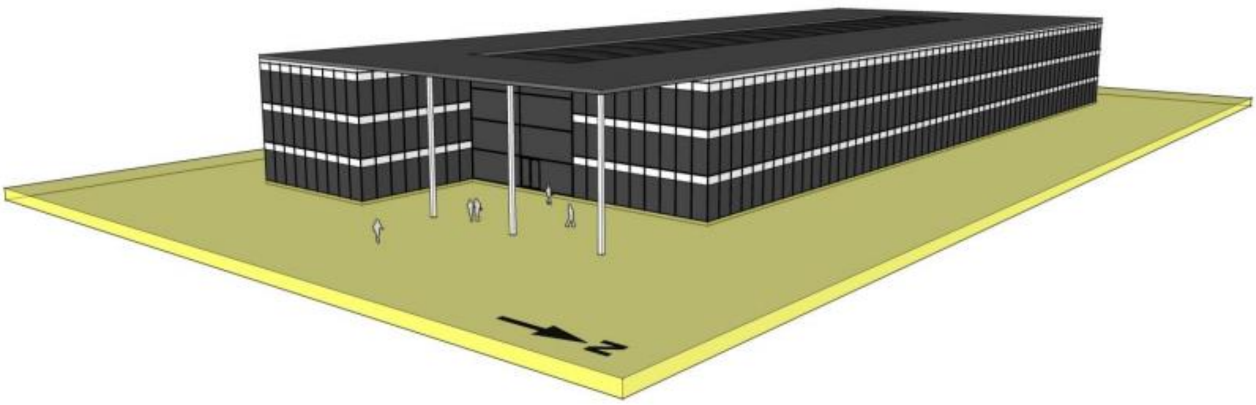


Figure 39: Side and front view of the office building

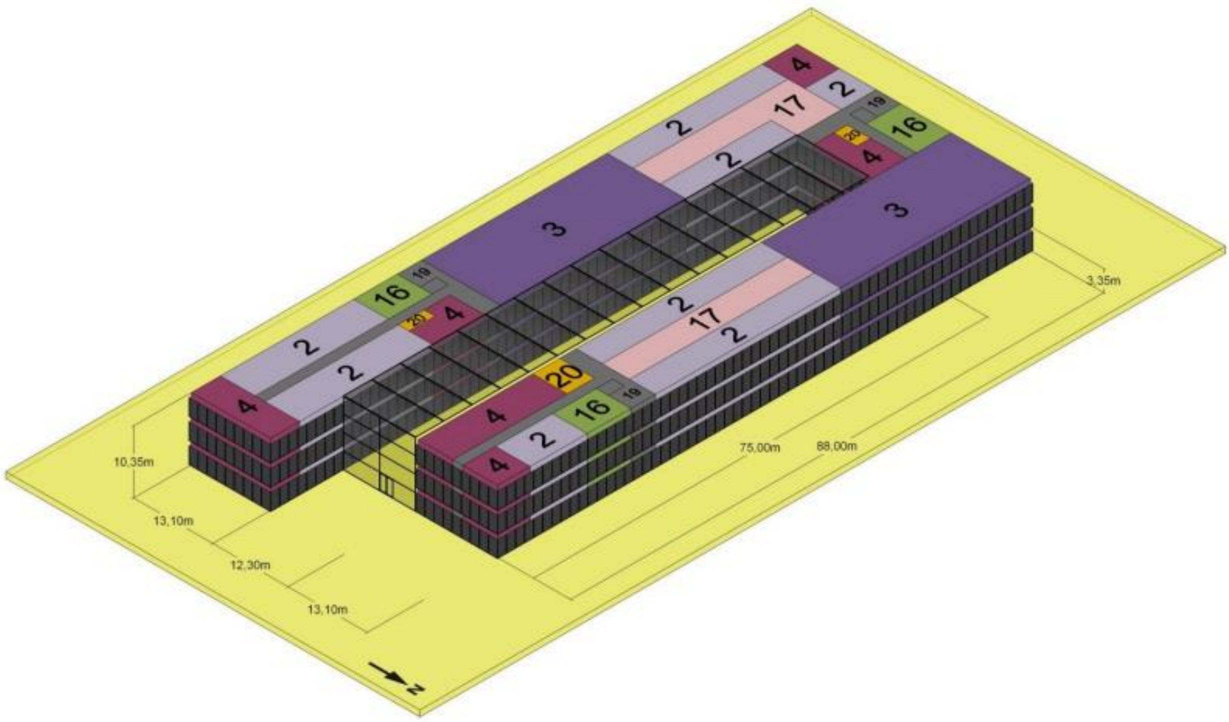


Figure 40: View on chapter and ground floor plan of the office building

The entire roof can be used for a PV-system. Solar irradiation is collected to substitute parts of the primary energy demand with renewable energy. Also the office building is equipped with an air-water heat pump for space heating and hot tap water.

Building Construction Variants and Materials (LCA stage I)

The thickness of the load-bearing layers of all wall constructions have been defined in consultation with experts. The statics of the timber-frame variant have been calculated in some more detail due to its complex, loadbearing, wooden structure. Based on the current building practice, the three most relevant mineral buildings materials are vertically perforated bricks, sand-lime bricks and reinforced-concrete/cellular concrete.

Basement

Regardless of the selected construction material for a building, the basement structure usually consists of reinforced concrete. However, their thickness strongly depends on the soil and the construction material. The choice of lightweight construction, such as wood frame construction, leads to an enormous reduction in the total weight of a building. The cellar walls can be built thinner due to the reduced weight of the overall construction. However, wooden buildings receive the same foundations as mineral buildings, which consist of concrete and whose dimensioning depends on the bearing capacity of the building ground.
For this study all calculations concerning the basement structure were chosen to be equally thick as the focus lies on the primary construction over ground. The basement components have the same impact on the LCA of all considered model buildings and can be neglected.
The layers of the foundation are as follows (from the inside out):

Table 8: Layers of the foundation for each model building

Number	Component	Thickness
1	Tiles and tile adhesives	1,0 cm
2	Cement screed + bitumen paper	5,0 cm
3	Impact sound insulation (mineral wool)	1,5 cm
4	Thermal insulation (mineral wool) + sealing made of glass fleece	5,0 cm
5	Reinforced concrete	25,0 cm
6	Subbase (concrete) + vapour barrier (PE-foil)	7,5 cm
7	Insulation (XPS-insulator) + Separating layer (geotextile)	8,0 cm
	Total	53,0 cm

The layers of the cellar walls are as follows (from the inside out):

Table 9: Layers of the cellar walls for each model building

Number	Component	Thickness
1	Synthetic resign dispersion + reinforced concrete	25,0 cm
2	Cement mortar	2,0 cm
3	Waterproofing (bitumen sheets)	0,6 cm
4	Perimeter insulation (XPS-insulator)	20,3 cm
5	Cement plaster + lime-cement plaster	2,3 cm
	Total	50,2 cm

Exterior Wall Structures

The exterior walls built the biggest portion of the building envelope. Thereby, they have a big impact on the energy balance, the mass balance and consequently the GHG-balance of a building. Due to the size of the MFH, the thickness of the load-bearing structure had to be adjusted for solid wood and wood frame variants. For the brick and sand-limestone the thickness of the load-bearing structure is sufficient to carry the weight of both the SFH and the MFH.

a) Variant 1 – Solid Wood

The load bearing construction of solid wood walls consist of continuous solid material. It is comparable to concrete and brick walls of conventional buildings. However, the specific density of wood is significantly lower than of conventional building materials. The layers of the solid wood wall are as follows:

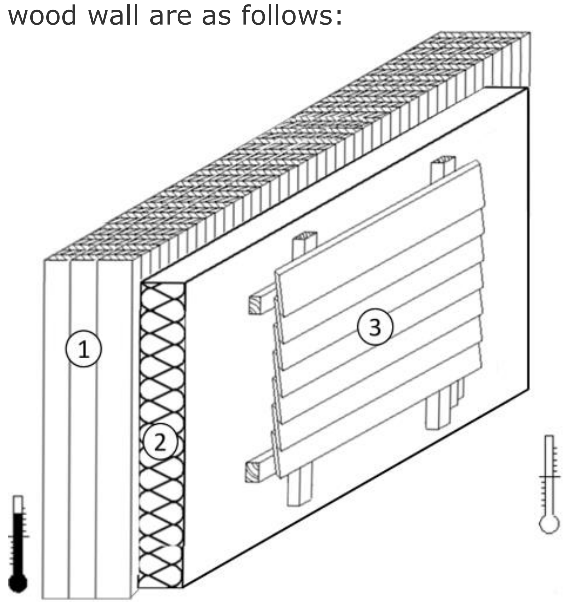


Figure 41: Layered structure of variant 1 – Solid wood wall [LEGEP]

Table 10: Components of wall SFH

Number	Component	Thickness		
		EFH	MFH	Office
1	Board stacking wall	18,0 cm	22,2 cm	20,3 cm
2	Wood-fibre insulation board	14,0 cm	13,0 cm	13,0 cm
3	Substructure + cladding (coniferous timber)	7,5 cm	7,5 cm	7,5 cm
	Total	39,5 cm	42,7 cm	40,8 cm

Due to the number of storeys of the MFH (and also the office building), the lower three levels must be stronger than the two top floors. Therefore, an average value of 22,2 cm of the bearing layer of the exterior walls is assumed for the calculations (see Table 11). To keep the U-value of 0,18 W/m²*K the insulation thickness had to be reduced accordingly. Nevertheless, the wall structure itself stays the same.

Table 11: Detailed and average thickness of the loadbearing layer of the MFH exterior wall

Storey	Thickness
1	25,0 cm
2	25,0 cm
3	25,0 cm
4	18,0 cm
5	18,0 cm

Table 12: Detailed and average thickness of the loadbearing layer of the Office exterior wall

Storey	Thickness
1	25,0 cm
2	18,0 cm
3	18,0 cm

b) Variant 2 – Wood Frame Construction

Typical and economic construction grids for wood frame construction are vertical and horizontal beam spacings of 625 mm. They are based on the standard format of planking material. The format of many insulating materials is also matched to these grids. Considering the right choice of beam size, the static of a building can always be achieved within this construction grid.

The model buildings are constructed in this specific construction grid. The beam size of the supporting framework of the SFH, the MFH and the office building differ from each other due to the different size of the buildings and the different number of storeys. On account of the five storeys, the pressure at the support points must be taken into account for dimensioning the supporting framework. To ensure the statics, the beam size must be as shown in Table 13.

Table 13: Detailed and average beam size of the MFHs exterior wall

Storey	Thickness [cm]	Average [cm]
1	24/24	
2	24/24	
3	18/24	18/24
4	12/24	
5	12/24	

For the calculations of the MFH and the office building an average beam size, resulting from the actual beam sizes of the different storeys, is being considered. The insulation thickness had to be adopted accordingly. The layers of the wood frame wall are as follows:

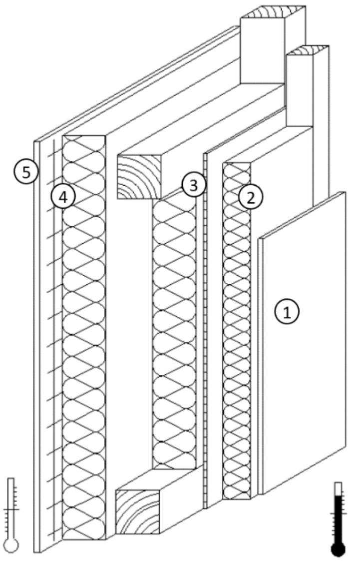


Figure 42: Layered structure of variant 2 - Wood frame construction [LEGEP]

Table 14: Components of wall variant 2

Number	Component	Thickness		
		SFH	MFH	Office
1	Plasterboard	1,2 cm	1,2 cm	1,2 cm
2	Facing shell with beams (coniferous wood) + insulation (flax)	5,0 cm	5,0 cm	5,0 cm
3	Wood frame construction (coniferous timber) with insulation (flax) + planking (OSB)	16/18 cm	18/24	18/24
4	Thermal insulation (wood fibre insulation board)	10,0 cm	13,0 cm	13,0 cm
5	Plaster (lime-cement)	0,5 cm	0,5 cm	0,5 cm
	Total	32,65 cm	30,9 cm	30,9 cm

c) Variant 3 – Vertically Perforated Bricks

The type of brick for this wall construction is a vertically perforated brick with integrated perlite insulation. The brick itself provides a good insulation value. Combined with perlite filled perforations, no further insulation on the outside is necessary to reach the desired U-value. Due to its load-bearing capacity the vertically perforated brick as shown in Table 15 is suitable for both, the SFH and the MFH. Bricks are not considered for Office buildings. The layers of the brick wall are as follows:

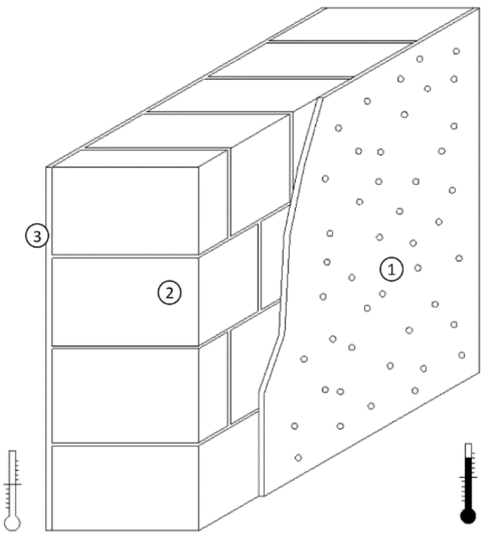


Figure 43: Layered structure of variant 3 – Bricks [LEGEP]

Table 15: Components of wall variant 3

Number	Component	Thickness (EFH + MFH)
1	Internal plaster	1,0 cm
2	Vertically perforated brick + perlite insulation + lime-cement mortar	49,0 cm
3	Exterior plaster (lime-cement)	1,5 cm
	Total	51,5 cm

d) Variant 4 – Sand-Limestone

The sand-limestone has no perforation. Sufficient insulation is provided by a thermal insulation composite system on the outside of the wall. Due to its physical properties, the sand-limestone with the specified wall thickness (see *Table 16*) is suitable for SFH, MFH and the Office building.

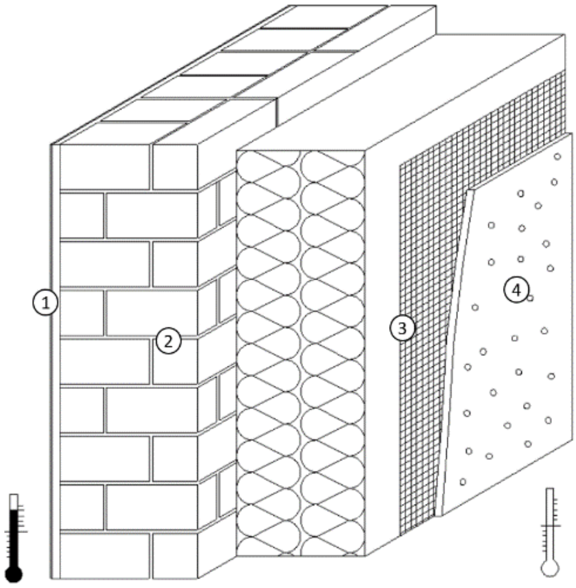


Figure 44: Layered structure of variant 4 - Sand-limestone [LEGEP]

Table 16: Components of wall variant 4

Number	Component	Thickness
1	Woodchip wallpaper + paste + gypsum plaster	1,5 cm
2	Sand-lime brick + lime-cement mortar	24,0 cm
3	Thermal insulation (mineral wool)	20,0 cm
4	Plaster (lime-cement)	0,6 cm
	Total	46,1 cm

e) Variant 5 – Reinforced concrete/ Cellular concrete
The concrete building structure consits of similar layers as the sand-linestone, but only with 20cm of reinforced concrete instead of the stone, see properties in Table 17. With its propeerties the wall structure is suitable for MFH and the office buildings (not relevant for SFH).

Table 17: Components of wall variant 5a – reinforced concrete

Number	Component	Thickness
1	Woodchip wallpaper + paste + gypsum plaster	1,5 cm
2	Reinforced concrete	20,0 cm
3	Thermal insulation (EPS)	20,0 cm
4	Plaster (lime-cement)	0,6 cm
	Total	42,1 cm

Table 18: Components of wall variant 5b – cellular concrete

Number	Component	Thickness (EFH + MFH)
1	Internal plaster	1,0 cm
2	Cellular concrete + lime-cement mortar	49,0 cm
3	Exterior plaster (lime-cement)	1,5 cm
	Total	51,5 cm

For cellular concrete, the properties are shown in

*Table **18***. They are quite similar to the layers for perforated bricks, since no additional insulation is required for the target energy efficiency level.

Storey Ceilings
In the following subchapters, the structure of the storey ceilings considered in this study are presented.

Variant 1 – Solid Wood
The loadbearing layer of the solid wood construction consists of bonded board stacking elements.

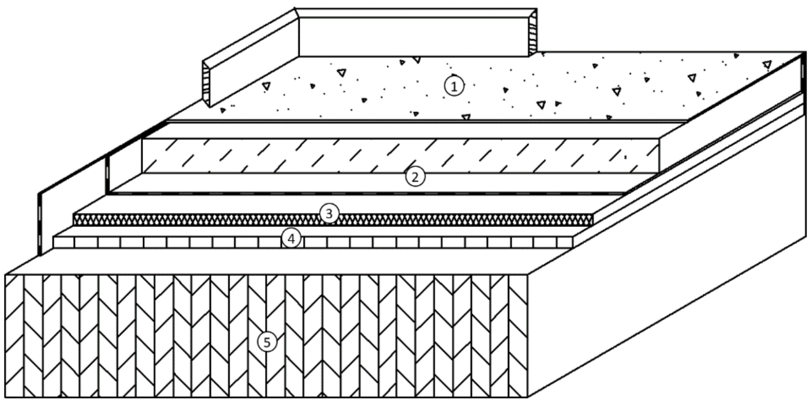


Figure 45: Layered structure of variant 1 – Solid wood

The layers of the solid wood ceiling are as follows:

Table 19: Components of ceiling variant 1

Number	Component	Thickness
1	Cork parquet	0,6 cm
2	Cement screed + bitumen paper	5,0 cm
3	Impact sound insulation (mineral wool)	2,0 cm
4	Planking (OSB)	1,9 cm
5	Board stacking ceiling	16,0 cm
	Total	25,5 cm

Variant 2 – Wooden Beams
The beam size of the loadbearing ceiling construction depends on the area to be bridged. For this purpose, the storeys of the model buildings are divided into chapters. For each chapter, the beam size is determined individually. The average beam size for the ceilings of the model buildings is height/width (h/w) = 8/24 cm (see Table 20). It is used for the calculations of this thesis and can be applied to the SFH, the MFH and

the office building. The geometric height of the beams always exceeds their width, because it increases the bending resistance moment[15].

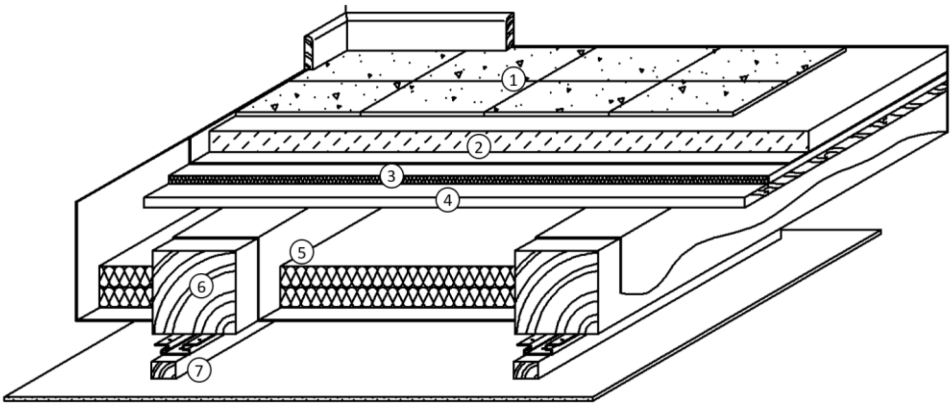


Figure 46: Layered structure of variant 2 – Wooden beams

The layers of the wooden beams ceiling are as follows:

Table 20: Components of ceiling variant 2

Number	Component	Thickness
1	Cork parquet	0,6 cm
2	Cement screed + bitumen paper	5,0 cm
3	Impact sound insulation (Mineral wool)	2,0 cm
4	Planking (flat pressed board)	2,2 cm
5	Insulation (Sheep wool) + trickle protection (Kraft paper)	10,0 cm
6	Wood frame construction (coniferous timber)	8/24 cm
7	Mounting (Steel and coniferous timber) + suspended ceiling (gypsum plasterboard)	4,0 cm
	Total	33,8 cm

Variant 3, 4 and 5 – Concrete

In mineral construction, ceilings generally consist of concrete. For that reason, the ceilings of the vertically perforated brick construction and the sand lime brick construction are the same. Concrete has a high load-bearing capacity and good impact sound properties.

[15] The bending resistance moment (also axial resistance moment) is required for the calculation of mechanical stresses under bending load. It can be used to determine the stiffness and deflection of geometric bodies under certain loads. An essential factor for the level of the bending resistance moment is the geometry of the beam cross-chapter and also the direction of the bending load [Altenbach, 2018; Maschinenbau-Wissen.de].

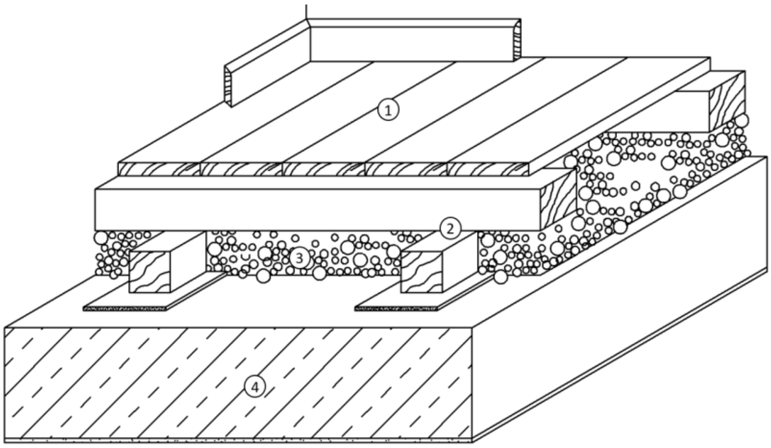


Figure 47: Layered structure of variants 3, 4 and 5 – concrete

The layers of the concrete ceiling are as follows:

Table 21: Components of ceiling variants 3, 4 and 5

Number	Component	Thickness
1	Floor boards (coniferous timber)	2,3 cm
2	Bearing timber construction (coniferous timber)	12,0 cm
3	Insulation (cellulose flakes)	12,0 cm
4	Reinforced concrete + dispersion paint	16,0 cm
	Total	30,3 cm

Roofs

The construction of the roof is identical for each SFH variant. It reflects a state-of-the-art construction. A good insulation is necessary for the roof of the SFH as well as for the roof of the MFH and offic building because the room underneath is used as living space. Especially during the summer months, the increased heat transfer of badly insulated roofs leads to the overheating of rooms. A distinction is made between the roofs of variant 1 – 2 and 3 – 5 of the MFH and the office building.

Roof of the SFH

The layers of the SFH roof are as follows:

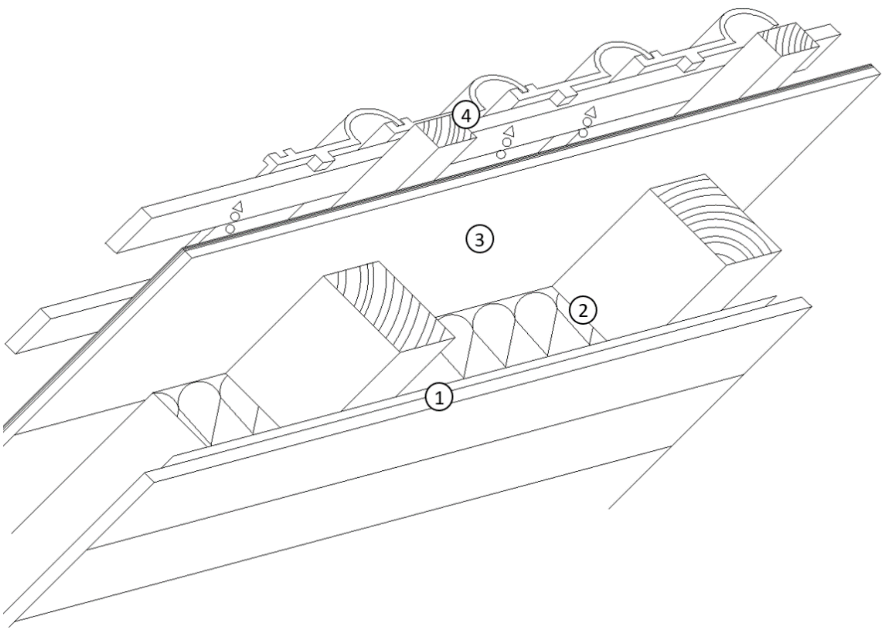


Figure 48: Layered structure of the roof for all SFH variants

Table 22: Components of the roof for all variants

Number	Component	Thickness
1	Visible shuttering + air sealing	2,4 cm
2	Beams (coniferous timber) + thermal insulation (cellulose flakes)	40/10 cm
3	Roof formwork (softwood fibreboard)	1,9 cm
4	Counter battening (coniferous timber) + roof battening (coniferous timber) + roof tiles	11,0 cm
	Total	55,3 cm

The entire useable surface of the roof is covered with polycrystalline photovoltaic (PV)-modules. The roof has a total surface area of 114 m² of which **112 m²** are covered with PV-modules. This corresponds to **80 PV-modules** as the size of a single module is 1,4 m². The roof surface faces south and is therefore ideally positioned for the use of a PV-system. Only the inclination of the pitched roof is not optimal at 12°, but due to the large area available it is inconsiderable.

Roof of the MFH/Office for variant 1 – 2
The load-bearing construction of the flat roof of the MFH for variant 1 – 2 consist of wooden double joists with thermal insulation in between.

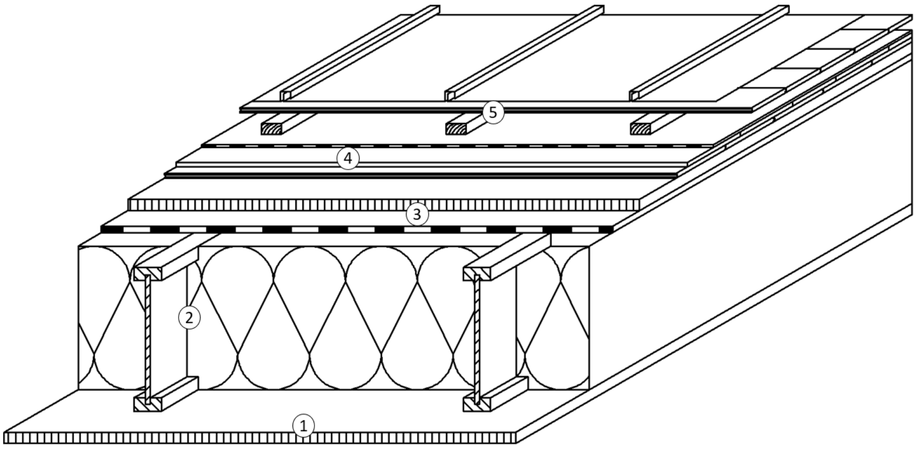


Figure 49: Layered structure of the roof variant 1 – 2 of the MFH/Office

The layers of the MFH/Office roof for variant 1 – 2 are as follows:

Number	Component	Thickness
1	Planking (OSB)	2,0 cm
2	Double joists + thermal insulation (mineral wool)	40/8 cm
3	Polypropylene fleece + Planking (OSB)	2,7 cm
4	Planking (coniferous timber) + separating layer (polyethylene)	2,5 cm
5	Battening (coniferous timber) + planking (coniferous timber) + metal covering	7,0 cm
	Total	54,2 cm

Roof of the MFH/Office for variant 3 – 5

Variant 3 – 5 of the MFH/Office are completed by a reinforced concrete roof, similar to their ceilings.

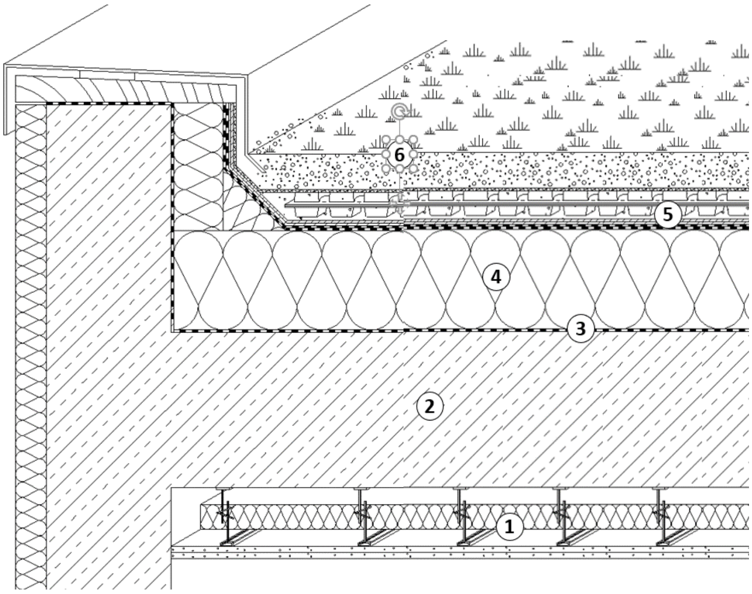


Figure 50: Layered structure of the roof variant 3 – 5 of the MFH/Office

The layers of the MFH/Office roof for variant 3 – 5 are as follows:

Number	Component	Thickness
1	Plasterboard and mineral wool insulation	8,0 cm
2	Reinforced concrete	25,0 cm
3	Bitumen sheets + bitumen paper	0,5 cm
4	Polystyrene rigid foam panels expanded	20,0 cm
5	Roof sealing (bitumen) + root protection (bitumen) with polyester fleece inlay	1,0 cm
6	Extensive substrate + gravel + vegetation	20,0 cm
	Total	74.0 cm

Windows and Doors

The share of windows and doors is equal to each model building, regardless of the construction material. All windows and doors are of identical quality to each variant. They have no impact on the ratio of the LCA's result.

The following chapters give an overview on the results of the LCA calculations with regard to the use phase (energy balances) and the construction-, demolition- and reuse-phase.

Energy Balance (LCA stage I)

This following sub-chapters give an overview on the energy balances of the reference building variants.

Single family house

As shown in the following table, the annual primary energy demand of each variant differs accordingly to the u-values of the exterior walls.

Table 23: Annual primary energy demand and u-values of all SFH variants

Energy	u-value wall	u-value roof	u-value win	final energy	primary energy
	W/(m²K)	W/(m²K)	W/(m²K)	kWh/(m²a)	kWh/(m²a)
Solid Wood (SW)	0,17	0,17	0,67	15,9	28,7
Wood Frame (WF)	0,17	0,17	0,67	15,9	28,7
Brick (BR)	0,17	0,17	0,67	16,0	28,7
Sand-Limestone (SL)	0,18	0,17	0,67	16,1	28,9
Cellular Concrete (CC)	0,18	0,17	0,67	16,1	28,9

Multi-family house

Table 24: Annual primary energy demand and u-values of all MFH variants

Energy	u-value wall	u-value roof	u-value win	final energy	primary energy
	W/(m²K)	W/(m²K)	W/(m²K)	kWh/(m²a)	kWh/(m²a)
Solid Wood (SW)	0,16	0,16	0,71	15,2	27,3
Wood Frame (WF)	0,17	0,16	0,71	15,4	27,7
Brick (BR)	0,17	0,16	0,71	15,3	27,5
Sand-Limestone (SL)	0,18	0,16	0,71	15,4	27,7
Reinforced Concrete (RC)	0,18	0,19	0,71	15,4	27,7

Office Building

Table 25: Annual primary energy demand and u-values of all Office variants

Energy	u-value wall	u-value roof	u-value win	final energy	primary energy
	W/(m²K)	W/(m²K)	W/(m²K)	kWh/(m²a)	kWh/(m²a)
Solid Wood (SW)	0,16	0,16	0,76	8,9	16,0
Sand-Limestone (SL)	0,18	0,18	0,76	8,9	16,0
Reinforced Concrete (RC)	0,17	0,17	0,76	8,9	16,0

Mass Balance (LCA stage II)

This following sub-chapters give an overview on the mass balances of the reference building variants.

Single family house

The mass balance of the variants strongly depends on the material used for the construction. Since wood has a lower density than mineral construction material, the mass of the two timber variants is lower than the mass of the two mineral variants (see Table 26). However, the ratio between the share of mass for the new construction and the maintenance is almost similar to each variant.

Table 26: Comparison of the mass of the SFH variants

Material	Mass total	Mass basement	Mass above basement
	t	t	t
Solid Wood (SW)	197	127	70
Wood Frame (WF)	194	127	67
Brick (BR)	335	127	208
Sand-Limestone (SL)	349	127	222

Material	Wood		Concrete		Bricks, Stones		Insulation		Steel		OSB	
	t	m3	t	m3	t	m3	t	m3	t	m3	t	m3
Solid Wood (SW)	40	88	136	59	-	-	5	71	6	1		
Wood Frame (WF)	16	33	136	59	11	7	7	126	6	1	6	10
Brick (BR)	5	9	195	84	102	124	3	65	8	1		
Sand-Limestone (SL)	5	9	196	85	85	61	13	101	8	1		

Multi-family house

The mass of the MFH increased, compared to the SFH, exponential to its size and the amount of construction material used. The ratio of the mass input for *new construction* and *maintenance* increased by 1 % and thereby nearly stayed the same to the SFH. The ratios can be taken from the following table.

Table 27: Comparison of the mass of the MFH variants

Material	Mass total	Mass basement	Mass above basement
	t	t	t
Solid Wood (SW)	666	312	354
Wood Frame (WF)	638	312	326
Brick (BR)	1.204	312	892
Sand-Limestone (SL)	1.530	312	1.218
Reinforced Concrete (R(	1.827	314	1.513

Material	Wood		Concrete		Bricks, Stones		Insulation		Steel		OSB	
	t	m3	t	m3	t	m3	t	m3	t	m3	t	m3
Solid Wood (SW)	205	460	375	165	-	-	19	220	36	5		
Wood Frame (WF)	82	171	377	167	61	37	27	313	34	5	22	38
Brick (BR)	3	4	725	331	346	486	35	334	40	6		
Sand-Limestone (SL)	6	11	1.022	456	330	237	67	400	56	7		
Reinforced Concrete (R(	6	11	1.565	669	81	58	33	411	85	11		

Office Building

Table 28: Comparison of the mass of the variants for the office building

Material	Mass total	Mass basement	Mass above basement
	t	t	t
Solid Wood (SW)	2.641	0	2.641
Sand-Limestone (SL)	6.535	0	6.535
Reinforced Concrete (R(	7.822	0	7.822

Material	Wood		Concrete		Bricks, Stones		Insulation		Steel		OSB	
	t	m3	t	m3	t	m3	t	m3	t	m3	t	m3
Solid Wood (SW)	1.675	3.758	966	425	0	0	155	1.797	294	41		
Sand-Limestone (SL)	49	90	2.785	1.243	2.696	1.936	547	3.268	457	57		
Reinforced Concrete (R(	49	90	6.147	2.628	662	474	270	3.357	694	90		

LCA Impact Assessment Details (LCA stage III)

This following sub-chapters give an overview on the life-cycle assessment (LCA) results for the reference building variants. In general, the LCA approach comprises a variety of environmental indicators and impact categories, but this analysis focuses on the Global Warming Potential (GWP) in CO_{2_eq} GHG emissions as main indicator.

Single family house

Table 29: Global warming potential of the four variants of the SFH

GWP (EU Data)	Manufacturing A1-A3	Retrofit B2+B4	Dsiposal C3-C4	End of LC D
	t CO_{2eq}	t CO_{2eq}	t CO_{2eq}	t CO_{2eq}
Solid Wood (SW)	-33,2	7,50	84,80	-46,20
Wood Frame (WF)	6,2	7,50	36,80	-23,80
Brick (BR)	72,5	7,50	17,70	-16,70
Sand-Limestone (SL)	67,9	7,90	18,90	-16,40

GWP (EU Data)	total	total	only Manu-facturing	only Manu-facturing
	t CO_{2eq}	kg CO_{2eq}/m2	t CO_{2eq}	kg CO_{2eq}/m2
Solid Wood (SW)	12,9	75,69	-33,2	-193,90
Wood Frame (WF)	26,7	156,11	6,2	36,23
Brick (BR)	81,0	473,74	72,5	424,03
Sand-Limestone (SL)	78,3	458,14	67,9	397,32

Multi-family house

Table 30: Global warming potential of the five MFH variants

GWP (EU Data)	Manufacturing A1-A3	Retrofit B2+B4	Dsiposal C3-C4	End of LC D
	t CO_{2eq}	t CO_{2eq}	t CO_{2eq}	t CO_{2eq}
Solid Wood (SW)	-218,7	34,40	422,00	-235,50
Wood Frame (WF)	-6,5	32,90	118,00	-102,70
Brick (BR)	320,6	32,60	53,10	-61,90
Sand-Limestone (SL)	318,9	49,60	70,30	-71,40
Reinforced Concrete (RC)	337,7	66,30	78,40	-92,20

GWP (EU Data)	total	total	only Manu-facturing	only Manu-facturing
	t CO_{2eq}	kg CO_{2eq}/m2	t CO_{2eq}	kg CO_{2eq}/m2
Solid Wood (SW)	2,2	2,85	-218,7	-286,29
Wood Frame (WF)	41,7	54,62	-6,5	-8,47
Brick (BR)	344,4	450,77	320,6	419,62
Sand-Limestone (SL)	367,4	480,85	318,9	417,37
Reinforced Concrete (RC)	390,2	510,74	337,7	442,03

Office Building

Table 31: Global warming potential of the three Office variants

GWP (EU Data)	Manufacturing A1-A3	Retrofit B2+B4	Dsiposal C3-C4	End of LC D
	t CO_{2eq}	t CO_{2eq}	t CO_{2eq}	t CO_{2eq}
Solid Wood (SW)	-1.631,8	256,64	3.148,31	-1.756,94
Sand-Limestone (SL)	1.710,9	266,12	377,18	-383,09
Reinforced Concrete (RC)	1.745,9	342,76	405,32	-476,66

GWP (EU Data)	total	total	only Manu-facturing	only Manu-facturing
	t CO_{2eq}	kg CO_{2eq}/m2	t CO_{2eq}	kg CO_{2eq}/m2
Solid Wood (SW)	16,2	2,60	-1.631,8	-261,46
Sand-Limestone (SL)	1.971,1	315,83	1.710,9	274,13
Reinforced Concrete (RC)	2.017,3	323,24	1.745,9	279,75

Annex II – Impact of Wooden Building on EU Building Sector – Details

Methodology – The Navigant BEAM² Model

This section gives an overview on the methodology used for the ex-ante assessment of policy option, which is the BEAM² model.

Terms and Definitions

As the **Built Environment Analysis Model BEAM²** model is set up in the framework of the European Energy Performance of Buildings Directive (EPBD), the general terms and definitions are aligned with it. The relevant document in that context is the umbrella document for all European standards within the EPBD, which is the Technical Report (TR): Explanation of the general relationship between various CEN standards and the Energy Performance of Buildings Directive (EPBD), see (CEN/TR 15615)[16]. They are also valid for the energy demand calculations for space heating and cooling from (DIN EN ISO 13790)[17], which are also referred to.

Scope

The scope of the model is described in this section. General references for the energy-related calculations are (CEN/TR 15615) and report by Boermans et al.[18].

The calculation methodology follows the framework set out in the Annex to the EPBD. For useful heating and cooling demand calculations the methodology in EN ISO 13790 (DIN EN ISO 13790) allows a simplified monthly calculation based on building characteristics. It is not dependent on heating and cooling equipment (except heat recovery) and results in the heating energy that is required to maintain the temperature level of the building. It can either be provided by the heating/cooling system or be recovered from the exhaust air stream. The calculations are based on specified boundary conditions of indoor climate and external climate, which are also given on monthly basis. Furthermore, information on the internal and solar heat gains as well as transmission and ventilation heat losses are required. Based that energy demand the delivered energy (final energy) for heating, cooling, hot water, ventilation and lighting if applicable are calculated per fuel type. It takes account of heat emission, distribution, storage and generation and includes the auxiliary energy demand from building-related components like fans and pumps.

In a last step the overall energy performance in terms of primary energy and CO_2 emissions is calculated. An overview of the calculation process is given in Figure 51, based on the umbrella document (CEN/TR 15615). It involves following the energy flows from the left to the right.

The three steps of the energy performance calculation are always done for reference buildings for a sector, age group, retrofit level and HVAC systems. Subsequently the energy costs per year and the investment costs in case of a new buildings or retrofit are calculated.

[16] *CEN/TR 15615. Technical Report - Explanation of the general relationship between various European standards and the Energy Performance of Buildings Directive (EPBD) - Umbrella Document, CEN April 2008 (English).*

[17] *DIN EN ISO 13790. Energy performance of buildings - Calculation of energy use for space heating and cooling (ISO 13790:2008), Beuth Verlag Berlin 1999 (German version EN ISO 13790:2008).*

[18] *Boermans, Thomas, Kjell Bettgenhäuser, Andreas Hermelink, and Sven Schimschar. May 2011. Cost optimal building performance requirements - Calculation methodology for reporting on national energy performance requirements on the basis of cost optimality within the framework of the EPBD, Final Report, European Council for an Energy Efficient Economy eceee, Stockholm (English).*

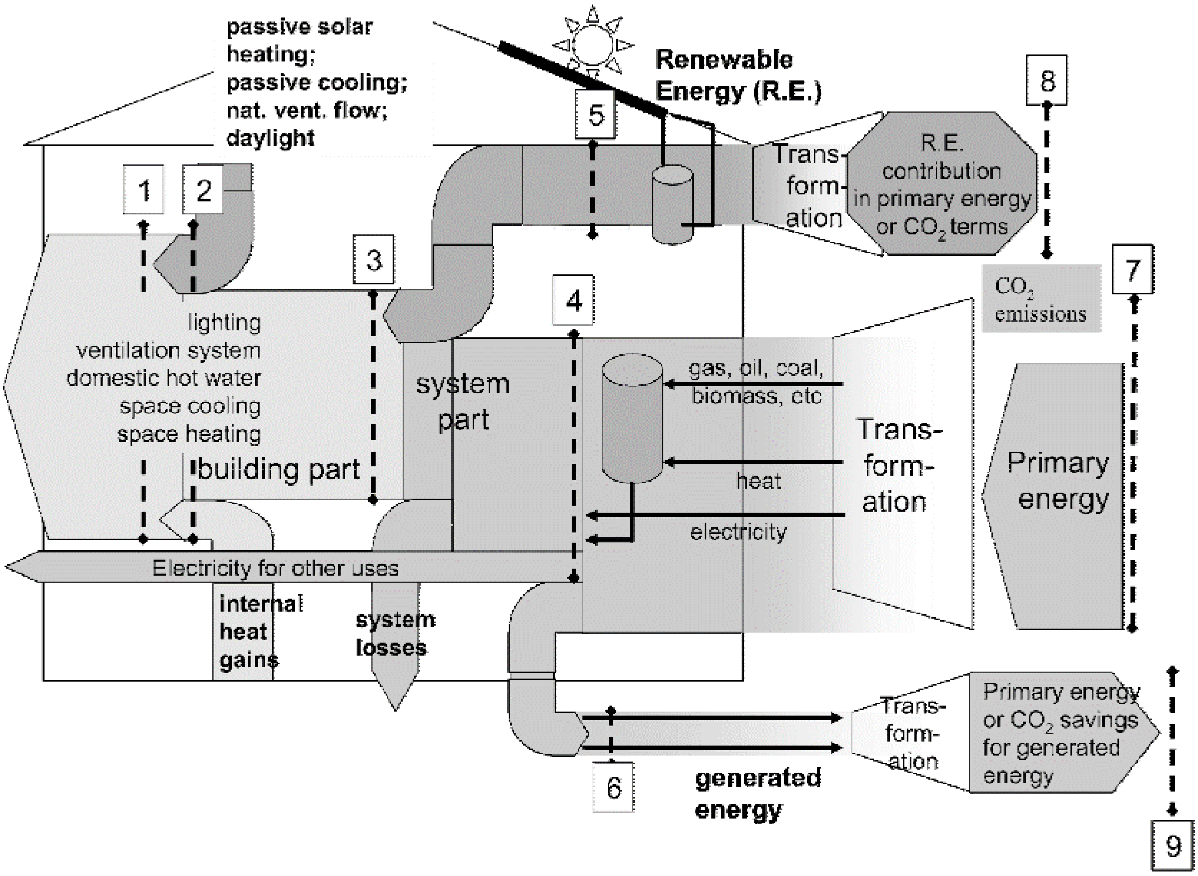


Figure 51: Schematic Illustration of the scope for the newly developed Built-Environment-Analysis-Model BEAM2, Source:(CEN/TR 15615)[19]

Key for Figure 51

(1) represents the energy needed to fulfil the users requirements for heating, cooling, lighting etc, according to levels that are specified for the purposes of the calculation.

(2) represents the "natural" energy gains - passive solar heating, passive cooling, natural ventilation, daylighting ˝U together with internal gains (occupants, lighting, electrical equipment, etc)

(3) represents the building's energy needs, obtained from (1) and (2) along with the characteristics of the building itself.

(4) represents the delivered energy, recorded separately for each energy carrier and inclusive of auxiliary energy, used by space heating, cooling, ventilation, domestic hot water and lighting systems, taking into account renewable energy sources and co-generation. This may be expressed in energy units or in units of the energy ware (kg, m3, kWh, etc).

(5) represents renewable energy produced on the building premises.

(6) represents generated energy, produced on the premises and exported to the market; this can include part of (5).

(7) represents the primary energy usage or the CO2 emissions associated with the building.

[19] *The figure is a schematic illustration and is not intended to cover all possible combinations of energy supply, on-site energy production and energy use. For example, a ground-source heat pump uses both electricity and renewable energy from the ground; and electricity generated on site by photovoltaic could be used entirely within the building, or it could be exported entirely, or a combination of the two. Renewable energy wares like biomass are included in [7], but are distinguished from non-renewable energy wares by low CO22 emissions. In the case of cooling, the direction of energy flow is from the building to the system.*

Structure and Methodology

The basic model setup and calculation process is shown in *Figure **52*** . It is based on the energy demand calculations for space heating and cooling from the ISO Standard 13790:2008 (DIN EN ISO 13790). As all calculations are executed for a highly disaggregated building stock with all its characteristics, the following description of the methodology and calculation process applies for all sub-segments of the building sector within the model.

Basic input to the model are data on the building stock such as building types, floor area, age groups, retrofit levels, HVAC systems in stock and population. Furthermore, the climate data such as temperature and irradiation is required. Based on this data a status-quo inventory of the building stock can be constructed.

For the scenario analysis as central part of the model, additional input data with respect to population forecast, GDP development, new building, demolition and retrofit activities, thermal insulation standards, heating, ventilation and air conditioning equipment, renewable energy systems and energy efficiency measures is required. Furthermore, energy costs, cost for energy efficiency measures at the building envelope and costs for heating, cooling and ventilation systems and renewable energy systems together with increase rates and discount rates are processed. With respect to the overall energy performance the greenhouse gas emissions factors and primary energy factors are required per fuel type and embodied energy and GHG emissions for energy efficiency and HVAC systems.

The calculation process over the scenario time frame is organized as follows. Based on the initial floor area distribution along the reference buildings (RB), age groups (AG), retrofit levels (RL), heating systems (HS)20, hot water systems (DHW)21 and cooling systems (CS) a forecast for the floor area is done taking into account new building, demolition and retrofit programs for all or parts of these combinations.

[20] Heating systems (HS) also include ventilation systems (VS) and solar thermal systems (STS) for HS support if applicable.
[21] Hot water systems (DHW) also include solar thermal systems (STS) for hot water if applicable.

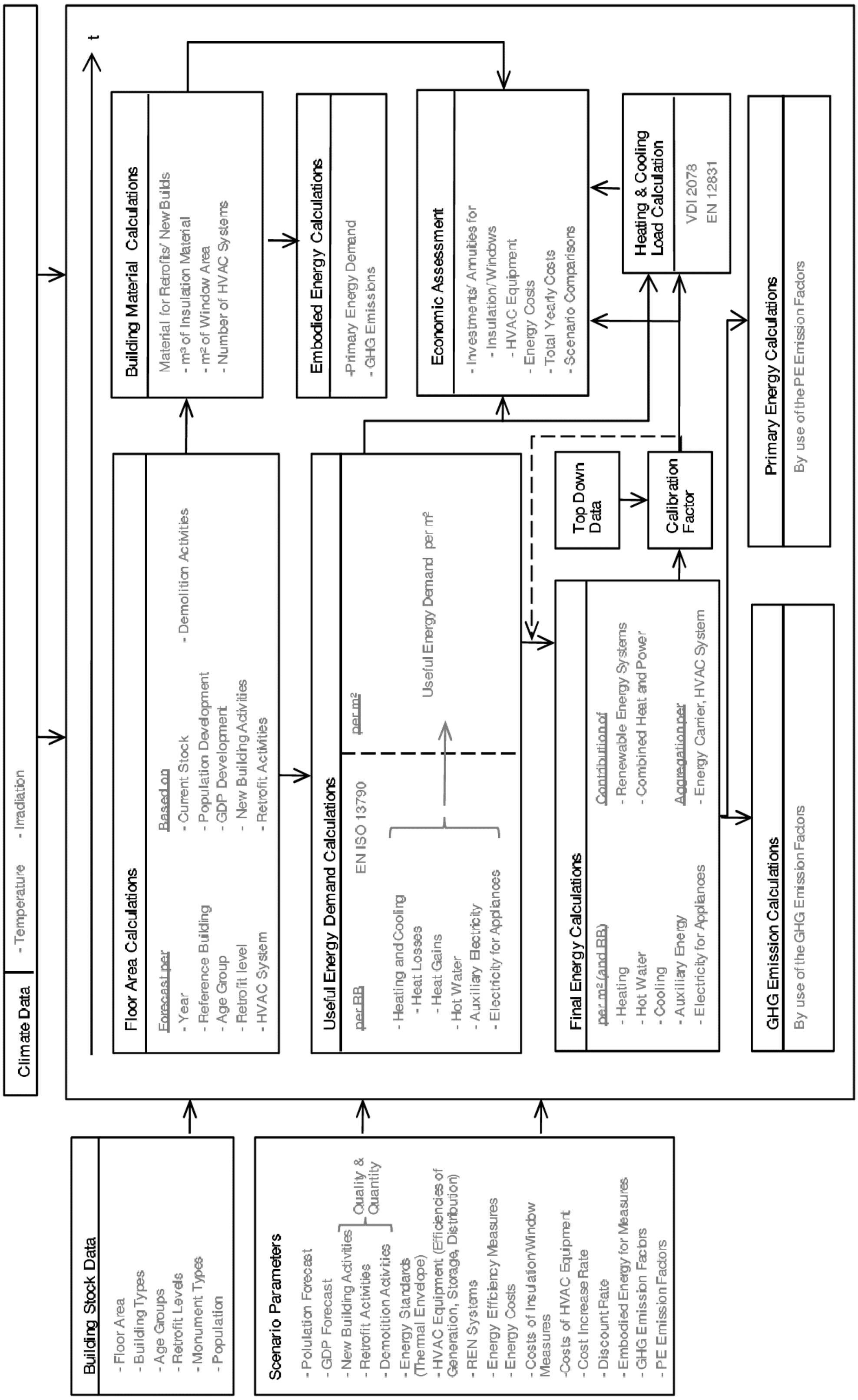


Figure 52: General Structure of the Built-Environment-Analysis-Model BEAM2

All activities in year i have an effect starting in year i+1. The useful energy demand for heating and cooling is derived from an integrated calculation algorithm based on (DIN EN ISO 13790). The energy demands for hot water, auxiliary energy and electrical appliances if applicable are also derived. The final energy is calculated based on the parameters of the HVAC systems[22]. The aggregated final energy for heating can be compared to top-down data. In this case a calibration factor is calculated, which can be applied to the final energy for heating. The delivered energy together with the primary energy and GHG emission factors are combined to the overall primary energy and GHG emissions. For the economic assessment heating and cooling loads per single building type are derived, which are relevant to the systems sizes and investment costs. The economic evaluation takes beside the investment costs also the energy costs into consideration. In addition to the above described output the embodied energy and primary energy for all energy-related components (efficiency and HVAC systems) are quantified in the model based on the total volumes of insulation, area of windows and number and power of HVAC equipment.

Scenario Results

Main outputs of the model are the floor area developments for RB, AG, RL, HS, DHW and CS in the first place. Next step is the calculation of the useful energy demands for heating, cooling and hot water. From this the final energy/ delivered energy for heating, cooling, hot water, ventilation and auxiliary energy is derived. For the overall energy performance the greenhouse gas emissions and primary energy is been calculated. Furthermore the embodied primary energy and greenhouse gas emissions of the energy related components for new buildings and retrofits are considered. For the economic evaluation energy costs per year are provided as well as investment costs in new buildings and retrofits. In order to compare yearly costs the investments are broken down along the lifetime of components to yearly costs by use of annuities. All results are given in specific units (e.g. per m^2) and for the overall building stock in the respective scenario.

Input Data

Input data to the model describes the current building stock as status-quo. This is e.g. the floor area distribution and the definition and specifications of reference buildings (RB), age groups (AG), retrofit levels (RL) and HVAC systems such as heating (HS), hot water (DHW), solar thermal systems (STS), ventilation systems (VS) and cooling systems (CS).

A more detailed description of the BEAM² model is available in the dissertation by Bettgenhaeuser[23].

EU Forest Sector

This chapter aims to answer the question how much timber can be extracted from the EU's forests up to 2050 for the purpose of building construction, and how much of a carbon sink this represents. As such, we first explain the dynamics of carbon sequestration in forests and products, and how the effects are measured. Subsequently, we discuss the structure and development of EU forests to 2030 and 2050 under different scenarios. Finally, we discuss the conversion and end-use sector, focusing on how much of the wood could be used for the production of end-products like sawn-wood, cross-laminated timber (CLT), glulam, oriented strand boards (OSB), wood fibre insulation boards (WFIB) or medium density fibre board (MDF).

[22] *The final energy is equal to the delivered energy plus energy produced in or on the building by solar or wind systems.*

[23] *Bettgenhäuser, K. (2013). Integrated Assessment Modelling for Building Stocks - A Technical, Economical and Ecological Analysis. Dissertation TU Darmstadt D17, Ingenieurwissenschaftlicher Verlag 2013.*

Carbon Sequestration in Forests and Wood Products

Before discussing the potential of the EU's forests to supply wood for the construction sector, it is important to create a common understanding of the dynamics of carbon sequestration in forests and products.
Forests impact greenhouse gas balances in two ways:

- Forests absorb CO2 from the atmosphere and sequester this in biomass, which thereby acts as a carbon stock.
- A share of this sequestered carbon is transferred to soils through litterfall from trees or turned into wood products through harvesting.

Carbon sequestration in wooden products with a long lifetime, such as wooden building frames, delays the release of carbon into the atmosphere and allows the regrowth of new forests which can then again absorb CO_2. Only a share of the harvested wood currently ends up in long-lived wood products, the largest part is used for bioenergy and paper/pulp.[24] Besides the sequestration effect, wood products can leverage emission savings by substituting fossil alternatives further down the value chain (see in-depth analysis in chapter 2).
The figure illustrates that when observing only the forest aspect, harvesting appears to lead to carbon losses to the atmosphere. However, when considering the entire wood value chain this effect is more nuanced and can lead to long-lived sequestration in products and various substitution effects that are higher than the (temporary) carbon loss from the forest.
In the past decades, European forests have shown a relatively stable rate of CO_2 removals from the atmosphere, mostly because the forest area expanded, and the annual increments of available wood also increased. At the same time, wood harvesting remained stable, meaning that the CO_2 removal rate could remain stable even though forests get older and on average take up less CO_2. Although it is very challenging to maintain such a rate of CO_2 removal due to the age structure of European forests[25], proper forest management and right harvesting forests can keep forests vital with a steady uptake of CO_2.

[24] Nabuurs et al. (2018), 'Effects of the EU-LULUCF regulation on the use of biomass for bio-energy', https://library.wur.nl/WebQuery/wurpubs/fulltext/449788
[25] Older forests have shown to have lower uptake of CO_2 compared to young-growth forests.

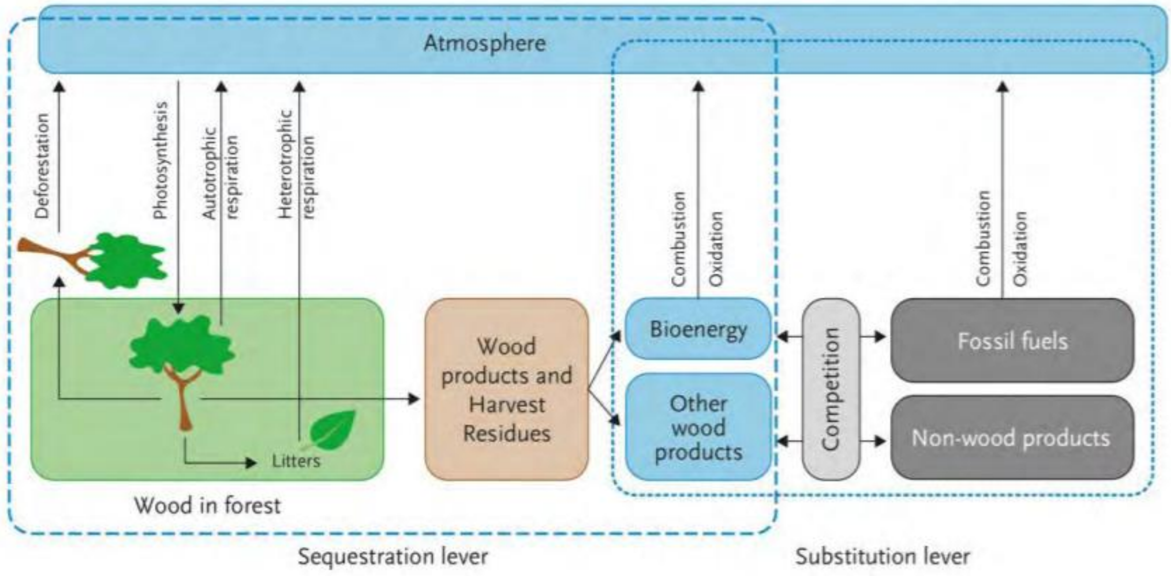


Figure 53: Flow diagram of carbon in a managed forest-wood products and energy chain.[26]

Wood Harvesting Scenarios

Various models exist that project the growth and availability of wood from EU forests, and scenario outcomes are dependent on parameters such as the assumed age structure of existing forests, harvesting intensity, rotation period of to be planted forest, forest management intensity and climatological conditions. Below we sketch a baseline for the 'net annual increment' of wood and different scenarios for the extraction of wood from the forest.

1. In the baseline, Nabuurs et al. (2018) assume a total net annual increment of 789 million m3 (Mm3) per year in 2015 and decreases slightly towards 2050 to about 777 Mm3. This is the amount of wood that could be theoretically harvested. However, to protect the forest carbon stock sustainable harvesting criteria should be applied, which would ensure that the harvesting level is below this net annual increment.

   Scenarios outlined by Nabuurs et al. (2018) show that harvesting removals could rise from 420 million m3 in 2015 to 420–560 million m3 in 2050 (*Figure 54*). All scenarios are modelled within the limitations – or rather possible interpretations – of the EU LULUCF Regulation. The LULUCF Regulation stipulates a no-debit target for every country, meaning that accounted emissions from land use are entirely compensated by an equivalent removal of CO_2 from the atmosphere through action in the sector. The level of harvesting very much determines the annual sink, and thus whether a country is 'debited'. All scenarios are modelled within the limitations – or rather possible interpretations – of the LULUCF Regulation.

[26] *Nabuurs et al. (2015), 'A new role for forests and the forest sector in the EU post-2020 climate targets', http://edepot.wur.nl/371799*

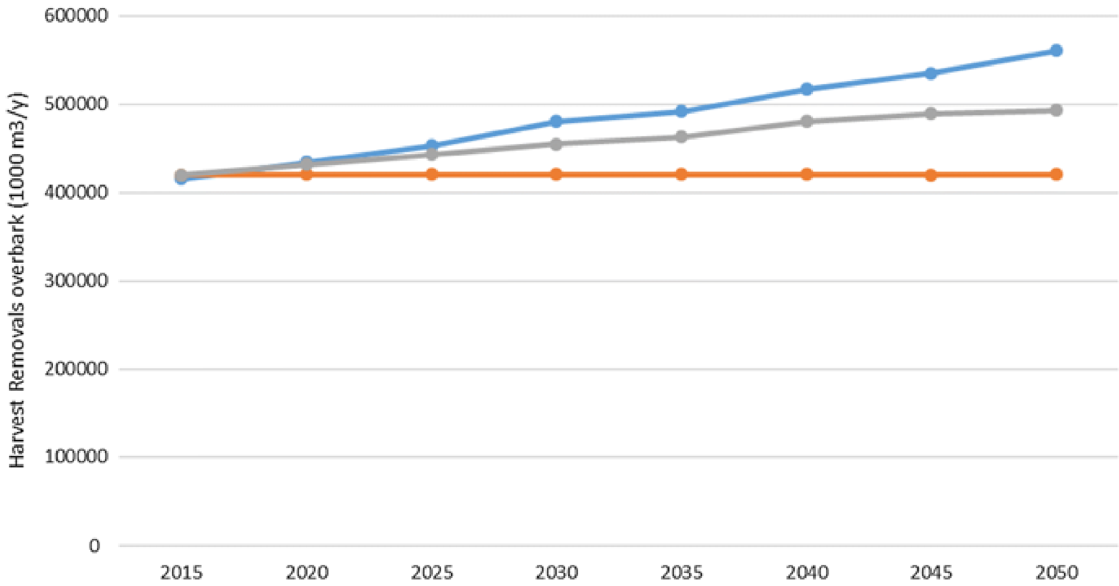


Figure 54: Development of harvesting removals within the limitations of the LULUCF Regulation.

The effect of these harvesting scenarios is that the current net forest sink would decrease from - 430 $MtCO_2$ in 2015 to between -275 and -90 Mt CO_2 in 2050. The main reason for this decline is the ageing of European forests and the corresponding decline in forest growth rate, combined with other trends like increasing wood demand and the related rising harvesting removals.
Despite a slight decrease of forest increment over time, in 2050 the increment is with 777 Mm3 still well above the total wood removals which sum up to 686 Mm3. Reasons for the declining forest increment are a change in age class structure towards a higher share of older forest stands that grow at lower rates and a saturation of biomass accumulation. European forests get older but also thicker and therefore grow relatively slower in the future.

2. Less recent studies like the European Forest Sector Outlook Study II from 2011 (EFSOS II) by UNECE also project harvesting potentials under various scenarios running up to 2030. The theoretical potential scenario explores the upper limit of wood harvesting while maintaining the growing stock of forest. Since the purpose of this study is to find the maximum amount of wood that could be extracted for the purpose of construction, the types of harvest selected are pre-commercial thinnings, regular stemwood thinnings and stemwood harvests.

   The net annual increment in this study increases from 744 Mm3 in 2010 to 860 Mm3 in 2030, which is higher than in the study by Nabuurs et al. The combined thinnings and stemwood harvests remain relatively stable over the assessment period, decreasing slightly from 657 Mm3 in 2010 to 655 Mm3 in 2030 – thinnings decrease and regular harvests increase. Within this study it is not taken as a boundary condition that the forest sink capacity is protected, which is the case in Nabuurs et al.
   By far the largest amounts of harvests in this study are concentrated in Sweden, Germany, France and Finland. However, Poland, Romania and Austria are also important for the European wood supply, all harvesting more than 15 Mm3 per year by 2030 with more than 10 Mm3 of thinnings.

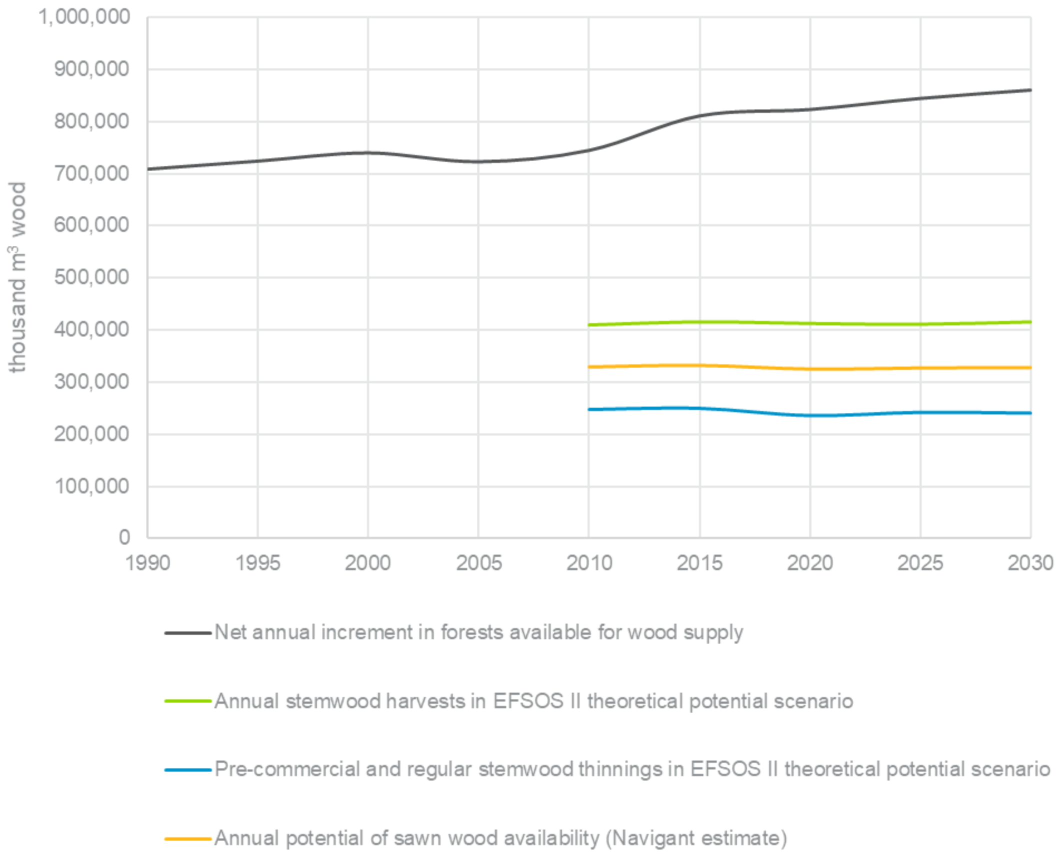


Figure 55: Overview of forestry parameters in the EFSOS II scenario, including an estimate of sawn wood available from harvest and thinning.

3. Besides the described studies, other forest assessments have been done by e.g. Jonsson et al (2018) using the CBM – GFTM model, the EU Reference Scenario 2016 and ReceBio. These assessments project a possible harvesting of 517 to 616 Mm3 already by 2030, which is predominantly driven by increased demand for fuelwood for bioenergy. Carbon stocks are often significantly affected in these studies due to the higher harvesting intensities which would lead to issues in complying with the LULUCF Regulation. As stated in the introduction, this may still be beneficial to do from a climate perspective since this carbon taken out of the forests is stored in the 'harvested wood products' pool and potentially leveraged to substitute more emission intensive products.

4. Finally, the SIMWOOD project should be mentioned, which aimed to demonstrate how the unused potential of European forests can be mobilised in a sustainable way, i.e. through increased and more collaborative forest management. Hence, compared to the previously mentioned studies the SIMWOOD operates a more bottom-up approach.
   Sweden and Finland are examples of countries with a large forest resource and well-developed forest-based sectors, where the wood mobilisation is already quite high in comparison to other countries. Germany also has quite high rates of utilisation, but the growing stock in German forests is also very high (as a result of a favorable climate and an accumulation of growing stock over decades and centuries). Slovenia also has a high growing stock that is increasing quickly. Ireland, the Netherlands and the UK are examples of

countries that have a relatively small amount of forest, but where the forests are growing fast and where the growing stock is increasing.
The study found that the largest total forest biomass potentials per unit of land can be found in Northern Europe (including the Baltic countries), central Europe, Slovenia, southwest France and central parts of Portugal. However, these do not represent additional potentials: a large part of this potential resource is already used to produce materials and energy and there is limited scope for further extraction of biomass in these areas. The location of the currently unused forest biomass potentials only partly correlates with regions that currently have high levels of wood production. This has implications for being able to mobilise and process additional wood volumes because the necessary infrastructure is possibly not yet in place to facilitate mobilisation. Quantitatively, the SIMWOOD project found that an additional **60 Mm³** may become available at the European scale compared to today's levels.[27]

Upon reviewing these modelling studies, we can conclude that estimates vary widely depending on the assumptions and boundary conditions that need to be met, e.g. existing policies (LULUCF Regulation), demand for bioenergy, and forest management practices:

- Bottom-up studies show that an additional 60 Mm3 may become available compared to the 2015 level of harvesting at 420 Mm3.
- Studies that respect the limitations stipulated by the LULUCF Regulation show that an additional 0–140 Mm3 can be harvested towards 2050.
- Studies that explore the upper limit of wood mobilisation in EU forests, while not letting harvests exceeding the net annual increment, show an additional potential of 97–235 Mm3 by 2030.

Forestry Sector Impacts

Building on the available potential of wood for construction from the EU's forests, this chapter will explore how much wood can be made available for the construction of wooden frames and building elements, its impacts on the forestry sector and how much carbon the wood can store. The forestry sector is a relatively complex economic sector, with various residue streams and recovered products that need to be taken into account in the balance. *Figure 22* illustrates the flows of woody biomass and wood products for 2015 in the EU.

[27] *SIMWOOD (2017), SIMWOOD: Sustainable innovative mobilisation of wood, https://www.wur.nl/en/project/SIMWOOD-Sustainable-innovative-mobilisation-of-wood.htm*

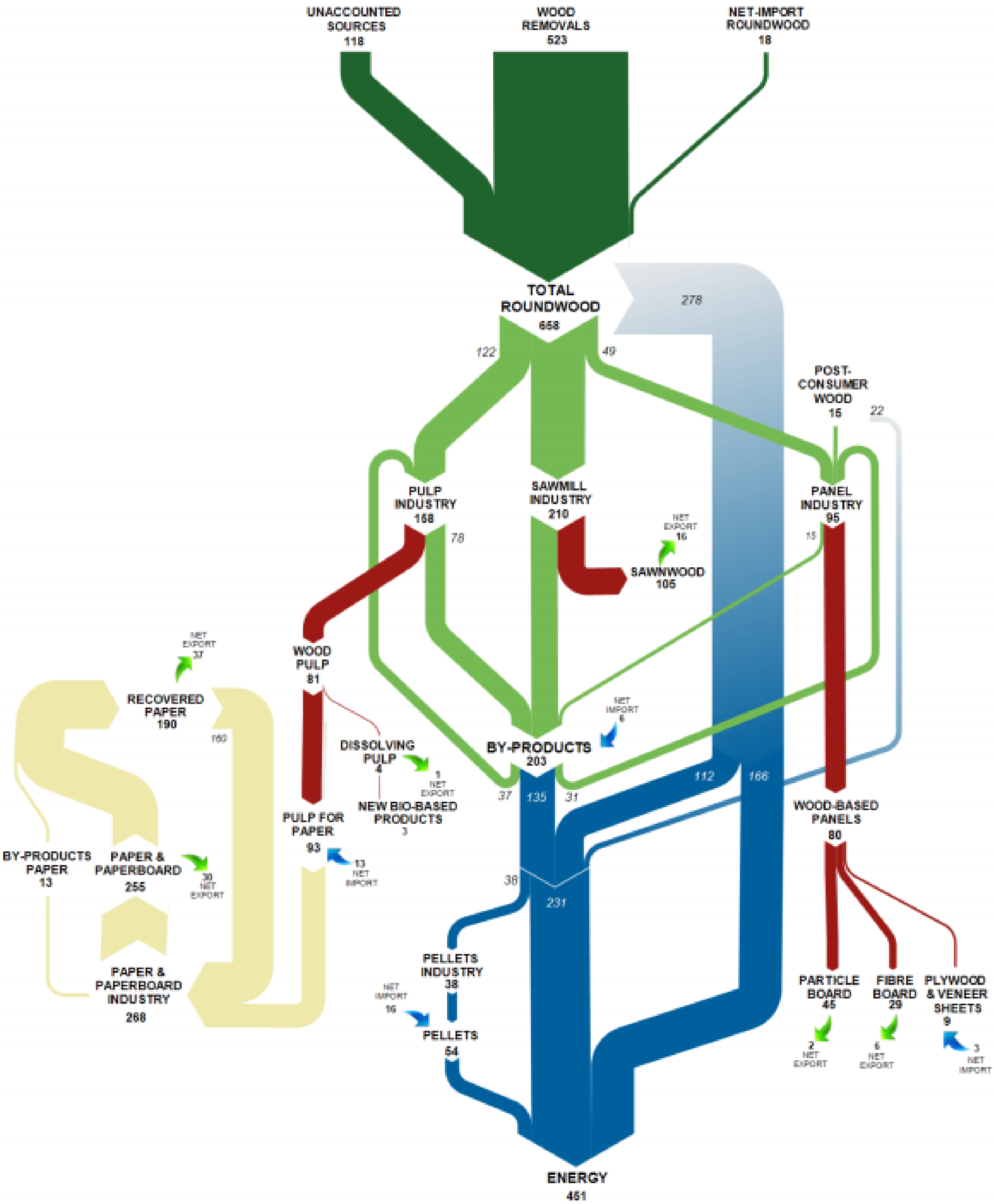


Figure 56: Sankey diagram of the EU's woody biomass balance in 2015 (units in Mm3).[28]

[28] JRC (2019), 'Sankey diagrams of woody biomass flows in the EU-28', https://publications.jrc.ec.europa.eu/repository/bitstream/JRC115777/jrc_sankey_2019_online.pdf

Construction wood mainly relies on large diameter logs, meaning the sawn wood/sawmill subsector. Of the harvested wood entering that sector, around half ends up as a residue going to the pulp or panel industry. Wood-based construction is therefore an important driver for raw material availability for pulp and paper and for emerging industries, as sawmilling generates raw materials for these industries (wood chips, bark, sawdust, and forest residues).

Wood Demand vs. Mobilisation Potential

The raw material impact of an increase in wood construction can be estimated as follows: A 100% market share of wood construction of all building in Europe would translate to a maximum direct annual demand of around 45–145 million m^3 of wood products, which translates then into around 100-400 million m^3 of raw wood, strongly depending on the raw material, species, production technique and product (sawn-wood needs to be produced from log-wood, while glulam or CLT, OSB, MDF and WIFB can also be produces from smaller logs and thinning). [29]

Cross-Laminated Timber

The main type of wood products used for modern wood construction are CLT, glulam, OSB and WFIB. A CLT panel consists of several layers of dried lumber boards stacked in alternating directions, bonded with adhesives and pressed to form a solid, straight, rectangular panel. An advantage of using CLT is that not only the large diameter logs can be used, but also thinnings. Pre-commercial and regular thinning are forest management activities aimed at maintaining forest health, and the harvested wood is generally used for bioenergy purposes. However, using thinnings as a resource for CLT production can increase revenue from thinnings and improve the economic feasibility of forest management.

CLT is typically made from Norway spruce, However, there is growing interest in and research on use of locally abundant, under-utilised timber resources for which there are no established structural properties as feedstocks for CLT. Examples include the use of Sitka spruce in Scotland and Ireland; Italian marine pine in Sardinia and European beech in Germany and Switzerland.[30]

Wooden Buildings as a Carbon Sink

Wood, on average, weighs 500 kg/m^3 and is made up of close to 50% carbon.[31] This implies that one m^3 of wood contains around 250 kg C, or 917 kg CO_2. If we assume that wooden construction reaches a market volume of 50 million Mm^3 of long-lived wooden products would be produced and 4.6 $MtCO_2$ would be locked into wooden construction elements annually. This is a figure for all of Europe, however there is a clear difference in market potential per region. Northern Europe has the highest market potential for additional wood construction, whereas this is lowest in Southern and Eastern Europe. This potential is based on local culture and structure of the construction sector and aligns well with the relative amount of harvests foreseen in e.g. the EFSOS study elaborated in the chapter on Wood Harvesting Scenarios.

---

[29] *Hurmekoski (2017), 'How can wood construction reduce environmental degradation?', European Forest Institute,* https://www.efi.int/sites/default/files/files/publication-bank/2018/efi_hurmekoski_wood_construction_2017_0.pdf*: The EU building stock is renewed at a 1% annual rate – an area of 240 million m2 is built annually1 . The wood use intensity of wood construction can be assumed to vary from 0.2 m3 /m2 (light frame) to 0.6 m3 /m2 (massive frame). Thus, a simple calculation suggests that 100% of the European construction markets could be covered with 45–145 million m3 of wood products, translating to around 100-400 million m3 of raw wood (the conversion factor to roundwood equivalent (RWE) ranging from 2.0 for sawnwood to 2.8 for cross-laminated timber (CLT)). As the increment in forests available for wood supply was 769 million m3 in 2010 in EU27 (Eurostat), a 100% market share of wood construction in Europe would require a maximum of 53% of the annual growth of European forests.*

[30] *Rose et al. (2018), Cross-Laminated Secondary Timber: Experimental Testing and Modelling the Effect of Defects and Reduced Feedstock Properties, doi:10.3390/su10114118*

[31] *Wood Ways (2018), Wood and Climate,* http://www.wooddays.eu/en/woodclimate/

Table 32: Market potential of wood construction in selected regions in Europe[32]

Region	Northern Europe	Central Europe and the UK	Western Europe	Southern and Eastern Europe
Market potential by 2030	High	Intermediate	Low to intermediate	Low
Countries	Finland, Norway, Sweden	Austria, Northern Italy, Southern Germany, Switzerland, The UK	France, Ireland, The Netherlands, Northern Germany	Czech Republic, Hungary, Poland, Southern Italy, Spain

Wood Market Dynamics

An important nuance in estimating the additional wood mobilisation potential in the EU for the construction sector is that over time demand for other end-uses also changes. If, for example, the potential is 60 million Mm^3 by 2030, but the demand for biomass for the pulp and panel industries increase by the same amount this leads to an allocation issue and would likely lead to wood imports to satisfy demand for all end-uses.

The UNECE EFSOS II study developed supply and demand pathways for different 'worlds', characterised by different GDP growth rates and population developments. One pathway (A1) is characterised by rapid economic and population growth, strong global trading networks and a consumer-oriented society. Due to rapid demand growth in this pathway, demand surpasses supply by 2020 creating a need for imports in the order of 300 Mm^3 by 2030. The Reference scenario, however, sees a slower demand growth and efforts to increase local production capacity which leads to an overall balance in wood supply and demand by 2030. Hence, developments in the wood market are sensitive to socio-economic factors and depending on socio-economic developments towards 2030, there may be a need to import wood products when additional wood mobilisation potential is allocated to the construction sector.

[32] *Adapted from Hurmekoski (2016), Long-term outlook for wood construction in Europe, https://www.dissertationesforestales.fi/pdf/article1994.pdf*

Table 1-2: Wood Resource Balance by all sectors

Wood Resource Balance							
Region		**EU27**		**IPCC Scenario:**			**A1**
potential	**2010**	**2020** M m³	**2030**	**2010**	**2020** M m³	**2030**	**demand**
stemwood C, ME	361.8	356.8	355.7	196.4	218.5	246.7	sawmill industry
stemwood NC, ME	182.3	178.1	181.0	11.4	14.2	17.3	veneer plywood
forest residues C+NC, ME	118.0	119.8	120.3	143.3	168.4	200.3	pulp industry
bark, C+NC, ME	23.7	23.3	23.4	92.3	110.1	135.7	panel industry
landsc. care wood (USE) ME	58.5	66.0	73.5	14.8	17.6	19.8	other material uses
				20.9	43.5	53.6	producer of wood fuels
sawmill by-products (POT)	86.6	96.0	107.8	85.5	98.3	113.9	forest sect. intern. use
other ind. res. reduced (POT)	29.7	34.9	41.7	83.2	242.0	377.1	biomass power plants
black liquor (POT)	60.4	71.3	84.9	23.2	68.8	81.5	households (pellets)
solid wood fuels (POT)	20.9	43.5	53.6	154.5	163.2	150.6	households (other)
post-consumer wood (POT)	52.0	58.7	67.3	0.0	0.8	29.0	liquid biofuels
total	**993.9**	**1,048.4**	**1,109.4**	**825.5**	**1,145.4**	**1,425.4**	**total**

Figure 57: Wood supply and demand in Scenario A1 (EFSOS II study).

Table 5: Balance between supply and demand in the Reference scenario

Components of wood supply									**Components of wood demand**
	source	2010	2020	2030	2010	2020	2030	source	
Stemwood removals	EFISCEN	595.1	649.5	684.7	237.7	244.8	252.9	EFI-GTM	Sawnwood
Harvest residues	EFISCEN	32.8	85.4	91.4	110.6	121.7	128.7	EFI-GTM	Panels
Stump extraction	EFISCEN	3.6	11.2	12.1	16.0	16.7	20.5	EFI-GTM	Plywood
Landscape care wood	EUwood	63.4	72.2	81.0	125.6	132.2	135.0	EFI-GTM	Chemical pulp
Post-consumer wood	EUwood	45.6	62.5	71.4	41.5	43.7	45.2	EFI-GTM	Mechanical pulp
Sawmill by-products	EFI-GTM	106.2	108.5	113.6	92.1	107.3	126.3	EUwood	Forest sector internal energy use
Black liquor	EFI-GTM	69.8	76.8	83.2	105.4	128.4	183.2	EUwood	Biomass power plants
Other industrial residues	EFI-GTM	34.4	37.7	40.6	23.5	43.4	49.5	EUwood	Households (pellets)
Net import	EFI-GTM	12.5	0.9	1.3	213.6	224.6	205.7	EUwood	Households (other wood energy)
					0.0	0.6	20.6	EUwood	Liquid biofuels
Total		**963.5**	**1 104.8**	**1 179.2**	**965.9**	**1 063.5**	**1 167.6**		**Total**

Figure 58: Wood supply and demand in Reference scenario (EFSOS II study).

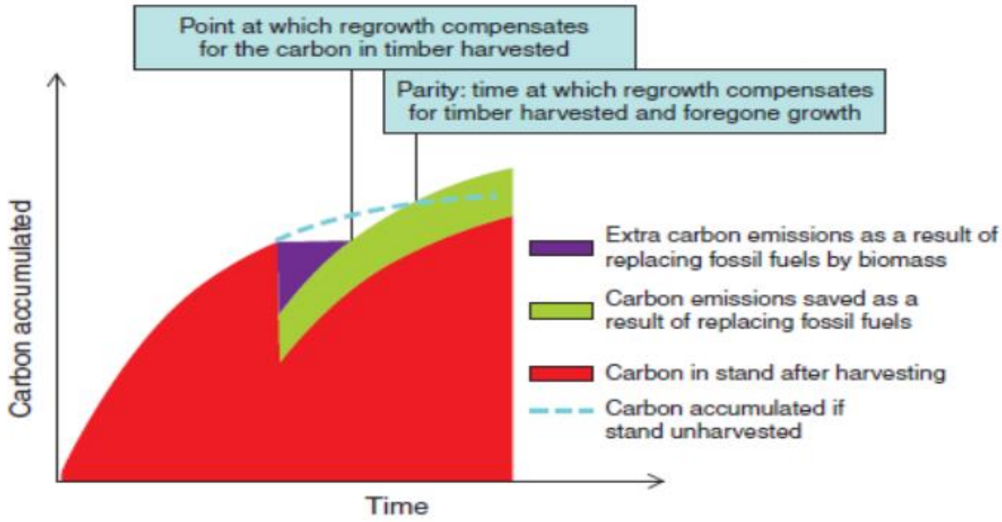


Figure 59 Carbon accumulation in trees over lifetime (EFSOS II study).

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

– by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

– at the following standard number: +32 22999696 or

– by email via: https://europa.eu/european-union/contact_en

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU publications

You can download or order free and priced EU publications at: https://publications.europa.eu/en/publications. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1952 in all the official language versions, go to EUR-Lex at: http://eur-lex.europa.eu

Open data from the EU

The EU Open Data Portal (http://data.europa.eu/euodp/en) provides access to datasets from the EU. Data can be downloaded and reused for free, for both commercial and non-commercial purposes.