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A partial life cycle assessment

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1 **Title**

2 Downsizing and the Use of Timber as Embodied Carbon Reduction Strategies for New-Build
3 Housing: A Partial Life Cycle Assessment

4 **Abstract**

5 The 2050 decarbonization goals coupled with the growing housing shortage in Europe intensify
6 the pressure on new-build dwellings to enhance their energy performance. Beyond a zero
7 operational energy, the focus has shifted towards reducing embodied carbon (EC). Against this
8 backdrop, this study investigates the simultaneous impact of downsizing and the use of timber
9 in new-build dwellings, EC reduction strategies seldom explored concurrently. Through partial
10 life cycle assessments, three scenarios are modelled: the Small, Medium, and Large House,
11 with two construction variations for each, comparing a modular timber design to a conventional
12 concrete alternative. Designs are based on dwellings built in Almere, the Netherlands. Data is
13 extracted from the Swiss Ecoinvent database using the TOTEM tool and the static -1/+1
14 approach for biogenic carbon accounting is adopted. Results show a total EC ranging from
15 42,608 to 70,384 kgCO₂eq for the timber designs versus 54,681 to 91,270 kgCO₂eq for their
16 concrete counterparts. Findings suggest that the relationship between house size and EC is
17 sublinear whereby a house twice the size entails less than twice the EC emissions. Only the
18 simultaneous implementation of downsizing and the use of timber achieved 53% carbon
19 savings. The discussion explores implications of outcomes across academic, industry and
20 policy perspectives, challenges in implementing smaller timber dwellings, and study
21 limitations and future research. Beyond its empirical contribution, this paper offers a practical
22 contribution with its hierarchical data analysis approach covering building, element and
23 component. This approach can be implemented by researchers and practitioners alike to inform
24 their design process.

25 **Keywords**

26 Embodied carbon, life cycle assessment, timber construction, downsizing, house size, housing

27

28

1 1. Introduction

2 In 2022, the global building sector accounted for over 30% of the final energy
 3 consumption, making it a significant contributor to climate change [1]. The impact is notably
 4 more accentuated in Europe where the building sector represents 40% of the region's energy
 5 demand [2]. Being a significant contributor is also an indication of where change is most
 6 needed. The Intergovernmental Panel on Climate Change (IPCC) has consistently highlighted,
 7 with high confidence, the potential for significant greenhouse gas (GHG) emissions reduction
 8 within the built environment to achieve the 2050 decarbonization goals [3]. However, recent
 9 reports, such as the Global Status report for buildings and construction by the United Nations
 10 Environment Programme (UNEP), reveal a widening gap between the observed performance
 11 of the building stock and the desired pathway towards a zero-carbon target in 2050 [4]. This is
 12 further corroborated by the International Energy Agency (IEA) in its own report on buildings,
 13 which categorizes the current status as 'not on track'. Therefore, given the pressing nature of
 14 climate change and the concerning trends emphasized by the UNEP and the IEA, there is an
 15 urgent need for more rapid change within the built environment to realign with the 2050
 16 decarbonization goals [1].

17 Given that the residential sector constitutes 75% of the European building stock and that
 18 housing was demonstrated to be responsible for 22% of a European household's carbon
 19 footprint [5], it is safe to say that housing is in itself a pivotal contributor to climate change in
 20 the European context [6]. Even more so considering that Europe is witnessing an increase in
 21 the total number of households, primarily composed of one to two persons, leading to an
 22 increase in housing demand [7]. This highlights another growing gap, this time between
 23 housing demand and housing supply [8]. Indeed, many European countries are facing a
 24 growing housing shortage [9] necessitating the construction of new-build dwellings to address
 25 this pressing issue. Thus, the housing sector's dominance in Europe, coupled with a growing
 26 housing shortage, presents a dual challenge. On the one hand, there is an urgent need for the
 27 built environment to expedite its transition toward a net-zero emissions scenario to combat
 28 climate change [1] and, on the other hand, future housing needs render the generation of added
 29 emissions inevitable. Overall, this amplifies the pressure on new-build dwellings to enhance
 30 their energy efficiency performance.

31 1.1. Research Background

32 When it comes to improving the energy performance of the built environment, the political
 33 focus has been on decreasing energy demand throughout a dwelling's operation phase [10].
 34 The European Energy Performance of Buildings Directive (EPBD) was a key catalyst with the

1 launch of NZEB: Nearly Zero-Energy Building, back in 2010 [11]. Conformingly, research has
2 focused on investigating the reduction of a dwelling's operational energy (OE) [12] and a zero
3 OE performance is now enforced by building regulations in several European countries.
4 However, a dwelling's environmental impact is not restricted to its use stage but also includes
5 GHG emissions released from the production, construction, and end-of-life stages, known as
6 embodied energy (EE). As such, characterizing a dwelling as zero-energy based on its OE alone
7 becomes inaccurate from a life cycle perspective. Even more so since it is argued that there is
8 a trade-off between OE and EE [12] and that emissions saved throughout the use stage are
9 partly, if not totally, off-set by emissions released in the initial stages due to the need for extra
10 building materials and technical systems [13]. Indeed, theoretically, with a zero OE
11 performance, EE makes up 100% of a dwelling's carbon footprint [14]. It becomes the sole
12 source of GHG emissions, hence, the most significant and influential one [13]. In practice, this
13 translates into the increase of the share of EE with the decrease of OE [15, 16], reaching 90%
14 in extreme cases [13]. This was designated as the 'carbon spike' effect indicating the high
15 carbon investment at the initial stages of a life cycle, a relatively shorter amount of time, risking
16 the dwelling's overall consumption budget [12, 17]. This increasing contribution of EE is
17 reinforced further when taking into account the future possibilities of the decarbonization of
18 the energy grids [13, 18, 19]. Hence, the normalization of a zero OE performance through
19 building regulations significantly increased the relevance of EE [19, 20]. This has forced a shift
20 of the political focus. What had been previously under-addressed amongst mitigation strategies
21 has now regained traction. The reduction of EE has reached the top priority level of several
22 international environmental programs [2, 4, 21] and it is necessary for research to follow suit
23 and focus on investigating strategies to reduce a dwelling's EE.

24 While research on EE has received less attention than OE, the exploration of embodied
25 carbon (EC) reduction strategies is not new [4, 15, 22]. Existing studies have predominantly
26 assessed the use of low-carbon materials through life cycle assessments (LCA) [23], with
27 timber being the most frequently studied material choice [12, 24-28]. However, the lack of
28 comparability of outcomes was identified as one of the most significant barriers hindering the
29 field's growth [10, 19, 20, 29-31]. For instance, reported carbon reduction outcomes from the
30 use of timber vary from 10% [18], to surpassing 50 % [26, 32]. Discrepancies between
31 outcomes are a result of significant variations of study characteristics, scope definitions, LCA
32 databases, the biogenic carbon accounting approach, and the lack of transparency around study
33 assumptions and modelling choices [13, 20, 33]. Variations in study characteristics include
34 differences in building types, size, geographic locations, structures, construction materials, and

1 building services rendering any attempt at a comparison invalid [13, 20, 29]. Variations in
 2 scope definitions are attributed to the system boundaries leading to the exclusion/inclusion of
 3 life cycle stages increasing the complexity of such comparisons [20, 34]. Limited system
 4 boundaries often lead to truncation errors whereby a dwelling's total EE is underestimated [18].
 5 Additionally, each implementation of LCA entails a level of uncertainty around EC estimations
 6 due to various assumptions made. Known examples concern the assumptions made around
 7 carbon storage accounting and end-of-life scenarios from the use of timber [19, 20]. Lastly, a
 8 lack of transparency obstructs the proper understanding of study outcomes and/or their
 9 verification and replication [10, 20]. Therefore, due to the lack of comparability of existing
 10 LCA studies, there is no general consensus on the extent of the effectiveness of EC reduction
 11 strategies. Transparency is key and there is a need for clear reporting of the decision making
 12 process to better grasp the impact of such decisions on overall results.

13 In light of the urgency of climate action, it is argued that reducing EE through the use of
 14 low-carbon materials alone is insufficient. Unlike OE, embodied emissions in a dwelling
 15 cannot be reduced once measures are implemented. Also, the implementation of any further
 16 measures automatically causes a further increase in the dwelling's EE regardless of its potential
 17 benefits [10]. This aspect of permanence that is peculiar to EE led to the call for the
 18 prioritization of the Sufficiency strategy promoting the avoidance of the demand for energy
 19 and materials over a building's life cycle [35-37]. Within the housing sector, sufficiency
 20 translates into building less by downsizing dwellings [36, 38]. Research investigating the
 21 impact of downsizing on a dwelling's EC remains limited [39]. Existing studies agree that
 22 larger houses tend to have a higher energy consumption including EC [15, 40-44], but diverge
 23 on the nature of this relationship, the definition of house size, and the reporting of outcomes.
 24 Findings concerning the relationship between house size and EC are contradictory and the
 25 correlation between them was demonstrated to be either super-linear [42, 45], or sublinear
 26 [46]¹. House size was either determined based on number of extra rooms in relation to the
 27 household size [42] or based on square meter of floor area [16, 45, 46]. Studies are often
 28 geographically located in contexts where the average house size investigated is considerably
 29 large reaching up to 328 m² in the U.S. and 246 m² in Australia [42, 45, 46]. This leads to
 30 outcomes that are not directly relatable to contexts like Europe where the average house size is
 31 known to be smaller and concepts such as the 'Tiny House' are being implemented [47]. Lastly,

¹ A linear correlation entails a 1:1 ratio. A house with double the size entails double the EC. A super-linear correlation exceeds a 1:1 ratio. A size with double the size entails more than double the EC. A sublinear correlation is less than a 1:1 ratio. A house with double the size entails less than double the EC.

1 when reporting outcomes, larger dwellings appear to be more energy efficient per square meter
 2 and smaller dwellings, with the lowest total emissions, have the highest emissions per square
 3 meter [16, 46, 48]. Therefore, not only is there a need to investigate the impact of house size
 4 on EC to promote downsizing, but there is also a need to clarify the nature of this correlation
 5 and to bring smaller dwellings into the discussion.

6 1.2. Research Gaps

7 These disparities in previous studies highlight the need to address several research gaps.
 8 First and foremost, while there are studies exploring the use of timber in housing as an EC
 9 reduction strategy, and others investigating the material impact of downsizing dwellings, these
 10 studies are typically conducted in isolation. Currently, there is a notable absence of research
 11 that examines the implementation of both strategies in tandem. Second, the lack of
 12 comparability of existing LCA studies investigating the use of timber in housing entails a lack
 13 of consensus on the extent of its effectiveness as an EC reduction strategy. This calls for more
 14 rigorous practices when implementing LCA methodology and reporting LCA outcomes and an
 15 increased transparency throughout for a better interpretation of results. Third, apart from the
 16 need to add to the restricted body of knowledge investigating downsizing as an EC reduction
 17 strategy, there is a need to address the contradictory findings regarding the nature of the
 18 relationship between house size and EC and investigate the impact of downsizing at the lower
 19 end of the range to reach outcomes that are more representative of the European context.

20 1.3. Research questions and objectives

21 To fill the identified gaps, this study aims to provide a detailed and thorough partial LCA
 22 that answers to the following main research question: *What is the impact of downsizing and the*
use of timber on the embodied carbon of a new-build dwelling? In addressing this main research
 23 question, the following research sub-questions are addressed: (1) To what extent does the use
 24 of timber, in comparison to traditional construction materials, contribute to the EC reduction
 25 of new-build dwellings? (2) To what extent does downsizing contribute to the EC reduction of
 26 new-build dwellings? (3) What is the nature of the relationship between house size and EC?
 27 (4) What is the combined impact of downsizing and the use of timber on the EC reduction of
 28 new-build dwellings? In answering the research questions, the specific objectives of this
 29 research are as follows: (a) to assess the EC of actual houses as case studies to reach outcomes
 30 that better reflect the European context and are more relatable to real-life especially when it
 31 comes to investigating the correlation between house size and EC, (b) to quantify EC savings
 32 from downsizing and the use of timber as individual EC reduction strategies, (c) to demonstrate
 33 the benefits of the simultaneous implementation of both strategies by emphasizing the

1 additional savings of implementing them together, and (d) to maximize transparency with a
 2 clear documentation of the decision making process underlying study outcomes.

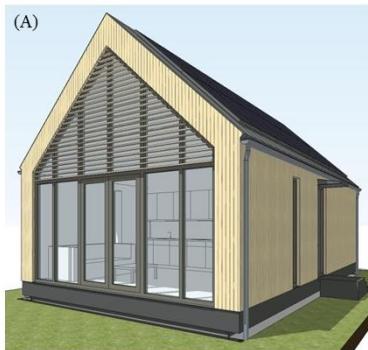
3 2. Material and Methods

4 2.1. Case study description

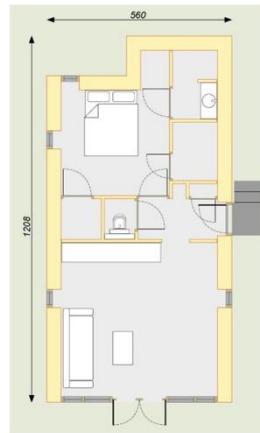
5 In the Netherlands, the average house size is around 106 m² [49] and Tiny houses are
 6 known to be between 15 and 50 m² [47]. Based on this range of dwelling sizes, this paper
 7 defines a small house to have a net floor area (NFA) of up to and including 50 m². A medium
 8 sized house has a NFA between 50 and 100 m² exclusively, and a large house has a NFA of 100
 9 m² and above. In accordance with this definition of house sizes, this study focuses on three
 10 distinct detached dwellings located in Almere, the Netherlands. These houses have respective
 11 net floor areas (NFAs) of 45, 76, and 104 square meters, collectively representing the small,
 12 medium, and large categories within the spectrum of *smaller* house sizes. As such, every
 13 dwelling size is referred to as a scenario: the “Small House” (45 m²), the “Medium House” (76
 14 m²), and the “Large House” scenario (104 m²). Figure 1 provides a description of each dwelling
 15 scenario with a render showing the exterior of the dwelling, a simplified floor plan and a list
 16 of the main dwelling characteristics.

17 The dwellings investigated were built as part of the project entitled Housing 4.0 Energy:
 18 Affordable & Sustainable Housing through Digitization (H4.0E) funded by Interreg North-
 19 West Europe [50]. Dwellings from the H4.0E project were selected due to their alignment with
 20 sustainability principles crucial for achieving the 2050 decarbonization goals, particularly in
 21 their use of sustainable building materials. All H4.0E dwellings follow ‘Wikihouse’, an open
 22 access design concept created to encourage self-building by providing digitally produced
 23 timber frame kits to be assembled on site [51]. With the exception of the dwellings’
 24 foundations, structural building elements such as beams and columns are made by assembling
 25 Multiplex wood panels. It is this uniformity in the dwellings’ structural design that
 26 distinguishes this case study. Since the dwellings only vary in size, hence material quantities,
 27 selecting this case study offers a unique opportunity to reach tangible outcomes that are more
 28 reflective of the actual impact of downsizing in a real-life setting. This comes in contrast to
 29 prior studies that gauge the impact of downsizing through a theoretical multiplication of house
 30 size [46]. In this way, examining H4.0E dwellings allows to provide insights that bridge the
 31 gap between theoretical models and the practical implementation of downsizing.

Scenario 1: Small House



(B)



(C) Dwelling type: Detached
Net floor area: 45 m²
Gross floor area: 59 m²
Number of floors: 1
Glazing: 23%

Scenario 2: Medium House



(B)

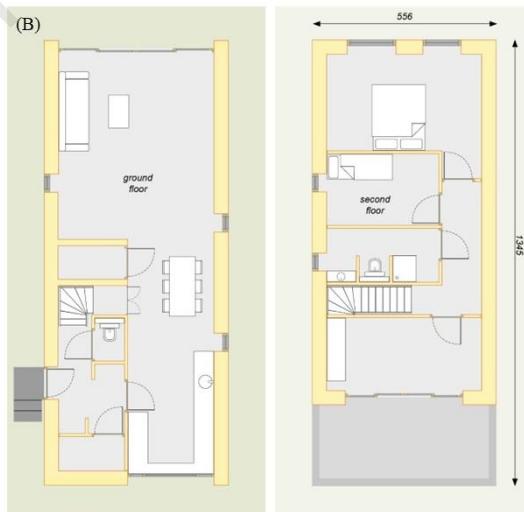


(C) Dwelling type: Detached
Net floor area: 76 m²
Gross floor area: 103 m²
Number of floors: 2
Glazing: 17%

Scenario 3: Large House



(B)



(C) Dwelling type: Detached
Net floor area: 104 m²
Gross floor area: 137 m²
Number of floors: 2
Glazing: 20%

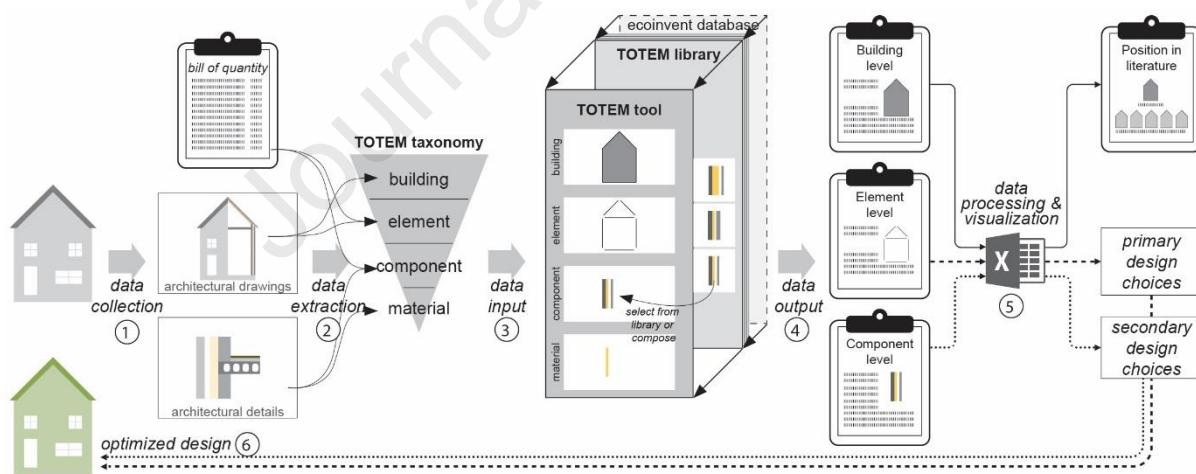
1

2 Figure 1: Characteristics of study scenarios (A) Dwelling exterior (B) Floor plans (C) Main dwelling characteristics

3

1 2.2. Research process

2 This study uses the Belgian based Tool to Optimize the Total Environmental Impact of
 3 Materials (TOTEM) for the EC analysis² [52]. TOTEM was selected for its accessibility as a
 4 free online tool, increasing the potential for study replication. It also taps into the Ecoinvent
 5 database [53] with a specific focus on the European/Belgian context which aligns well with the
 6 Dutch setting. Figure 2 provides a visual representation of this study's research process
 7 according to the following consecutive steps: data collection, data extraction as per the TOTEM
 8 taxonomy, data input following the TOTEM library, data output, data processing and
 9 visualization, finally leading to the optimized design³. Initially, data was collected in the form
 10 of bill of quantities, architectural drawings, architectural details and additional information
 11 provided by architects and engineers involved in the H4.0E project for the detailed composition
 12 of the dwellings. TOTEM adopts a hierarchical structure that divides a building into four levels:
 13 building, element, component, and material, referred to as the TOTEM taxonomy.
 14 Subsequently, the data extracted from the H4.0E project had to be transformed to match the
 15 TOTEM taxonomy to allow data input. The three main functional units for data entry are:
 16 square meters (m^2) for plane surfaces (roof, walls, floors, windows), linear meter (m) for
 17 structural elements (beams) and individual piece for other elements (doors) [52].



18
 19 Figure 2: Visualization of the research process

20 TOTEM also provides access to a library that includes predefined building elements and
 21 components. This feature grants users the flexibility to model a dwelling either by utilizing

² The methods underlying TOTEM abide by the European standards relevant to the assessment of the environmental performance of buildings and building products. These include the standard for sustainability of construction works, environmental product declarations (EN 15804+A2 and TR 15941), assessment of environmental performance of buildings (EN 15978), and the framework for assessment of buildings and civil engineering works (EN 15643).

³ Refer to Appendix A for a detailed step-by-step guide outlining the study's research process.

1 predefined building elements or by creating custom building elements using predefined
 2 building components. More importantly, this feature not only reduces the need for assumptions
 3 regarding material types and quantities but also becomes a means to verify that no element,
 4 component, or material have been overlooked. In this study, following data extraction, data
 5 input consisted of composing building elements by finding a match between the details
 6 provided by bill of quantities, architectural drawings, and architectural details and the
 7 predefined building components and materials provided by the TOTEM library. In that way,
 8 the TOTEM library enhances the precision and reliability of the data input as it serves as a
 9 cross-reference and validation of dwelling designs in addition to an initial confirmation by
 10 project architects and engineers. Figure 3 presents the data that was inputted into TOTEM
 11 through section drawings showing the detailed composition of the timber dwellings' main
 12 building elements.

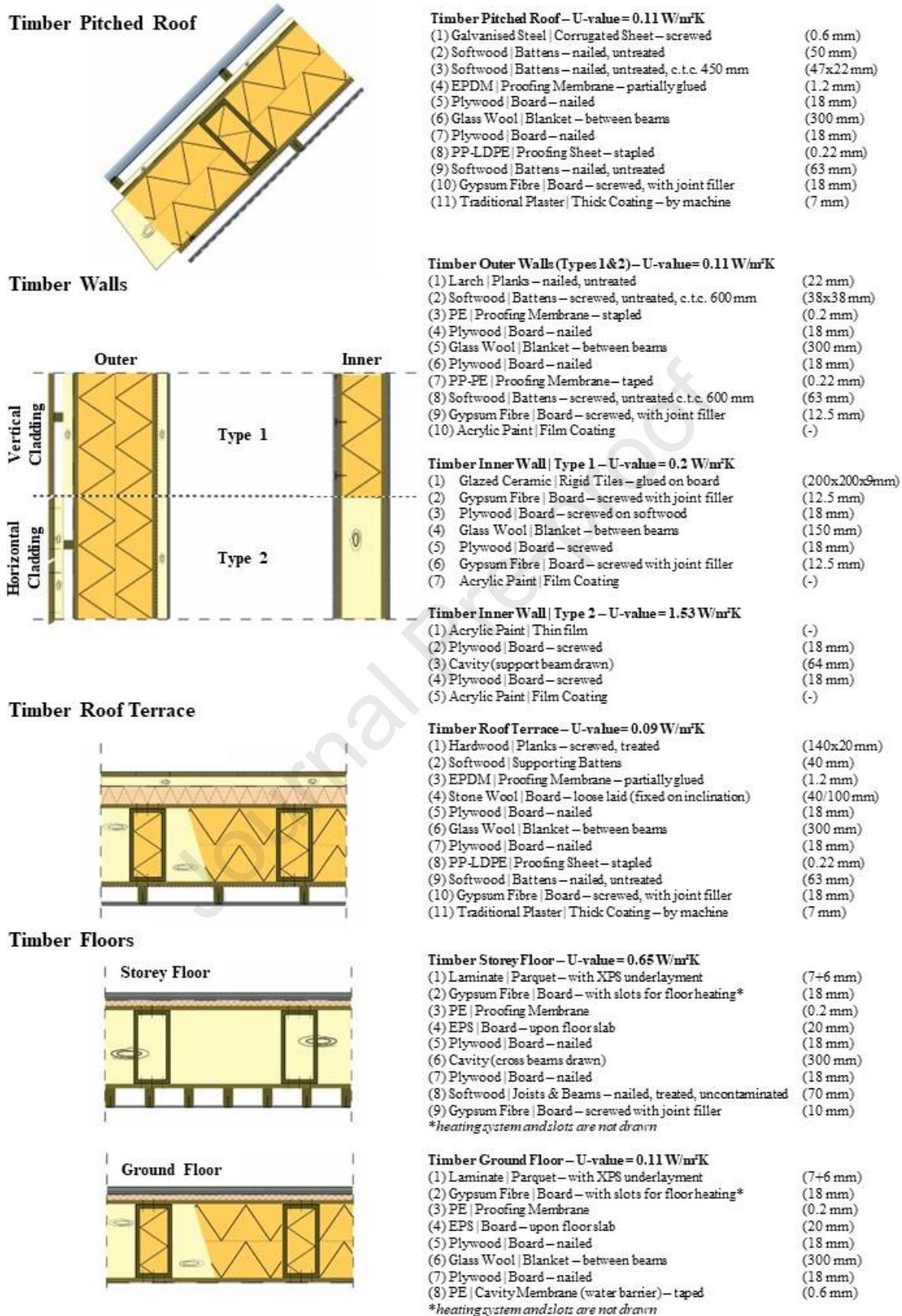
13 Next, in terms of data output, TOTEM provides results at the building, the building element
 14 and the building component levels, thus allowing the analysis to go across different levels of
 15 detail, from the aggregated to the specific. Then, in terms of data processing and visualization,
 16 on an aggregated level results pertaining to the building allowed situating the study outcomes
 17 in existing literature. On a more specific level, results pertaining to the building elements
 18 guided primary design choices related to the main materials of the building frame. Results
 19 pertaining to the building components informed secondary design choices including the choice
 20 of flooring, roofing and coating among others. Finally, the knowledge gained from the data
 21 processing and visualization allowed the revisiting and refining of the dwelling designs. Based
 22 on the newly acquired insights, an optimized design was modelled to demonstrate further EC
 23 reductions.

24 2.3. Baseline design

25 To investigate the impact of timber as the main building material, there is a need for a
 26 benchmark or reference dwelling incorporating conventional building materials and
 27 construction methods. For this purpose, a theoretical baseline was created with concrete, both
 28 prestressed and cast in-situ, and limestone blocks and bricks as the main building materials.
 29 Concrete was chosen as the base for the alternative construction variation considering it
 30 remains the standard go-to building material in the sector [12]. The detailed baseline designs
 31 were tailored to the Dutch context based on the input of practitioners within the H4.0E project.
 32 These baseline designs will serve as the control group to draw comparisons when quantifying
 33 the EC reductions from downsizing and the use of timber. Figure 4 provides section drawings

1 showing the detailed composition of the baseline dwellings' main building elements. It is worth
2 noting that the thermal performance of the H4.0E building envelope, represented in the timber
3 dwellings, surpasses Dutch standards. This was maintained the same when designing the
4 building envelope of the baseline alternatives⁴. Thus, overall two construction variations were
5 assessed: the timber-based (H4.0E) construction and the concrete-based baseline as the
6 conventional alternative, resulting in six different models. In each scenario, the timber design
7 and the baseline alternative have the same floor space and the engineering integrity of the house
8 was preserved in each variation.

⁴ A known advantage to timber construction is the use of the added space within the building frame to enhance the thermal performance of the building envelope. Expectedly, maintaining the same thermal performance in the concrete-based baseline designs resulted in unusual dimensions due to an increased insulation thickness added to a solid building frame. These occurrences are highlighted in orange in Figure 4.

⁵ This study's detailed material inventory can be found in the supplementary data.

BASELINE Pitched Roof – U-value = 0.11 W/m²K	
(1) Unglazed Ceramics Roof tiles – clipped	(246x195 mm)
(2) Softwood Battens – nailed, treated, uncontaminated	(32x26 mm)
(3) Softwood Battens – nailed, treated, uncontaminated	(30x20 mm)
(4) PP-LDPE Proofing Membrane – stapled	(0.22 mm)
(5) Sandwich Panel – screwed	
(5a) Chipboard	(3 mm)
(5b) EPS Graphite	(150 mm)
(5c) Chipboard	(8 mm)
(6) Softwood Beams – nailed, treated, uncontaminated	(65x175 mm)
(7) <i>Stone Wool</i> Blanket – <i>between beams</i>	(150 mm)
(8) Gypsum Fibre Board – screwed with joint filler	(12,5 mm)
(9) Acrylic Paint Thin Coating	(-)

BASELINE Outer Walls – U-value = 0.11 W/m²K	
(1) Fired Clay Bricks – laid in cement mortar	(188x88x48 mm)
(2) Cavity Ventilated	(40 mm)
(3) PE Proofing Membrane – stapled	(0.2 mm)
(4) Steel Cavity Ties - (4 ties/m ² , 180 mm, d=3.5 mm)	(n.a.)
(5) PVC Insulation Clips – for cavity wall	(n.a.)
(6) <i>Stone Wool</i> Blanket	(300 mm)
(7) Limestone Hollow Bricks – glued	(298x150x148 mm)
(8) Plaster Thick Coating – reinforced base	(6 mm)
(9) Acrylic Paint Film Coating	(-)

BASELINE Inner Wall Type 1 – U-value = 0.2 W/m²K	
(1) Acrylic Paint Film Coating	(-)
(2) Traditional Plaster Thick Coating – by machine	(7 mm)
(3) Stone Wool Board	(150 mm)
(4) Limestone Solid Blocks – glued	(298x150x148 mm)
(5) Glazed Ceramic Rigid Tiles – glued on board	(200x200x9 mm)

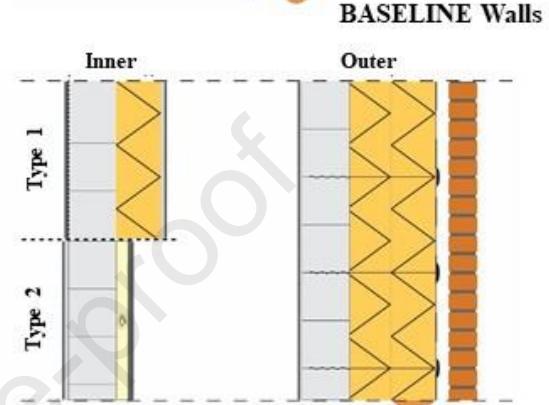
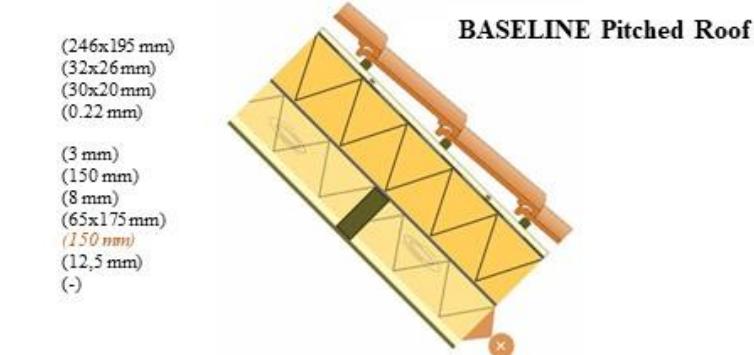
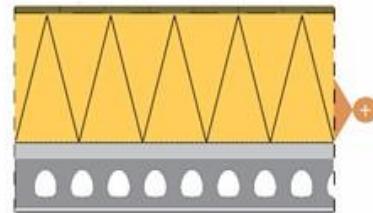
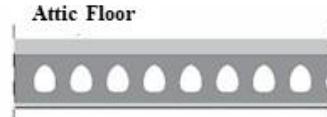
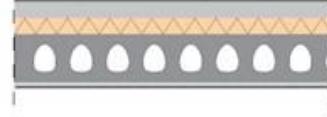
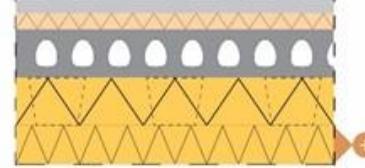
BASELINE Inner Wall Type 2 – U-value = 1.79 W/m²K	
(1) Acrylic Paint Film Coating	(-)
(2) Gypsum Fibre Board – screwed, with joint filler	(12,5 mm)
(3) Softwood Battens – screwed, untreated, c.t.c. 300 mm	(38x38 mm)
(4) Limestone Hollow Bricks – glued	(298x150x148 mm)
(5) Traditional Plaster Thick Coating – by machine	(12 mm)
(5) Acrylic Paint Film Coating	(-)

BASELINE Roof Terrace – U-value = 0.09 W/m²K	
(1) Hardwood Planks – screwed, treated	(140x20 mm)
(2) Softwood Supporting Battens	(40 mm)
(3) PE Proofing Membrane – stapled	(0.2 mm)
(4) Stone Wool Board – loose laid (fixed on inclination)	(40/100 mm)
(5) <i>Stone Wool</i> Board – <i>upon floor slab</i>	(300 mm)
(6) EPDM Proofing Membrane – partially glued	(1,2 mm)
(7) Concrete Screed	(50 mm)
(8) Steel Mesh Reinforcement – 50x50	(n.a.)
(9) Concrete Hollow Slab Floor - prestressed	(150 mm)
(10) Traditional Plaster Thick Coating – by machine	(7 mm)
(11) Acrylic Paint Film Coating	(-)

BASELINE Attic Floor – U-value = 1.9 W/m²K	
(1) Concrete Screed	(50 mm)
(2) Steel Mesh Reinforcement – 50x50	(n.a.)
(3) Concrete Hollow Slab Floor - prestressed	(150 mm)
(4) Traditional Plaster Thick Coating – by machine	(7 mm)
(5) Acrylic Paint Film Coating	(-)

BASELINE Storey Floor – U-value = 0.52 W/m²K	
(1) Laminate Parquet – with XPS underlayment	(7+6 mm)
(2) PE Proofing Membrane	(0.2 mm)
(3) Concrete Screed	(50 mm)
(4) Steel Mesh Reinforcement – 50x50	(n.a.)
(5) Stone Wool Board – <i>upon floor slab</i>	(50 mm)
(6) Concrete Hollow Slab Floor - prestressed	(150 mm)

BASELINE Ground Floor – U-value = 0.11 W/m²K	
(1) Laminate Parquet – with XPS underlayment	(7+6 mm)
(2) PE Proofing Membrane	(0.2 mm)
(3) Concrete Screed	(50 mm)
(4) Steel Mesh Reinforcement – 50x50	(n.a.)
(5) Stone Wool Board – <i>upon floor slab</i>	(50 mm)
(6) Concrete Hollow Slab Floor - prestressed	(150 mm)
(7) <i>Stone Wool</i> Board – <i>below floor slab</i>	(275 mm)
(8) PE Cavity Membrane (water barrier) – taped	(0.6 mm)

Figure 4: Detailed composition of main building elements under the baseline design ⁶.**BASELINE Roof Terrace****BASELINE Floors****Storey Floor****Ground Floor**⁶ This study's detailed material inventory can be found in the supplementary data.

1 2.4. Research scope

2 The physical system boundary of a dwelling is associated with the different materials,
 3 components and elements that make up the dwelling [18]. It is composed of its structural
 4 elements and building services including renewable energy technologies. Table 1 lists the
 5 building elements included and excluded from this study's physical system boundary. This
 6 study incorporates all building materials, components and elements related to the construction
 7 of the dwellings considering structural elements can be responsible for up to 50% of the initial
 8 EC and 20% of the whole life cycle carbon [19]. Including sanitary elements and furniture is
 9 not common practice in LCA studies and were excluded from this investigation in an effort to
 10 increase the comparability of outcomes. Due to uncertainties around the estimation of EC
 11 values and assumptions on the maintenance, replacement, and end-of-life of building services
 12 and renewable technologies, these were also excluded from this study. Additionally, it should
 13 be highlighted that larger dwelling sizes require additional fittings and furniture [54]. Including
 14 such elements would accentuate the EC savings of smaller dwellings and excluding them
 15 indicates that this study's outcomes are conservative.

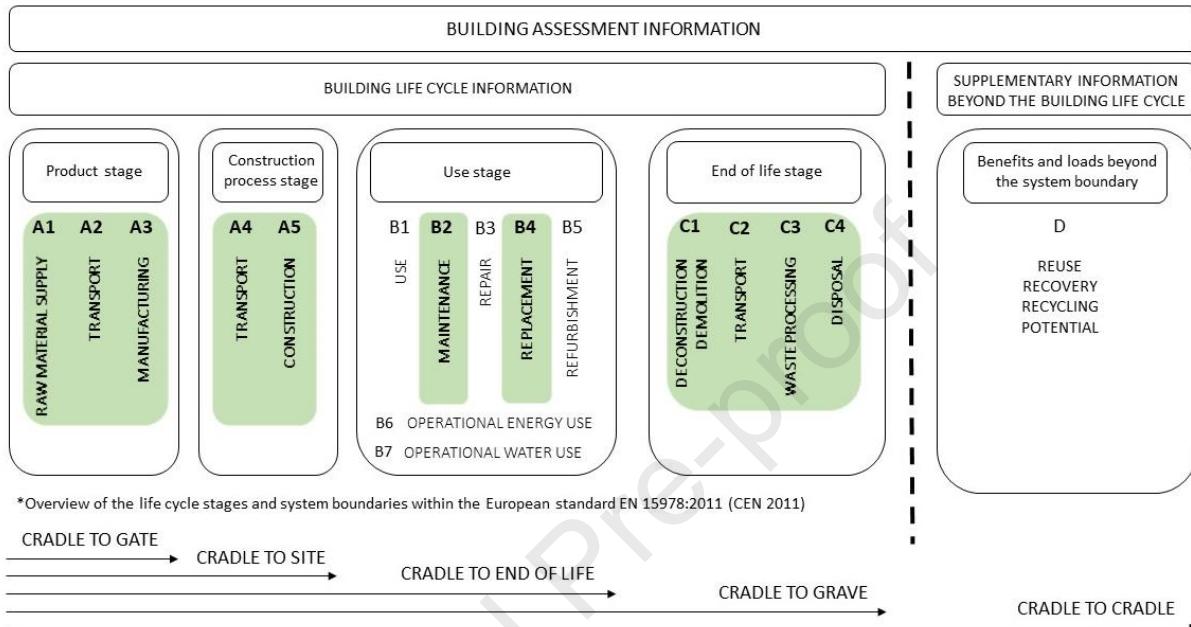
16 Table 1: Building elements included and excluded from the study's physical system boundary

Building Elements Included	Building Elements Excluded
Excavation	Building Services
Foundations	Renewable Technologies (PV panels)
Building Frame	Bathroom Fittings
Structural Columns/Beams	Kitchen Fittings
External Walls	Furniture
Internal Walls	
Ground Floor	Windows
	External/Inside Doors

17 A dwelling's temporal system boundary is linked to its service life and includes the
 18 different modules of a LCA as defined in the standards [18]. It ranges between 30 and 100
 19 years, with the most common estimated service life (ESL) duration varying between 50 and 60
 20 years. Although the average lifespan of a dwelling is more than 60 years, it is known that severe
 21 renovations will be required after this period. As such, the ESL of choice in this study is
 22 assumed to be 60 years [52]. In terms of LCA modules, Figure 5 illustrates the different
 23 temporal system boundaries as per the life cycle modules of the European standard
 24 EN15978:2011 [14]. Modules highlighted in green are the ones included in this investigation.
 25 To focus on material impact, OE use related modules B1, B6 and B7 were considered beyond
 26 the scope of this study and were assessed separately⁷. Since repair activities are user-specific

⁷ H4.0E dwellings were designed to have a (near) zero OE and as part of the H4.0E project, the OE use of the dwellings was monitored. Refer to Appendix B for more information on the OE performance of the dwellings.

1 and no default scenarios are readily available [52], module B3 was excluded from the temporal
 2 system boundary of this study. Considering, the focus of this investigation is new-build and
 3 with a service life of 60 years, refurbishment activities (B5) also fall outside of the scope.
 4 Lastly, following the European standard cut-off, module D is considered beyond the scope of
 5 this study.



6
7 Figure 5: EN 15978 Life cycle stages modules within different temporal system boundaries

8 2.5. Study assumptions

9 Central to achieving transparency is a clear communication of the main study assumptions.
 10 The main assumptions abided by through the use of TOTEM are listed herein [52].

11 • The static -1/+1 approach for biogenic carbon is adopted where a negative value of
 12 carbon emissions is assigned in the product stage of the biomaterial and is cancelled
 13 out by the equivalent positive value in its end-of-life⁸ stage, mostly through
 14 incineration, making the carbon balance neutral from the whole life cycle perspective.
 15 The impact from the incineration of construction and demolition waste is allocated in
 16 its entirety to the material being incinerated.

17 • Maintenance and replacement scenarios are based on the type and function of every
 18 building element. Elements that serve the safety or comfort of the residents undergo
 19 maintenance/replacement interventions regardless of the expected service life of the
 20 dwelling. Elements that serve aesthetic reasons only undergo interventions when the

⁸ Refer to Appendix C, Figure C.1. for end-of-life scenarios per building material/component.

1 remaining service life of the dwelling is equal to or exceeds half of the original
 2 frequency time of the intervention⁹.

3 • The carbonation of concrete was not integrated in the EC calculations because of its
 4 expected negligible impact within the lifespan considered [19].

5 3. Results

6 3.1. Total embodied carbon outcomes at the building level

7 The key metric focused on in this paper is the global warming potential (GWP) and the
 8 EC dioxide equivalent (CO₂eq) is used to capture it [18]. Table 2 provides the total life cycle
 9 EC in kilograms of CO₂ equivalent (kgCO₂eq) for every scenario over an ESL of 60 years. For
 10 the timber scenario, results reveal a total EC of 42,608 kgCO₂eq for the ‘Small House’, 52,883
 11 kgCO₂eq for the ‘Medium House’, and 70,384 kgCO₂eq for the ‘Large House’. These
 12 outcomes confirm previous findings underlining the fact that a larger dwelling inevitably has a
 13 higher EC due to a bigger floor area and the need for more construction materials [13, 15, 40].
 14 The scaling of outcomes through the use of a spatial functional unit leads to a change in order
 15 where the ‘Small House’ timber scenario has the highest EC of 722 kgCO₂eq per square meter
 16 (kgCO₂eq/m²), the ‘Medium House’ 512 kgCO₂eq/m², and the ‘Large House’ 514
 17 kgCO₂eq/m². This is a direct manifestation of how this plays in favour of larger dwellings by
 18 masking the differences between the total impact of the dwellings as brought to attention in
 19 previous studies [16, 55]. In that way, this study echoes previous research findings stating that
 20 solely measuring EC per spatial functional unit is not enough as it inadequately captures the
 21 actual environmental impact of the dwelling and additional metrics are necessary for a more
 22 accurate representation [46, 48]. Additionally, when comparing construction alternatives,
 23 Table 2 also shows that all three timber models (Models 1, 3, and 5) achieve an EC that is lower
 24 than their baseline counterparts (Models 2, 4, and 6). This echoes the unanimity of previous
 25 studies around the better performance of timber as a construction material [12, 24-28].

26 Table 2: Total life cycle material impact of H4.0E dwellings and their baseline alternatives

Scenario	Small House		Medium House		Large House	
Partial life cycle embodied carbon	Timber (Model 1)	Baseline (Model 2)	Timber (Model 3)	Baseline (Model 4)	Timber (Model 5)	Baseline (Model 6)
Total Outcome (kgCO ₂ eq)	42,608	54,681	52,883	69,725	70,384	91,270
Outcome per spatial FU (kgCO ₂ eq/m ²)	722	927	512	675	514	666

⁹ Refer to Study Inventory in the supplementary materials for more information on the ESLs per individual building complement within all building elements included in the study.

1 Figure 6 shows EC reductions achieved from cradle to gate, cradle to site, cradle to end-
2 of-life and cradle to grave. When comparing timber to baseline designs, a recurrent pattern
3 reveals itself whereby achieved EC reductions start off considerably high from cradle to site,
4 varying between 80 to 90%, to slowly being reduced to 22 to 24% from cradle to grave. This
5 demonstrates that the production of building materials used to represent a dominating share of
6 life cycle emissions. However, with the use of timber as the main building material, this initial
7 carbon spike is tempered and the production of a timber dwelling is up to 90% less carbon
8 intensive than the production of a concrete dwelling. Instead, another carbon spike occurs
9 throughout the end-of-life of a dwelling where a significant amount of reductions are offset.
10 This can be attributed to the choice of the static carbon storage accounting model (-1/+1) where
11 a zero biogenic carbon balance is assumed over the life cycle of the material. This translates
12 into timber structures having a greater amount of carbon emissions in their end-of-life stage
13 due to the assumption of incineration as the end-of-life scenario, as brought to attention in
14 earlier work [28]. In that way, this gradual presentation of outcomes confirms the importance
15 of exploring different biogenic accounting methods and end-of-life scenarios for timber, as was
16 highlighted in previous studies [19, 24, 32], to better represent its benefits as a fractional
17 reduction in these stages would have a large reduction effect on the total EC of timber
18 dwellings.

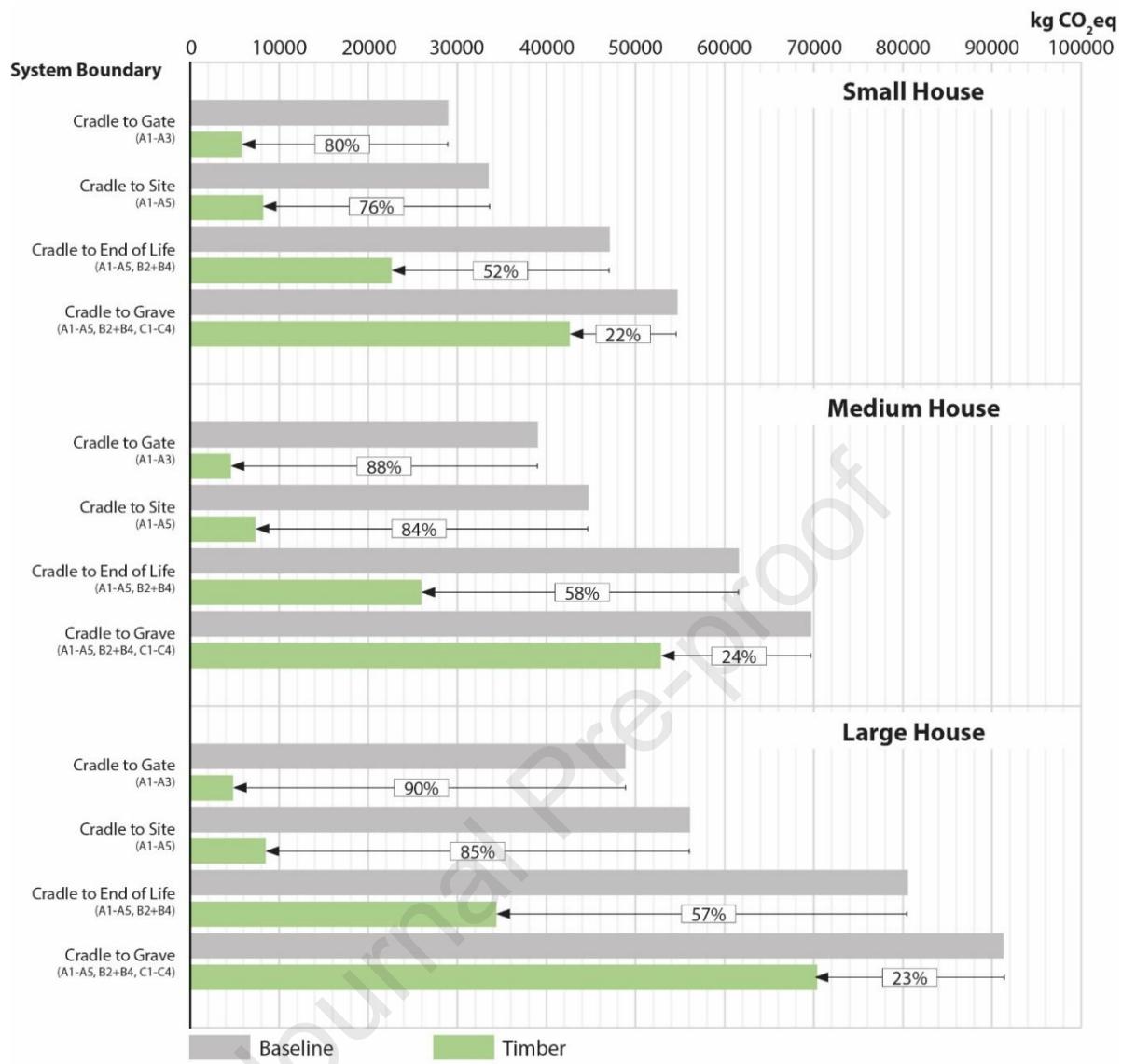


Figure 6: Total embodied carbon reductions per temporal system boundary

3.1.1. Embodied carbon reductions from downsizing and the use of timber

Figure 7 shows the EC reductions from the implementation of downsizing and the use of timber and provides a visual representation of the relationship between house size and EC. The comparison of outcomes between timber designs and their baseline alternatives within each scenario traces reductions strictly from a change in building materials. Accordingly, using timber as the main construction material resulted in EC reductions varying between 22 and 24%. The comparison of outcomes between baseline designs alone traces reductions resulting strictly from a change in house size. As such, downsizing resulted in EC reductions varying between 22 and 40%. By comparing the large baseline house, Model 6¹⁰, and the timber dwelling designs, Models 1 and 3, the simultaneous reductions from both downsizing and the

¹⁰ Model 6 was considered the reference since it better represents the conventional dwelling design and the average dwelling size.

1 use of timber can be traced. Overall, only the implementation of both strategies together
 2 achieves the highest EC reduction with 42% for the Medium House and 53% for the Small
 3 House scenario. All reduction percentages exceed the TOTEM significance threshold of 20%
 4 thus ruling out potential changes in outcomes due to uncertainties around the assumptions made
 5 [52].

6 3.1.2. The relationship between house size and embodied carbon

7 Contrary to what was suggested in prior work, this study's findings indicate that the nature of
 8 the relationship between house size and EC cannot be considered super-linear [45]. In
 9 comparing the timber dwellings, the Large House (GFA: 137 m²) is 2.33 times bigger than the
 10 Small House (GFA: 59 m²). However, it consumes 1.65 times more EC. Likewise, the Medium
 11 House (GFA: 103 m²) is 1.75 times bigger than the Small House and consumes 1.24 times
 12 more EC. In comparing the concrete dwellings, outcomes are similar with the Large House
 13 consuming 1.67 time more and the Medium House consuming 1.26 times more than the Small
 14 House. Only the outcomes between the Large and Medium House scenarios suggest a linear
 15 relationship between house size and EC considering the former consumes 1.33 more EC for
 16 timber and 1.3 times more EC for concrete. Overall, results are more inclined towards
 17 indicating a sublinear relationship between house size and EC, aligning with the conclusion
 18 drawn by Stephan and Crawford [46]. Only when timber and downsizing strategies are
 19 implemented simultaneously, results suggest either a super-linear or a linear relationship seeing
 20 as the ratio of EC emissions of a large concrete house and a medium timber house is 1.73 which
 21 exceeds the ratio of dwellings sizes (1.33) and the ratio of EC emissions of a large concrete
 22 house and a small timber house is 2.14 which is almost as much as the ratio of their sizes (2.33)
 23 as can be seen on Figure 7. In practice, these results indicate that architectural details render
 24 the relationship between house size and EC emissions more complex and that having a smaller
 25 living space comes at the cost of a disproportional decrease in EC depending on the
 26 architectural design choices made. Downsizing alone is not enough and the simultaneous
 27 implementation of EC strategies is necessary to increase the chances of achieving at least a
 28 linear decrease of EC emissions. More importantly, the results suggest there being an optimal
 29 point beyond which further reductions in dwelling size may not result in the equivalent
 30 significant reductions in EC emissions.

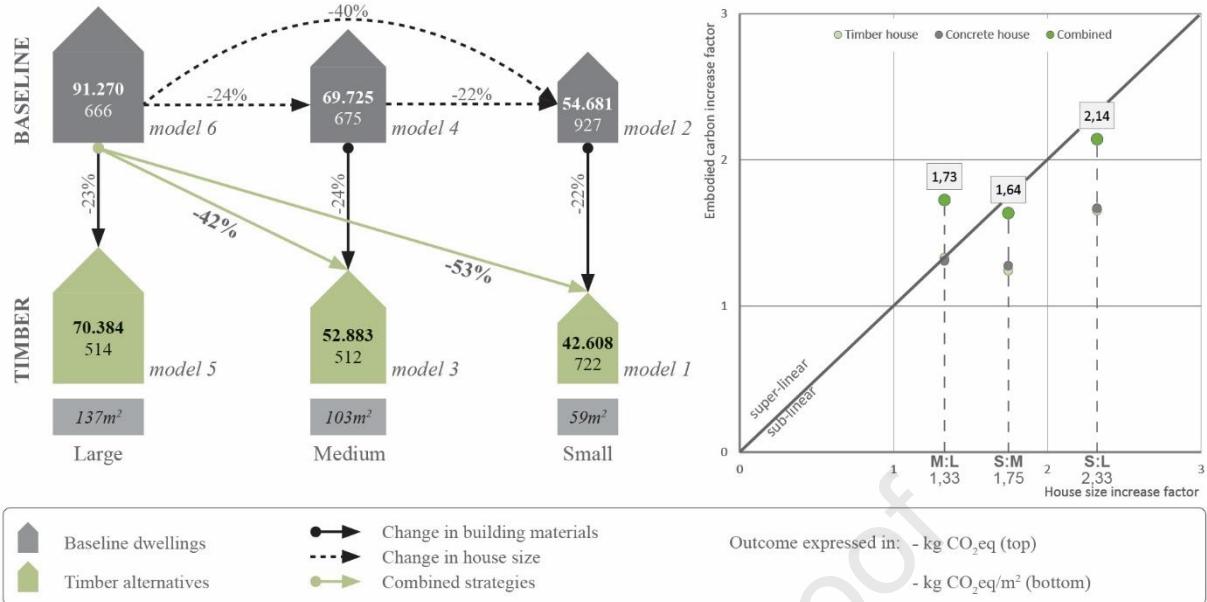


Figure 7: Embodied carbon reductions per strategy and the relationship between house size and embodied carbon

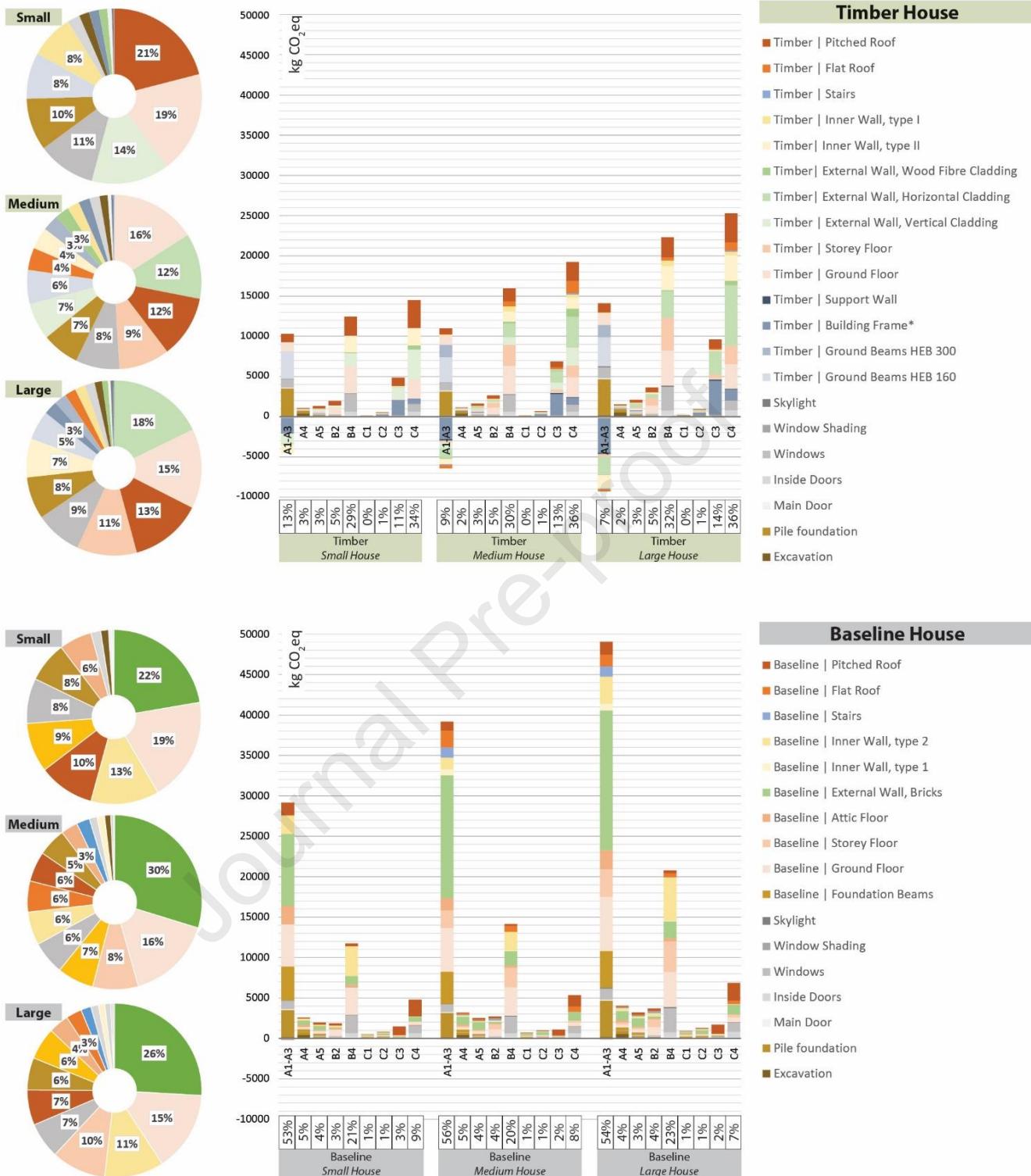
3.2. Embodied carbon outcomes at the building element level

Figure 8 shows the impact share of every building element on total EC outcomes and the impact share of these building elements within each life cycle module. On the one hand, this presentation of outcomes reveals that the building envelope yields significant influence on EC outcomes. In the timber-based designs, the pitched roof, ground floor and external walls are important contributors taking up altogether 48 to 56% of the dwellings' total footprint. In the concrete-based baselines, the external walls and ground floor are dominating taking up 41 to 46% of their total impact. Such variations in the impact shares of main building elements between a timber-based dwelling and its baseline have been identified in previous work where the roof and the foundations were the most impactful building elements in a timber dwelling versus external walls and floors in its masonry counterpart [56]. Differences in the ranking of building elements per dwelling can be attributed to the differences in overall architectural designs such as the surface area of the pitched roof or the glazing (refer to Figure 1). That is to say that, in terms of architectural design choices, these results underscore the importance of primary design choices related to the design and composition of the building frame by manifesting their significant impact on a dwelling's total EC footprint, a finding that is consistent with previous investigations [30, 57, 58].

On the other hand, when looking into life cycle modules, outcomes reiterate the significant impact of the biogenic accounting approach adopted considering the disposal module C4 is dominated by building elements made of timber with higher end-of-life emissions. Whereas production modules A1 to A3 are controlled by building elements made of concrete, most of

1 which is assumed to be recycled in its end-of-life [28]. More importantly, for both designs, the
2 results reveal replacement module B4 as a significant contributor to the dwellings' EC footprint
3 with a share of 20% to 32%. This has been flagged by previous studies stressing on the
4 importance of accounting for the maintenance and/or replacement of building elements
5 throughout the building's service life [42]. This confirms previous research findings
6 demonstrating that larger dwellings do require more upkeep seeing as the share of EC
7 emissions coming from Module B4 increases with the size of the dwelling in both construction
8 alternatives [42]. Additionally, doors, windows and skylights, elements that are not always
9 included in LCA studies, were revealed to be amongst the important contributors, in addition
10 to main building elements such as ground floor, external walls, and pitched roof as was also
11 highlighted by Resch et al. (2020) [30]. This is a direct manifestation of how the exclusion of
12 such elements can lead to truncation errors and the underestimation of a dwelling's total EC
13 footprint.

14



1

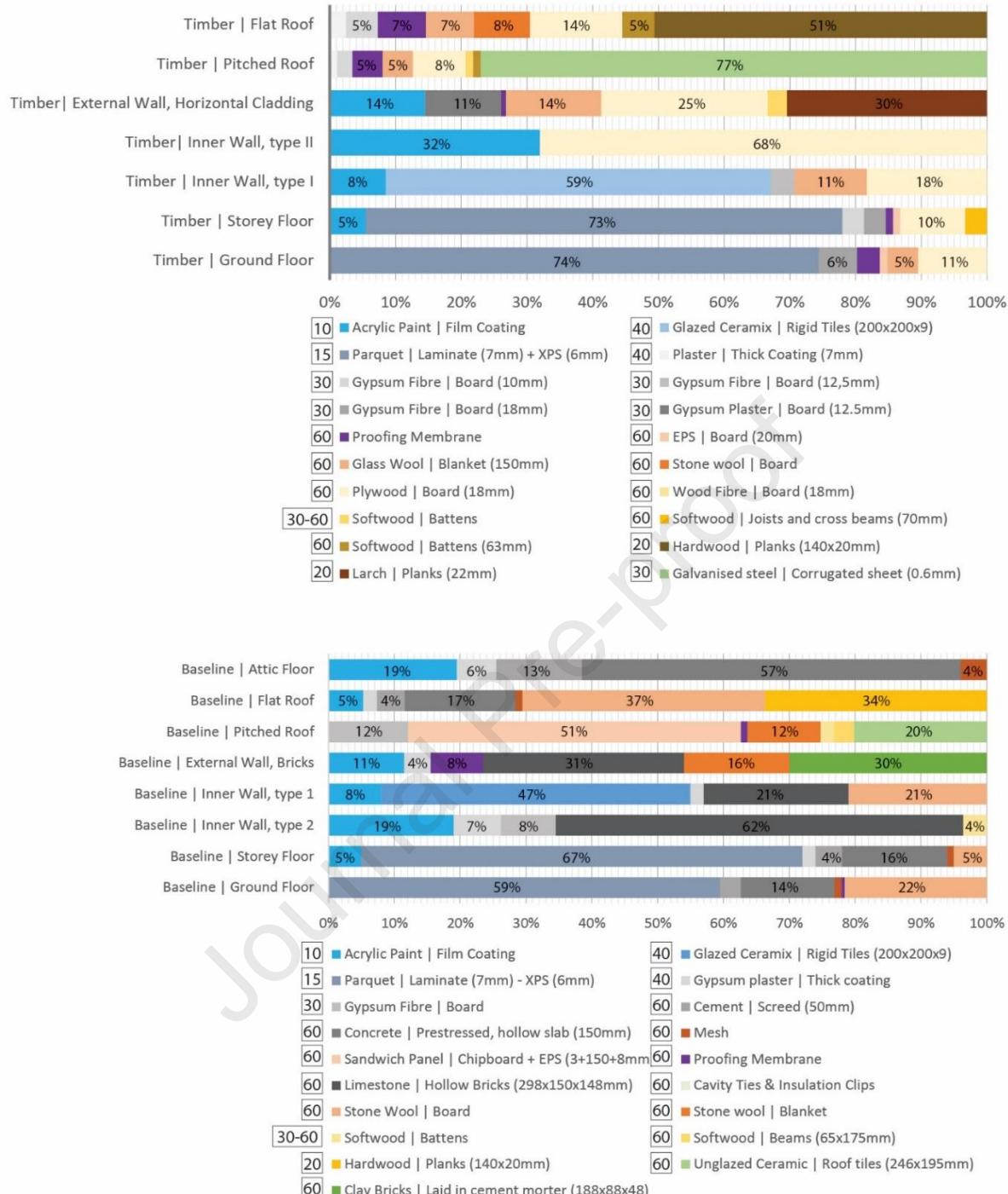
2 Figure 8: Embodied carbon outcomes per building element and per life cycle module

3 3.3. Embodied carbon outcomes at the building component level

4 Figure 9¹¹ displays the shares of EC contributions at the building component level for the
5 main elements of both construction variations. The ESL of every building component is also¹¹ For the purpose of conciseness, results reported in this section are restricted to the Medium House scenario.

1 indicated. This presentation of outcomes reveals that finishing components are major
 2 contributors in both the timber and the concrete construction variations. In the dwelling floors,
 3 parquet laminate, a common choice of flooring in the Netherlands, accounted for the majority
 4 of the EC reaching 74% of the total impact of the floors in the timber dwelling and ranging
 5 from 59% to 67% in the baseline design. In the pitched roof, galvanized steel was chosen as
 6 the finishing of the timber dwellings in the H4.0E project and amounted to 77% of the building
 7 element's total EC. This finding resonates with observations made by Ximenes et. al. where
 8 roofing also emerged as the building component with the largest impact within the roof element
 9 [32] and Taylor et. al. who demonstrated significant differences in material impact between
 10 different roofing variations [55]. In the walls, although not dominant, acrylic paint is
 11 responsible for a considerable share of total EC and becomes even more significant when
 12 considering its cumulative share in all building elements. Following the same reasoning,
 13 insulation (EPS board and glass wool blanket insulation) becomes another design choice with
 14 significant EC consequences considering it is also a recurrent component in several building
 15 elements of the dwelling. A different choice of insulation could reduce the material impact of
 16 the dwelling while maintaining a similar thermal performance¹², as was highlighted by Petrovic
 17 et. al. [31]. Additionally, finishing components tend to have shorter service lives than the
 18 structural and insulating components. Galvanized steel roofing has a service life of 30 years,
 19 parquet laminate flooring 15 years, and acrylic paint coating 10 years. Considering this study
 20 includes maintenance and replacement modules in its analysis and taking into account the ESL
 21 of 60 years for the entire dwelling, this leads to having several rounds of
 22 maintenance/replacement. In this light, the importance of the choice of finishing materials is
 23 highlighted when it has often been overlooked in the past since accounting for finishing is not
 24 common practice in LCA studies [26]. Overall, by demonstrating their aggregated significant
 25 impact on a dwelling's total EC footprint, the presentation of outcomes at the building
 26 component level allowed the identification of highly carbon intensive secondary design choices
 27 outside of the primary design choices, confirming the conclusion reached by Petrovic et. al.
 28 [59]. Practically, these outcomes emphasize the need for well-informed decisions at every stage
 29 of the design process, even when accommodating user preferences, particularly concerning
 30 choices related to flooring, roofing, coatings, and insulation types to ensure more effective and
 31 sustainable outcomes.

¹² Refer to Appendix C, Figure C.2 that traces the carbon intensity of different insulation types versus their thermal performance (R-value)



1

2 Figure 9: Material impact per building component in the main building elements of the Medium House scenario in the timber
 3 and baseline construction variations. Numbers in squares are the estimated service life of the components within each element.

4 3.4. Optimized design

5 The hierarchical structure of outcomes allowed the identification of most carbon intensive
 6 building elements and components. Changes with the highest potential of decreasing the EC of
 7 the dwellings were identified. Accordingly, a better performing scenario was modelled to
 8 numerically gauge the corresponding reductions. Modifications consist of substituting
 9 finishing materials with natural based alternatives. This includes changing the galvanized steel

1 roofing to local slating, the parquet laminate flooring to hardwood flooring and eliminating all
 2 acrylic paint coatings. The glass wool insulation layers were also substituted with cellulose
 3 insulation and, when applicable, rigid insulation such as EPS was replaced with wood based
 4 rigid insulation. Table 3 presents the outcomes of the optimized design modelled based on the
 5 Medium House scenario. In comparison to the timber design, these changes resulted in an
 6 overall 29% additional reduction in EC emissions, surpassing the 20% significance threshold.
 7 This outcome confirms the importance of accounting for secondary design choices in a LCA
 8 and doing so at an early design stage to prevent countering savings. While this optimized design
 9 achieves higher EC savings, this study recognizes that its implementation in practice is not as
 10 straightforward. For instance, in the case of the H4.0E project, residents opted for glass wool
 11 instead of cellulose insulation to decrease their costs. That is to say that material choices, which
 12 are dependent on user preferences, are in-turn determined by external factors including the
 13 affordability, availability and established norms around natural based materials.

14 Table 3: Embodied carbon material impacts per medium dwelling scenario

Life cycle embodied carbon		Medium House - Baseline	Medium House - Timber	Medium House - Optimized
Stage	Module			
Production	A1-A3	377	41	-69
Transport to site	A4	31	11	12
Construction and Installation	A5	24	16	13
Maintenance	B2	26	26	24
Replacement	B4	137	158	63
Deconstruction/Demolition	C1	6.7	1.1	1.1
Transport end-of-life	C2	10	4.8	5.3
Waste Processing	C3	11	67	65
Disposal	C4	52	186	246
Outcome per spatial FU (kgCO ₂ eq/m ²)		675	512	361
Total Outcome (kgCO ₂ eq)		69,725	52,883	37,291
Reduction Percentage		0%	24%	29%

15 3.5. Situating study outcomes in existing literature

16 Table 4 enumerates relevant previous studies by listing their EC outcomes in a decreasing
 17 order and distinguishing location, building type, floor area, ESL, EC reduction percentage from
 18 the use of timber (TR), life cycle modules, biogenic carbon, and used database(s). The studies
 19 were searched through the databases of the Delft University of Technology Library [60] and
 20 Web of Science [61], using the following keywords: (Timber OR Wood) AND (Housing OR
 21 House* OR Dwelling*) AND (Life cycle assessment OR LCA OR Embodied Carbon OR Life
 22 cycle analysis). The initial screening was done through scanning titles and keywords followed
 23 by reading abstracts. Priority was given to studies that had a similar research goal which is to
 24 investigate the use of timber as an EC reduction strategy compared to more conventional

1 building materials in new-build construction. As per this research goal, articles that did not
2 include timber as a main construction material were excluded. Articles that did not include
3 housing at all, be it in the form of individual dwellings or residential buildings, were excluded.
4 Articles that solely focused on existing buildings/dwellings and the material impact of
5 renovation measures were excluded. Articles that investigated temporary timber housing with
6 lifespans below 25 years were excluded. Lastly, to increase comparability, articles that did not
7 convey the material impact expressed in kilograms of carbon dioxide equivalent per square
8 meter of floor area were excluded¹³. The resulting studies vary between literature reviews, case
9 studies, benchmark studies, and global trend studies with a particular focus on timber
10 construction and residential buildings or dwellings.

¹³ The last search was performed on the 5th of January 2024

1

Table 4: An overview of literature specific to EC studies and timber construction

Study	Reference	Description	Location	Building Type	Floor Area ¹⁴ (m ²)	ESL (years)	Outcome (kgCO ₂ eq/m ²)	TR ¹⁵ (%)	Life Cycle Modules ¹⁶	Biogenic Carbon ¹⁷	Database ¹⁸
1	[62]	Literature review	V ¹⁹	Building	V	50	179 to 1050	-	V	V	Mixed ²⁰
2	[30]	Case study	Norway	Building	102 (HFA)	60	968 ^a	-	A1-4, B4	No	Self-acquired
3	[24]	Case study	France	Dwelling	122 (NFA)	100	574 to 820	33%	A1-5, B4, C1-4	Yes	Ecoinvent 3.01
4	[31]	Case study	Sweden	Dwelling	180 (GFA)	100	600	-	A1-5, B1-5, C1-4	No	OneClickLCA
5	[63]	Benchmark study	V	V	V	≥30	<500	-	V	V	Mixed
6	[64]	Case study	New Zealand	Dwelling	198	90	446	-	A1-4, B2, B4, C1-4	No	Ecoinvent 3.0
7	[55]	Case study	New Zealand	Dwelling	230 (GFA)		124 to 445	-	A1-D	No	BRANZ
8	[65]	Benchmark study	V	Building	V	60	444	-	V	No	OneClickLCA
9	[19]	Case study	Australia	Building	43,229 (GFA)	50	417	10%	A1-5, B1, B4, C1, C3, C4	Yes	Mixed
10	[66]	Case study	New Zealand	Dwelling	107 (GFA)	90	414	-	A1-5, B4, C1-4	Yes	Okobandat
11	[57]	Case study	U.K.	Dwelling	45 (GFA)	-	405	34%	A1-5	No	Mixed
12	[27]	Case Study	V	Dwelling	56 (GFA)	100	380	34%	A1-4	No	ICE v. 2.0
13	[13]	Global trend study	V	V	V	50	377	-	A1-A5	No	Mixed
14	[67]	Case study	Poland	Building	153 (GFA)	25	311 to 362	15-20%	A1-5, B1-5	No	OneClickLCA
15	[68]	Literature review	V	V	V	-	-445.6 to 333.5	32%	V	Yes	Mixed
16	[25]	Case study	Uruguay	Dwelling	63 (GFA)	60	328.5 ^a	50%	A1-5, B2-B4, B6, C1, C2, C4	No	Mixed

¹⁴ The definition of floor area varies per study and can designate the heated floor area (HFA), the net floor area (NFA), or the gross floor area (GFA)

¹⁵ Abbreviation TR for reduction percentage from the use of timber.

¹⁶ Life cycle modules are specified as per the EN 15978 standard.

¹⁷ When biogenic carbon was not addressed at all in the reference studies it was assumed to be excluded from the analysis and also entered as a 'No' in the table.

¹⁸ Reference studies tap into a wide range of databases including private LCA datasets, publicly available datasets, previous research outcomes, published EC reports, environmental product declarations (EPD), and European and global averages. Specific examples cited are Ecoinvent, Building Product Life Cycle Inventory, Inventory of Carbon and Energy (ICE), Environmental Performance in Construction, Integrated Carbon Metrics Embodied Carbon Life Cycle Inventory, and Building Construction Information Service among others.

¹⁹ Literature reviews and benchmark studies cover variable locations, building types, floor areas, and ESLs, which is denoted by the letter 'V' in the table.

²⁰ When studies tap into several databases, the occurrence is designated as 'Mixed'.

17	[18]	Case study	U.S.	Building	356 (HFA)	60	297	-	A1-5, B4, C2-4	No	Mixed
18	[69]	Case study	Sweden	Building block	-	100	281	42%	A1-5, B6, C1-4	Yes	Ecoinvent 2.2
19	[16]	Case study	Norway	Dwelling	102-202 (HFA)	60	263	-	A1-4, B4 ^b	No	Ecoinvent 3.0
20	[59, 70]	Case study	Sweden	Building	180 (GFA)	50-100	174 to 245	-	A1-4, B1-5, C1-4	Yes	OneClickLCA
21	[71]	Case study	Italy	Building	820 (GFA)	-	224	25%	A1-3	No	Ecoinvent 3.0
22	[58, 72]	Case study	Denmark	V	238-805 (GFA)	50	200	-	A1-5, B4, C3-4	Yes	Okobandat
23	[26]	Case study	Germany/ Austria	Dwelling	176	50	<200 ^a	35- 56%	A1-3, B2, B4, C3- C4	Yes	Oekobau.dat 2015
24	[20]	Literature review	V	V	V	V	174.03	43%	V	V	Mixed
25	[73]	Case study	Slovakia	Dwelling	80	60	148	-	A1-5, B1-2, B5, C4	Yes	CoM
26	[32]	Case study	Australia	Dwelling	221-296	50	100 to 145 ^a	50%	A1-4, B2-3, C4 ^b	No	Mixed
27	[74]	Case study	Chile	Building	1405	50	105	37%	A1-5	No	Mixed
28	[75]	Case study	China	Dwelling	143.56	-	41.54 to 44.19	-	A1-5, C1-4	No	EPDs
29	[56]	Case study	Poland	Dwelling	139.8 (GFA)	50	17.56	-	A1-3	No	Okobandat

^a These values were extracted from graphs

^b Specific life cycle modules were not listed in the study and the corresponding data entry was formulated based on the understanding of the text.

Figure 10 consists of a visual representation of where this study's outcomes stand in comparison to previous studies. Under timber reduction percentages, ranging from 10 to 56%, they fall in the lower range of the band with the EC savings from the use of timber limited to an average of 23%. Under EC outcomes, ranging from 17.6 to 1050 kgCO₂eq/m², they fall in the upper range of the band with a minimum of 512 kgCO₂eq/m² and a maximum of 722 kgCO₂eq/m². When looking into reasons underlining variations in outcomes, apart from major variations in study characteristics such as geographic context and building design as is the case with study 16 located in Uruguay where a full wooden design is assessed including foundations, cladding and flooring [25], several differences in study scope come to light.

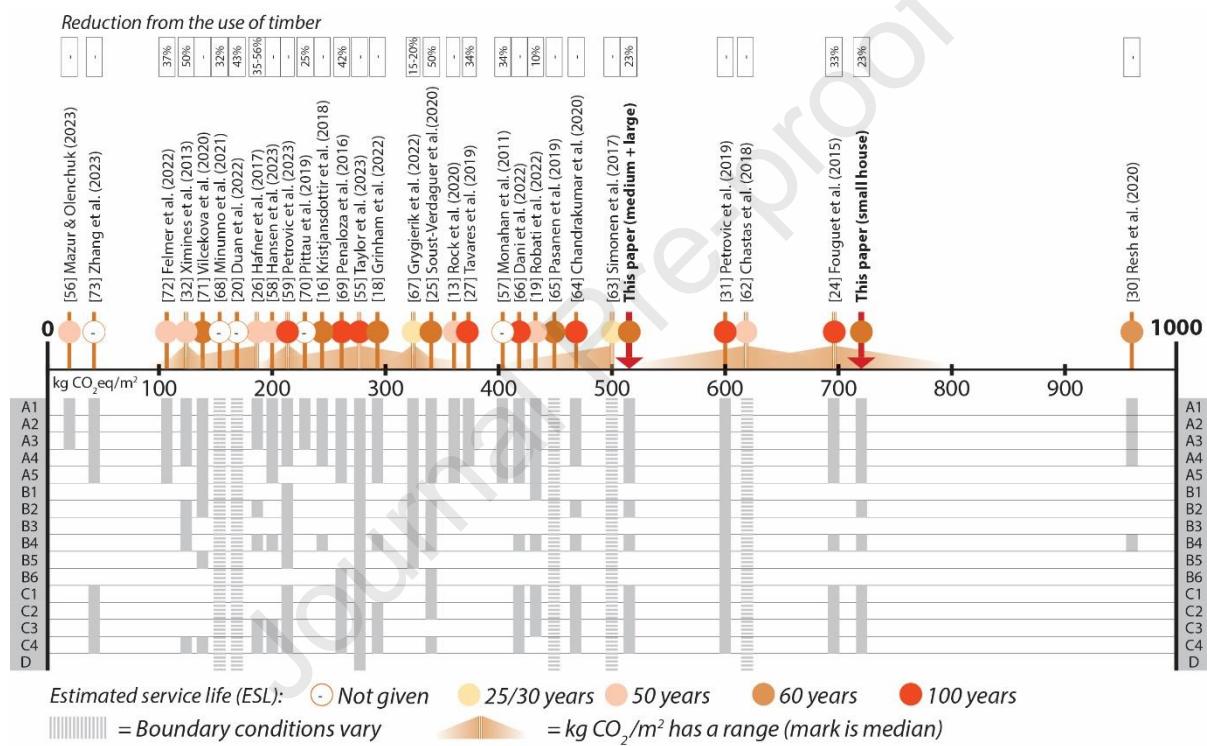


Figure 10: A visual representation of situating this study's outcomes in previous literature

Differences in temporal system boundaries

Accounting for different life cycle modules explains some of the large differences in outcomes [18], as is the case with studies 5 [63], 8 [65], 11-13 [13, 27, 57], 17-19 [16, 18, 69], 21-29 [13, 18, 20, 26, 27, 32, 56-58, 63, 65, 71, 73-75]. For instance, study 18 excluded maintenance and replacement modules B2 and B4 in their investigation of an increased use of bio-based materials [69]. In this paper, these modules alone constituted up to 37% of the timber dwellings' EC footprint. Studies 11 and 12 on modular and prefabricated timber housing only include modules A1 to A5 limiting the scope to the construction site stage [27, 57]. Applying such system boundaries to this paper's outcomes would lead to a much higher average reduction of

1 51% from the use of timber and much lower total EC values with an average 61 kgCO₂eq/m²
 2 from cradle to gate, 93 kgCO₂eq/m² from cradle to site, and 299 kgCO₂eq/m² from cradle to
 3 end of use. Adopting a different ESL can also cause differences in outcomes considering a
 4 shorter ESL of up to 50 years is not indicative enough as it does not factor in the full EC related
 5 to the maintenance and replacement of building components, as is the case with studies 1 [34,
 6 62], 9 [19], 13 [13], 14 [67], 22 [58], 23[26], 26 [32], 27 [74] and 29 [56]. Likewise, a ESL of
 7 a 90-100 years factors in advantages that go beyond the service life of a building and attenuates
 8 the initial, replacement and end-of-life carbon spikes that occur in the first 60 years, as is the
 9 case with studies 3 [24], 4 [31], 6 [64], 12 [27], and 18 [69].

10 **Differences in biogenic carbon accounting**

11 Differences in outcomes are further accentuated by adopting a different biogenic accounting
 12 approach. For instance, studies 10 and 11 adopt the static 0/0 model for biogenic carbon [57,
 13 66]; whereas this study adopts the static -1/+1 model, hence the lower reported impact
 14 throughout modules A1 to A5. In contrast, studies 3 and 18 adopt the dynamic model which
 15 better represents the actual benefits of using timber versus concrete, hence their higher
 16 reduction percentages reported [24, 69]. The importance of decision making around the end-
 17 of-life of timber appears with study 26 where long-term carbon storage in landfilling resulted
 18 in a 40 to 60% difference in GHG emissions outcomes [32] as opposed to not accounting for
 19 carbon storage. This is in agreement with other studies that identified landfilling as the least
 20 carbon intensive end-of-life scenario compared to incineration or recycling [19, 24, 32].
 21 Considering this study assumes 85 to 100% incineration of its wood, this is another explanation
 22 to the difference in outcomes. In confirmation, study 9 demonstrates through an uncertainty
 23 analysis the extent to which EC savings are dependent on the assumptions made and the input
 24 data used which in turn explains the low reduction percentage reported [19].

25 **Differences in physical system boundaries**

26 Variations in the building elements included in previous studies also explain differences in
 27 outcomes. For instance, study 7 restricted its boundaries to the building envelope [55], study
 28 21 excluded internal partitions and doors due to variations based on residents' spatial needs
 29 [71], and study 23 categorized the following elements; flooring, external cladding, roofing,
 30 shading, windows, and doors, as finishing and omitted them [26], while study 26 did not
 31 consider components like insulation, proofing membranes or coatings [32]. Studies prioritizing
 32 comparative outcomes excluded building elements arguing that they would not influence
 33 differential percentages. These range from design details such as wall coating, glass, or roof

1 asphalt to core elements such as foundations, basement and ground floor [26, 32, 69, 71]. While
 2 this approach sheds light on the intended purpose of the study, it does not give an outcome
 3 representative of the total emissions of a dwelling as a whole. Less detailed inventories lead to
 4 lower EC emissions and do not represent a comprehensive picture of a dwelling's emissions
 5 [16]. Despite also having a comparative purpose, EC models in this paper were based on actual
 6 dwelling designs and user choices around spatial distribution and varying finishing materials
 7 were included in the analysis. Building elements were composed to the slightest detail based
 8 on architectural drawings, bill of quantities and input from professionals, hence the outcomes
 9 that were higher than 25 reference studies in terms of total EC expressed in $\text{kgCO}_{2\text{eq}}/\text{m}^2$.
 10 Overall, it is recognized that the results looked at for comparison are not harmonised in terms
 11 of study characteristics and scopes which entails systematic uncertainties. Nevertheless, these
 12 general trends provide a precedent against which findings of this paper can be compared.

13 4. Discussion

14 4.1. Academic, industry and policy implications of study outcomes

15 The goal of this research was to investigate the impact of the simultaneous implementation
 16 of downsizing and the use of timber as EC reduction strategies by conducting a detailed
 17 assessment that aligns closely with real-life scenarios. In pursuit of this goal, the study not only
 18 achieved an in-depth analysis of the designated strategies but also brought to the forefront
 19 implications extending beyond its immediate scope. From the academic perspective, in the
 20 attempt of situating its outcomes in existing literature, this paper faces the lack of comparability
 21 of LCA studies, reiterating it as a significant barrier as was flagged by previous research [10,
 22 19, 29, 30]. By tracing discrepancies in study characteristics and scoping, this study highlights
 23 the importance of prioritizing transparency in LCA studies emphasizing the need in the global
 24 scientific community for clear, harmonized guidelines on how to perform their assessment,
 25 document their process and report their outcomes [13, 14, 31]. From the industry perspective,
 26 by focusing on material impact alone and through its hierarchical analysis, this paper
 27 demonstrates how design decisions shift when the focus is to lower EE versus when it is limited
 28 to lowering OE. Notably, the consideration of various insulation types with equivalent thermal
 29 performance but differing EC impacts serves as a concrete example [31]. Another example is
 30 user choices encompassing finishing, flooring, and roofing [32, 55]. These choices are typically
 31 excluded from design considerations due to their dependency on individual preferences.
 32 However, the focus on material impact reduction emphasizes their significance, making the
 33 role of designers pivotal in advising users towards more informed decisions. From the policy
 34 perspective, this paper demonstrates how adopting different temporal and physical system

1 boundaries can lead to truncation errors and the underestimation of a dwelling's carbon
 2 footprint. Such discrepancies may pose potential long-term issues, giving rise to an EE
 3 performance gap resembling the challenges encountered in managing an OE performance gap
 4 [10]. Building on this premise, it becomes important for regulations concerning EE to transition
 5 from recommendations to mandatory requirements. This would create a ripple effect,
 6 prompting the construction and product industry to get familiar with different LCA tools,
 7 develop their environmental product declarations, which would in turn enhance the accuracy
 8 of carbon footprint calculations [14]. Drawing a parallel to the history of NZEBs, which were
 9 introduced years ago, attaining a zero OE balance took longer than anticipated. Similarly,
 10 incorporating EE into regulations is likely to face a learning curve. Given this, it becomes all
 11 the more crucial to initiate this transition sooner rather than later, aligning policies with
 12 sustainability aspirations for a more effective and timely impact.

13 4.2. Challenges of implementing downsizing and timber construction

14 This paper effectively demonstrates how downsizing and the use of timber reduces the
 15 carbon footprint of dwellings. However, the practical implementation of smaller, timber
 16 dwellings already confronts numerous challenges, let alone the implementation of the
 17 optimized design. A prior study investigating institutional barriers to the uptake of smaller, low-
 18 carbon, and (near) zero-energy dwellings identified several hindrances within local policies
 19 [76]. For instance, land allocation policies that favour large plots for single detached dwellings
 20 may impede the development of compact constructions. Social housing policies that aim for
 21 universal architectural designs to facilitate the allocation process can obstruct housing designs
 22 aiming for compact space efficiency. Another study investigating the development of timber
 23 construction in European countries identified the lack of knowledge and skills and concerns
 24 regarding fire safety and structural stability as major barriers [77]. Affordability concerns, user
 25 preferences favouring larger conventional dwellings [78], and extended testing periods for
 26 timber constructions further increase the complexities [76]. From a broader perspective,
 27 concerns around the insufficient supply of timber and deforestation arise. While it is argued
 28 that the benefits of timber construction could counter deforestation concerns through
 29 afforestation, it is recognized that the anticipated surge in demand requires immediate proactive
 30 measures [79]. This emphasizes the complexity in implementing sustainability mitigations and
 31 highlights the need for a broader outlook to achieve more effective outcomes. Thus, this paper
 32 acknowledges the intricate nature and challenges associated with the uptake of smaller timber
 33 dwellings and highlights the need for them to be addressed for overall better chances at
 34 achieving the 2050 decarbonization goals.

1 4.3. Limitations and future research

2 4.3.1. Geographical representativeness

3 This study is subject to a low geographical representativeness as most EC data is
 4 specific to Europe including some that are made more specific to the Belgian context [52]. This
 5 is recognized to potentially have induced systematic uncertainty in this study's calculations. In
 6 subsequent research, a comparative assessment can be conducted to contrast national databases
 7 across Europe to highlight the potential differences in the energy mix, in the transportation of
 8 materials, and other underlying factors influencing construction practices, material sources and
 9 energy production methods. Likewise, this study adopts the tool's maintenance and
 10 replacement scenarios and biogenic carbon accounting approach. Considering the assumptions
 11 and underlying uncertainties involved in both, future research can complement their
 12 assessments with a sensitivity analysis exploring the impact of changing these assumptions
 13 which will emphasize their significant role.

14 4.3.2. Temporal and physical system boundaries

15 Another study limitation lies in the temporal and physical system boundaries. In an
 16 effort to conduct an in-depth EC assessment, life cycle modules related OE consumption were
 17 assessed separately²¹. For a complete overview of the full life cycle performance of smaller
 18 timber dwellings, future research should account for OE use while maintaining a high level of
 19 detail in its EC assessment. Additionally, furniture and sanitary elements were excluded due to
 20 data scarcity as including these building elements is not common practice in LCA studies.
 21 Likewise, building services were also excluded since calculating their EC has still not been
 22 standardized and modelling uncertainties remain. In terms of the relation between house size
 23 and EC, these exclusions render this study's outcomes conservative. Taking into account these
 24 additional elements would have further accentuated the relationship between house size and
 25 EC seeing as larger dwellings usually require more amenities and bigger building services
 26 systems [40, 54]. As such, future research should also aim to gauge the additional EC emissions
 27 from sanitary elements, furniture and building services for a more comprehensive total EC
 28 footprint further accentuating the benefits of downsizing.

29 4.3.3. Environmental impact category

30 This study restricts its analysis to the GWP impact indicator as it is crucial for climate
 31 change policies [25]. However, it is essential to acknowledge that LCAs encompass a spectrum
 32 of impact categories. In the specific context of this study, considering various end-of-life

²¹ Refer to Appendix B: Operational energy use.

1 scenarios unique to timber, such as incineration or landfilling, could introduce additional
2 impact indicators of significance. For instance, the evaluation of toxic substance emissions or
3 the potential contamination of groundwater resources becomes pertinent in a broader
4 environmental context [32]. While this study does not delve into these aspects, it recognizes
5 the importance of expanding LCA boundaries to encompass other impact indicators. Future
6 research endeavours could explore the broader environmental implications associated with
7 timber use, providing a more comprehensive and holistic understanding of the contribution of
8 GHG emissions to climate change and other environmental concerns. Even more so when
9 considering that the inclusion of additional impact indicators is said to favour timber dwellings
10 over concrete dwellings [80].

11 5. Conclusions

12 This paper addresses three main research gaps. The first gap pertains to the need for
13 research that examines the simultaneous implementation of downsizing and the use of timber
14 as EC reduction strategies. The second gap revolves around the lack of comparability in
15 existing LCA studies on the use of timber. The third gap concerns the need to contribute to the
16 limited body of knowledge on downsizing as an EC reduction strategy. Specifically, this gap
17 addresses the contradictory findings on the relationship between house size and EC and
18 investigates the impact of downsizing at the lower end of the range for outcomes that are more
19 representative of the European context. To address these gaps, this study conducts partial LCAs
20 of three actual new-build timber dwellings (small, medium and large) and their concrete
21 counterparts.

22 In terms of the direct implications of study outcomes, this paper demonstrates that having
23 a smaller dwelling leads to a disproportional decrease in EC depending on the architectural
24 design choices made considering the relationship between house size and EC was revealed to
25 be sublinear with a correlation ratio below 1:1. Outcomes highlight that downsizing or the use
26 of timber alone is not enough and the simultaneous implementation of both strategies is
27 necessary to increase the chances of achieving a linear or super-linear decrease of EC emissions
28 considering the simultaneous implementation of both reduction strategies led to the most
29 significant carbon savings of 53%. More importantly, results suggest there being an optimal
30 threshold beyond which further reductions in dwelling size may not result in significant
31 justifiable reductions in EC emissions. This serves as a foundation for future research to build
32 on and focus on finding that optimal balance between dwelling size and EC emissions

1 reductions. Such investigations would play a vital role in safeguarding the comfort and well-
2 being of residents from being compromised.

3 In terms of implications beyond the direct study context, from the academic standpoint,
4 this research points out the lack of comparability of LCA studies emphasizing the global need
5 for harmonized implementation and documentation guidelines in the scientific community.
6 From the industry standpoint, by focusing solely on material impact, this study highlights how
7 design decisions shift when the reduction of EC becomes the goal, stressing on the pivotal role
8 of designers in helping users make more informed choices. From a policy standpoint, this study
9 confirms truncation errors with its higher EC outcomes and sheds light on the risk of giving
10 rise to an EE performance gap thus underlining the need for a timely transition towards
11 mandatory EE regulations.

12 Besides addressing the identified gaps, this study makes two main contributions. The first
13 contribution is practical. By proposing a hierarchical data analysis approach that covers
14 building, element and component, this study allows a gradual gain of insight in understanding
15 design choices that increases in depth with every level of information. This division allows a
16 closer alignment between the requirements for conducting a LCA and the needs of housing
17 designers and practitioners, overall providing a more representative depiction of the housing
18 design process and making LCAs more accessible within the realm of housing design. This
19 study also demonstrates how this gradual gain of insight can be turned into actionable
20 applications for designers and practitioners. It showcases the implementation of insights gained
21 from its hierarchical analysis through modelling an optimized design that confirms further
22 improvement with 29% of additional EC savings. The second contribution is empirical. By
23 conducting detailed partial LCAs of actual dwelling designs, this study serves as a valuable
24 reference on the material impact of smaller, new-build, timber dwellings in the European
25 context achieving outcomes that better reflect real-life scenarios. More importantly, through its
26 meticulous documentation of its research process, study scope and assumptions, and its use of
27 a freely accessible online platform, this study facilitates its replication. Accordingly,
28 researchers and practitioners alike can use this study to build their own models and implement
29 the suggested hierarchical analysis to inform and enhance their design at an early stage, thus
30 improving the EC footprint of dwellings and preventing unnecessary emissions simultaneously.

31 Despite all outcomes confirming the advantages of smaller timber housing, this study
32 recognizes the practical challenges of their implementation. Many barriers exist, whether in

1 public perceptions, construction practices, or policies. The alignment of such designs with
2 current housing demand, economic feasibility and compatibility with urban planning and
3 housing policies remains to be seen. Considering the aspect of permanence of EC, it becomes
4 worthwhile for future research to investigate current housing preferences, assess affordability
5 and cost-effectiveness, and identify institutional barriers. Such investigations would help in
6 promoting the establishment of practices that align more closely with the environmental
7 imperative of striving for sufficiency. It is also essential to note that this study has certain
8 limitations, including a low geographic representativeness, limited system boundaries, and a
9 focus restricted to the GWP environmental impact indicator. Future research can address these
10 limitations by conducting more extensive geographic analysis, expanding system boundaries
11 and exploring additional climate change indicators for a more comprehensive understanding of
12 the climate impact of smaller, new-build timber dwellings.

13 **Authorship Contribution Statement**

14 **Cynthia Souaid:** Conceptualization, methodology, formal analysis, investigation,
15 visualization and writing – original draft. **Nick ten Caat:** Investigation, visualization and
16 writing – original draft. **Arjen Meijer:** Supervision and writing – review & editing. **Henk
17 Visscher:** Supervisions and writing – review & editing.

18 **Declaration of Competing Interests**

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

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25

1 **Appendix A: Step-by-step Guide**

2 • Step 1: Data collection

3 This step revolves around gathering the necessary data and information needed about the
 4 composition of the dwelling/building to be modelled on TOTEM. In the case of this study, data
 5 sources varied between bill of quantities (BOQ), architectural drawings, and architectural
 6 details provided by housing practitioners.

7 • Step 2: Data extraction as per the TOTEM taxonomy

8 Unlike conventional life cycle assessment tools that require quantities in bulks of materials, the
 9 TOTEM tool requires data at the building, building element and building component levels.
 10 This hierarchical approach is referred herein to as the TOTEM taxonomy. Accordingly, when
 11 extracting data from sources such as BOQs, architectural drawings, and details, the following
 12 must be retrieved:

13 At the building level: *How big is the building/dwelling?*

- 14 - Gross floor area in square meters,
- 15 - Net floor area in square meters,
- 16 - Number of floors

17 ➤ In this study, this information was extracted from architectural drawings.

18 At the building element level: *What are the main elements that make up the building/dwelling?*

- 19 - Building element type: examples are pitched/flat/terraced roof, external/internal wall,
 20 ground/story floor, main/inside doors, excavation, among others.
- 21 - Building element quantity: in square meters for roofs, walls, floors and windows, in
 22 linear meters for beams, in units for doors.
- 23 - Building element's overall thickness expressed in meters.
- 24 - Building element's thermal performance described by the U-value in W/m²K.
- 25 - Building element's lifetime in number of years.

26 ➤ In this study, this information was extracted from both BOQ and architectural drawings.

27 At the building component level: *What are the main components making up the different
 28 building elements of the building/dwelling?*

- 29 - Building component type: examples are softwood battens, plywood boards, glass wool
 30 blanket insulation, plaster coating, galvanized steel sheets roofing, among others.
- 31 - Building component's thickness expressed in millimetres.
- 32 - Building component's lifetime expressed in number of years.

33 ➤ In this study, this information was extracted from both BOQ and architectural details.

1 • Step 3: Data input as per the TOTEM library²²
 2 Considering the TOTEM library includes predefined buildings, elements, and components, the
 3 user is given a choice between modelling their building/dwelling by employing predefined
 4 elements/components or by composing their own. In composing building elements, a match
 5 must be made between the details provided by BOQ, architectural drawings, and architectural
 6 details and the materials and components provided by the TOTEM library. In this study, all
 7 building elements were composed.

8 • Step 4: Data Output

9 The environmental impact of the building/dwelling can be extracted from the TOTEM tool at
 10 the building, the building element, and the building component levels. The user can filter their
 11 data output depending on their specific research goals and scope. In this study, the focus was
 12 the embodied carbon of new-build dwellings, otherwise known as the material impact, with a
 13 particular focus on the global warming potential.

14 At the building level: The material impact of the building/dwelling is provided by TOTEM per
 15 life cycle stage expressed in kgCO_{2eq}/m². The addition of all impacts and multiplication per the
 16 GFA provides the total material impact of the dwellings in kgCO_{2eq} as per the specific research
 17 scope and boundaries.

18 At the building element level: The material impact of the building elements is provided by
 19 TOTEM in percentage shares of the total material impact of the building/dwelling. The
 20 multiplication of this percentage share by the total material impact computed at the building
 21 level provides the material impact of building elements in kgCO_{2eq}.

22 At the building component level: The material impact of the building components is provided
 23 by TOTEM in percentage shares of the material impact of the building elements in the
 24 building/dwelling. The multiplication of this percentage share by the material impact computed
 25 at the building element level provides the material impact of building components in kgCO_{2eq}.

26 • Step 5: Data processing and visualization²³

27 Data processing and visualization varies depending on the study aim and objectives. In this
 28 study, data processing and visualization at the building level was used to situate study outcomes
 29 in existing literature. Whereas, data processing and visualization at the building element and

²² Refer to Study Inventory in the supplementary materials for the detailed and complete data input inventory.

²³ Refer to Study Output in the supplementary materials for the data processing and visualization document behind the output presented in this study.

1 building component levels were used to identify carbon intensive elements and components
 2 and inform primary and secondary design choices respectively.

3 • Step 6: Optimized design

4 Having identified EC intensive design choices, the final step consisted of remodelling the
 5 dwelling design according to the knowledge gained in Step 5. This iterative approach, which
 6 revisits and refines the initial design based on newly acquired insights effectively closes the
 7 design loop.

8 **Appendix B: Operational energy use**

9 In the context of residential buildings, operational CO₂ emissions arise from the combustion of
 10 carbon-based fuels (like oil, natural gas, wood) that occur through processes like heating the
 11 house with a boiler, warming tap water with a heater, or cooking on a gas stove. These CO₂
 12 emissions are considered to be direct. However, operational CO₂ emissions can also be
 13 indirectly generated when using electricity that is produced from fossil fuels. As a result, to
 14 accurately assess the CO₂ emissions associated with OE consumption, it becomes essential to
 15 account for both gas and electricity usage. In doing so, a comprehensive view can be obtained
 16 of the operational environmental impact stemming from the energy needs of residential
 17 dwellings.

18 Various models exist for assessing the OE performance of houses, differing in their level of
 19 detail and complexity. These models range from generic ones, which rely on a handful of key
 20 parameters like floor area, insulation thickness, types of installations, and location. These are
 21 often employed in relation to the EPBD [81]. More intricate models such as Transient System
 22 Simulation Program (TRNSYS) demand much more detailed information, including specifics
 23 like air leakage areas, and are typically implemented by experts due to their complexity [82].

24 While these theoretical energy models can provide a preliminary estimate of a house's OE
 25 consumption, they often diverge from actual energy usage due to variations in real-world
 26 parameters and the dynamic behaviour of residents. This concept is well known in existing
 27 literature and is referred to as the energy performance gap [83]. As a result, to accurately gauge
 28 the true energy performance of a dwelling, it becomes essential to employ a monitoring
 29 approach for OE consumption. This approach ensures that real-life data is collected, offering
 30 insights that generic and even detailed models might overlook, which is why it is the approach
 31 that was adopted in the H4.0E project.

1 Within the H4.0E project, the monitoring equipment consisted of electricity meters, indoor
 2 climate sensors, and a central hub. The electricity meters were installed in the fuse box of the
 3 houses continuously measuring the electricity consumptions at a 5 minutes interval. Indoor
 4 climate sensors were used to measure indoor temperature, relative humidity and air quality
 5 through the level of CO₂ concentration at a 30 minutes interval. The central hub collects and
 6 stores both electricity and indoor climate data that is sent in regular intervals to the server where
 7 it can be accessed for analysis. The monitoring period varied between the dwellings as can be
 8 seen in Table B.1. below.

9 Table B.1: Operational energy monitoring periods

Dwelling	NL1	NL2	NL3	NL4
Start	06-02-2022	05-03-2022	20-02-2022	05-03-2022
End	23-02-2023	23-02-2023	23-02-2023	23-02-2023

10 All dwellings had the same heating system installed which consisted of a heat pump and all
 11 dwellings had PV panels installed for the generation of renewable energy. Additionally, all
 12 installations in the dwellings run on electricity and there are no connections to natural gas.
 13 Table B.2. presents the total OE consumption resulting from the monitoring of four dwellings.
 14 The table lists the dwellings' total uptake and feedback from and to the grid which leads to the
 15 net consumption over the monitoring period. These outcomes are then extrapolated to obtain
 16 the net energy consumption of the dwellings throughout the year. The yearly energy
 17 consumption (presented in kWh) is then multiplied by the CO₂ emissions factor for electricity
 18 to obtain the yearly total operational CO₂ emissions in kilograms of CO₂ equivalent. The CO₂
 19 emissions factor for electricity in the Netherlands is 0.456 [84]. Table A.2. also provides the
 20 energy generated from the PV panels for reference.

21 Table B.2: Total operational energy consumption

Dwelling	NL1	NL2	NL3	NL4
Main meter uptake from the grid (in kWh)	3019.3	7517.5	3855.1	6035.3
Main meter feedback to the grid (in kWh)	4252.6	3026.7	5149.9	4631.9
Net consumption (in kWh)	-1233.3	4490.8	-1294.8	1403.4
Net yearly energy consumption (in kWh)	-1226.2	5159.8	-1245.9	1688.8
Total operational CO₂ emissions (KgCO₂eq./year)	-559	2352	-568	770
*PV Panel production (in kWh)	5245.7	5046.9	6779.5	5707.1

22 The results exhibit significant variations among the four monitored dwellings, with NL1 and
 23 NL3 standing out as energy-positive examples. However, due to privacy constraints, the
 24 monitoring data had to be disassociated from the specific monitored dwellings, limiting the
 25 ability to directly correlate OE consumption with factors such as dwelling size, NFA, and
 26 household size. An in-depth analysis of these correlations could have provided valuable
 27 insights into the observed discrepancies. It is important to note that the monitoring

1 encompassed both installation-related energy consumption (heating, cooling, ventilation, hot
 2 water) and user-related energy consumption (appliances), and considering the influence of
 3 dwelling and household size could have further clarified the variations in the results.

4 Combining the operational carbon emissions outcomes with the embodied emissions outcomes
 5 results in a full energy consumption ranging between 142 and 3062 KgCO_{2eq}/year for the Small
 6 House, 313 and 3233 KgCO_{2eq}/year for the Medium House and 605 and 3525 KgCO_{2eq}/year
 7 for the Large House. Overall, the total energy consumption results do not reach a net-zero
 8 yearly balance despite both the OE-plus and low EC.

9 These findings are a direct manifestation of the fact that achieving a net zero-balance in terms
 10 of carbon emissions of a dwelling is a great challenge. The interplay of various elements,
 11 including user behaviour, energy systems, and construction materials, ultimately determines a
 12 dwelling's overall carbon footprint. Notably, the results demonstrate that efforts to minimize
 13 both operational and EC do not guarantee successful outcomes. Nevertheless, it is crucial to
 14 highlight that these findings do not contradict the central argument put forth in this paper, which
 15 advocates for a heightened focus on reducing EE. In fact, these results further support this
 16 position, particularly when considering the energy-positive dwellings. The outcomes suggest
 17 that even greater reductions in EE could have led to the attainment of a net-zero yearly balance.
 18 In essence, reducing EE remains a critical priority, as it significantly enhances the prospects of
 19 achieving favourable life cycle energy consumption outcomes, especially when considering the
 20 element of permanence that is peculiar to EE versus the future decarbonization of the
 21 electricity grid which will further decrease the impact of OE.

22 Indoor environmental conditions

23 Table B.3. presents the average monthly indoor temperature and relative humidity (RH) per
 24 dwelling. Indoor temperature thresholds for overheating vary based on regional climate
 25 conditions, building design, and individual comfort preferences. In the Netherlands, in
 26 dwellings designed to be NZEB, overheating occurs when the indoor temperature is above
 27 27°C exceeding the 450 WHOs (Weighted Overheating Hours) threshold [85]. The optimal
 28 level of the RH falls within the range of 45 to 60% [86]. As can be seen, the dwellings did not
 29 overheat throughout the monitoring period considering the maximum average indoor
 30 temperature did not reach 27 °C that summer. The recorded maximum was 26.2 °C in NL1 and
 31 NL4 during the months of July and August 2022. Nevertheless, this does not exclude the
 32 possibility of overheating in the future. For that, there are certain post-construction strategies

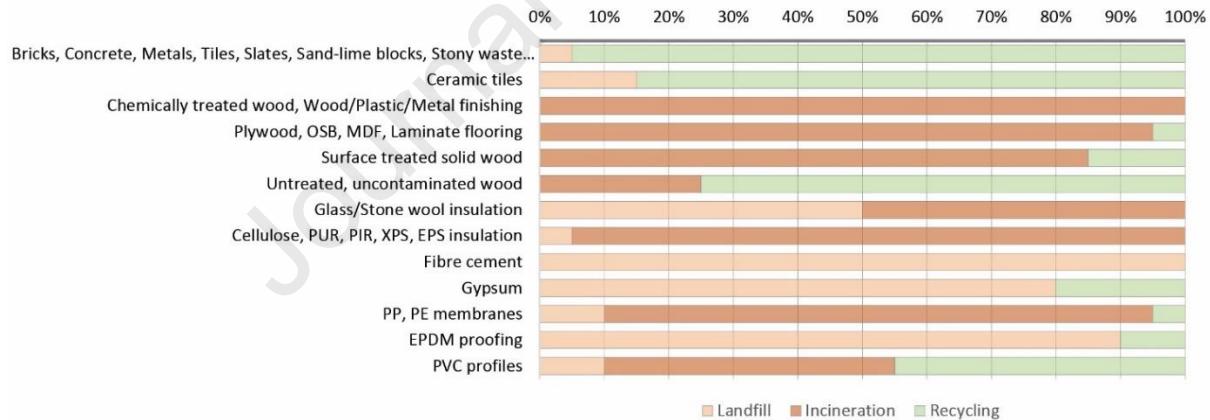
1 that can be implemented to mitigate this issue. The most common ones are shading to block
 2 direct sunlight and cross-ventilation.

3 Table B.3.: Indoor environmental conditions in the dwellings throughout the monitoring period

Monitoring period	NL1		NL2		NL3		NL4	
	06-02-2022	23-02-2023	22-07-2022	23-02-2023	20-02-2022	23-02-2023	05-03-2022	23-02-2023
	Year	Month	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
2022	February	21.3	46.5	-	-	20.8	43.2	-
	March	22.9	40.3	-	-	21.7	38.4	19.4
	April	23.1	42.0	-	-	21.7	40.6	19.7
	May	24.7	45.7	-	-	21.8	46.7	22.5
	June	25.8	48.6	-	-	22.5	50.8	25.2
	July	25.7	50.4	23.8	52.6	22.5	52.6	26.2
	August	26.2	53.0	25.3	52.9	23.2	54.6	26.0
	September	24.0	51.0	22.7	51.6	21.3	52.3	21.5
	October	23.0	54.0	21.2	54.7	20.7	53.9	21.2
	November	21.0	52.3	20.5	50.1	20.0	50.8	18.8
	December	19.2	48.3	19.3	44.5	19.6	44.0	16.4
2023	January	19.7	49.3	20.6	44.7	19.5	45.7	17.8
	February	20.1	50.5	20.8	44.4	20.0	45.1	17.8

4 Appendix C: Miscellaneous

5 Figure C.1. displays the assumptions around the end-of-life scenarios of the main building
 6 components used in this assessment.



7
 8 Figure C.1.: End-of-life scenarios (adapted from [52])

9 Figure C.2. displays the material impact of different insulation types versus their thermal
 10 performance. Generally, soft insulations have a lower material impact than rigid insulations.
 11 Yet, within the different types of soft insulations, cellulose insulation has the lowest material
 12 impact while maintaining a similar thermal performance as its counterparts.

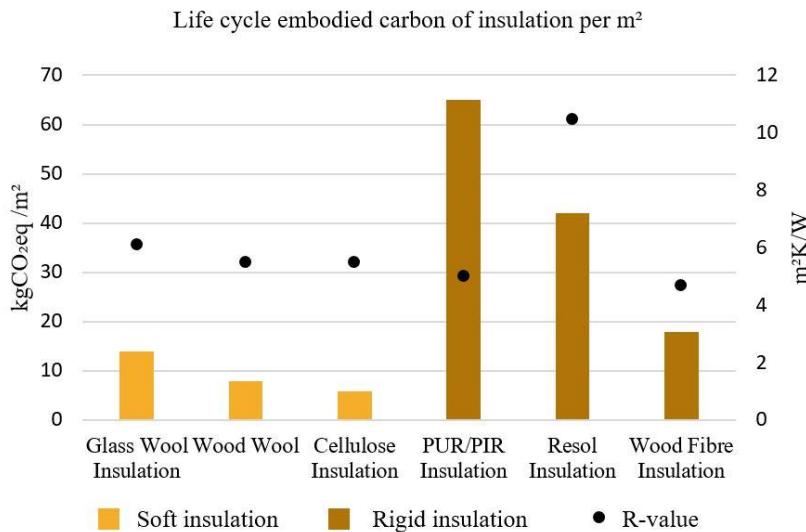


Figure C.2.: Material impact versus thermal performance of different insulation types for the same thickness of 220 mm

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Revised Highlights

- Downsizing and timber are assessed in tandem as embodied carbon reduction strategies
- The embodied carbon of actual European housing scenarios is investigated
- A proposed hierarchical approach decomposes the house into elements and components
- The hierarchical analysis links architectural design choices to embodied carbon
- A small timber house consumes half the embodied carbon of a large concrete house

Declaration of interests

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

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: