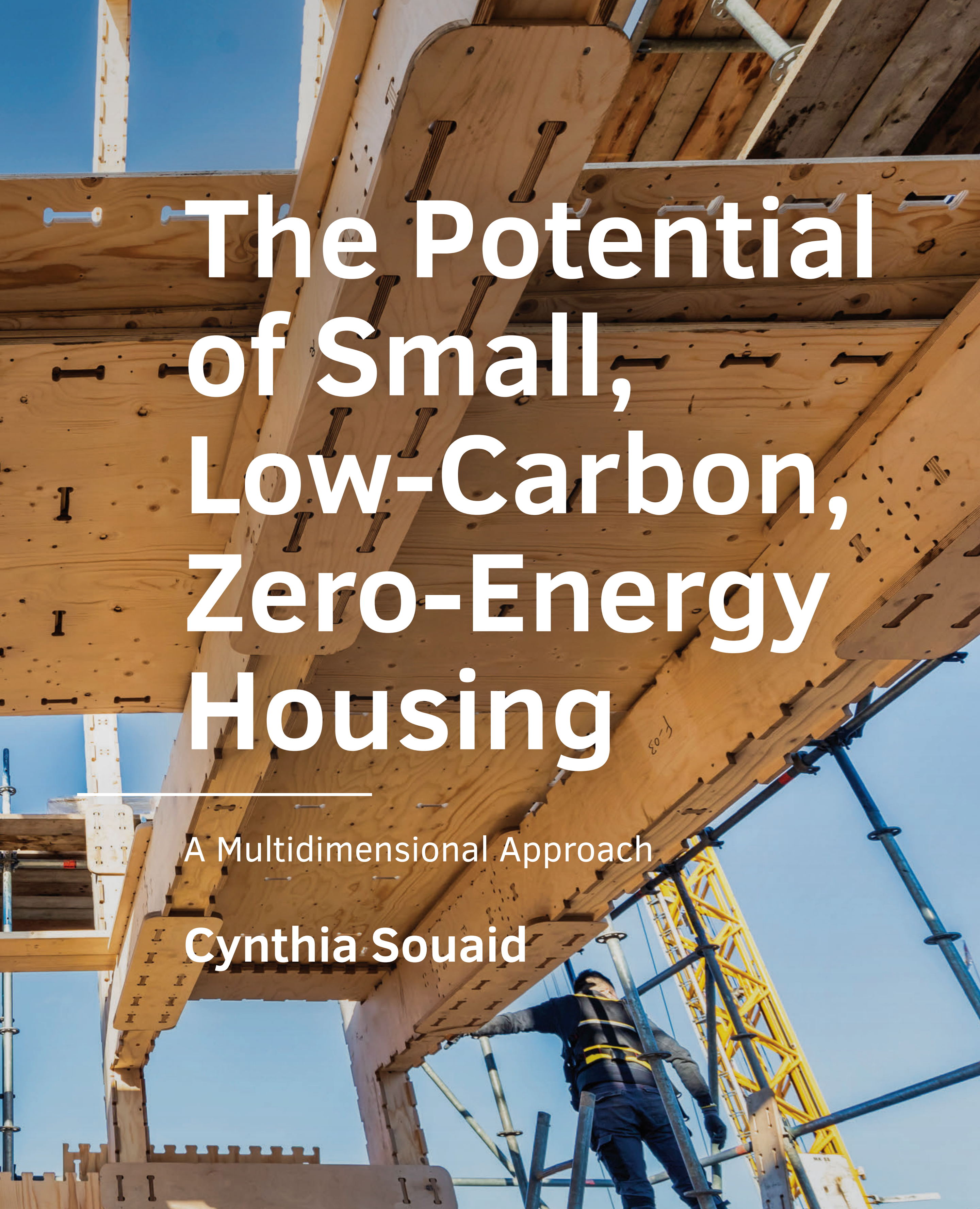
The Potential of Small, Low-Carbon, Zero-Energy Housing

A Multidimensional Approach

Cynthia Souaid



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Cover photo | Close-up showing the building frame composed of Multiplex wooden panels in the timber dwellings built in Almere in the Netherlands as part of the Housing 4.0 Energy project funded by Interreg North-West Europe. Copyright: Wikihouse.

Keywords | small housing, institutional barriers, perceived barriers, multi-attribute utility theory, housing preferences, life cycle assessment, embodied carbon emissions

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The Potential of Small, Low-Carbon, Zero-Energy Housing

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by

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Through the Housing 4.0 Energy project, I had the unique opportunity to collaborate with and learn from professionals across five different European countries. This experience allowed me to pursue an academic career path while witnessing how the work is practically implemented in industry, a perspective for which I am deeply grateful. Moreover, the project gave me the opportunity to present my research at various project meetings and conferences where I received constructive and motivating feedback that greatly contributed to the advancement of my work. I would like to extend my sincere appreciation to our project partners, Katrien, Sofie, Ivar, Shane, Ralf and Alex who not only participated in the research but facilitated its execution by providing essential information, data and tools.

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Summary

It is widely acknowledged that the global efforts to mitigate the consequences of climate change and achieve the established sustainability goals have encountered significant challenges. Currently, it's become clear that incremental changes are no longer possible and that the response to the threat of climate change needs to be strengthened and radically accelerated, hence Europe's decarbonization plan by 2050. The built environment is known to be a significant contributor to climate change that is responsible for almost 40% of global greenhouse gas emissions. Seeing as the residential sector in particular constitutes 75% of the European building stock it is safe to state that housing is in itself a significant contributor to climate change.

In parallel, different demographic, societal and economic developments observed within the European housing sector are said to have changed the nature of housing demand. These developments have led to a growing housing shortage in most European countries making the construction of new-build dwellings much needed. As such, while there is increasing pressure on the housing sector from the sustainability perspective to prevent additional greenhouse gas emissions, the construction of new-build dwellings is inevitable considering the simultaneous pressure, from the housing market perspective, to respond to the growing housing shortage.

In response to this twofold challenge, the latest energy policy developments have been aiming for stricter regulations. A zero operational energy performance is now mandatory in several European countries, and the political focus has shifted towards adopting a life cycle perspective where the reduction of the embodied carbon of buildings regained priority. Additionally, the latest environmental programmes have been promoting the avoidance of the demand for energy and materials as the new primary sustainability strategy. Within the residential sector, when the avoidance strategy is confronted with an alarmingly growing need for new-build housing, it translates into building less through downsizing dwellings.

Research aim

Given this backdrop, small, low-carbon, (near) zero-energy dwellings are being proposed as a housing solution that would both address sustainability challenges and answer to the growing housing shortage in Europe. As part of the project entitled **Housing 4.0 Energy: Affordable & Sustainable Housing through Digitization** and funded by Interreg North-West Europe, the aim of this research is to investigate the implementation of small, low-carbon, (near) zero-energy dwellings in practice and assess their potential as a housing solution. Accordingly, it addresses the following main research question:

– **To what extent are small, low-carbon, (near) zero-energy dwellings a housing solution in North-West Europe?**

This research builds upon established theoretical frameworks within energy literature to construct its own conceptual framework. This conceptual framework is designed to address the main research question by adopting a multidimensional outlook that encompasses the institutional, social and technical aspects related to small, low-carbon, (near) zero-energy dwellings. In doing so, this research combines a top-down evaluation of existing policies with a complementary bottom-up approach. It recognizes the pivotal role of the human factor in the process of change, both on the supply and demand side of the housing market, while concurrently investigating the material impact of these innovative dwelling designs.

This research draws upon findings from the H4.0E project and extracts data from three pilot projects taking place in Belgium, Ireland, and the Netherlands. Stemming from this conceptual framework are four research sub-questions that were answered in four separate studies as summarized below.

Study 1: Institutional Barriers to Nearly Zero-Energy Housing: A Context Specific Approach

In this study, the institutional dimension surrounding small, low-carbon, (near) zero-energy dwellings is addressed. Recalling the importance of having an encouraging policy environment for a more effective implementation and uptake of sustainability measure, the intention here is to adopt a top-down outlook that recognizes the potential impact of established policies for a more holistic understanding. As such, this study explores current established contextual policies by investigating potential institutional barriers to the implementation and uptake of small, low-carbon, (near) zero-energy dwellings. Considering the investigation of barriers is one of the primary and foundational actions taken to evaluate the implementation of new sustainability measures for an overall effective market response this study answers the following research sub-questions:

- **What are the institutional barriers to the implementation and uptake NZEBs? What insights can be gained from the investigation and identification of these institutional barriers and how can they inform policy?**

Barriers to the implementation of sustainability measures, including (near) zero-energy buildings/dwellings, have been extensively examined in academic literature. Despite variations in research scopes, perspectives, locations and timeframes, previous studies have consistently arrived at similar conclusions. This study argues that while this could be interpreted as a validation of outcomes, it could also highlight a limitation associated with conducting the analysis at a general level. In response to this limitation, this study contributes to the ongoing discourse by adopting a context-specific approach in its investigation of barriers. A qualitative methodological approach was adopted and the data was collected from a series of focus group discussions organized with housing professionals in Leuven, in Belgium, Kilkenny, in Ireland, and Almere, in the Netherlands. Upon conducting descriptive coding, the study's findings echoed the results of previous research. Delving deeper with inferential coding, the study identified an additional 21 contextual barriers paving the way for the formulation of more specific policy suggestions each with a different allocation of precedence tailored to the specific context in question.

Study 2: Perceived Barriers to Nearly Zero-Energy Housing: Empirical Evidence from Kilkenny, Ireland

In this study, the social dimension surrounding small, low-carbon, (near) zero-energy dwellings is addressed with a focus on the provision end of the housing market. By now, it is recognized that the successful implementation and uptake of sustainability measures entail social changes just as much as technical changes. As such, the research scope needs to account for the potential impact of the human factor in the investigation. While the recognition of the importance of the human factor has been increasing in energy and buildings research, the focus has been directed mostly on investigating end-users. Moreover, end-users have predominantly been included as *recipients of change* rather than *actors for change*. In other words, research has focused less on investigating the human factor in the provision of sustainability measures and, by including individuals as recipients of change, it has also overlooked the potentially significant impact of their actions, underpinned by their perceptions in the process of change. In response to the limited research on housing professionals and their perceptions as actors in the process of change, this study investigates the human factor on the supply side of the housing market and brings the perceptions of housing professionals to the forefront in its investigation of institutional barriers to the implementation and uptake of small, low-carbon, (near) zero-energy dwellings. Accordingly, it answers the following research sub-question:

- **To what extent do the perceptions of housing professionals affect the identification of barriers to the implementation of NZEBs?**

A qualitative methodological approach was adopted and the data was collected through a focus group and semi-structured interviews with housing professionals in Kilkenny, Ireland. Through an iterative research process this study traces a distinction between actual and perceived barriers identified by housing professionals. Descriptive coding, inferential coding, and fact tracing revealed that 6 out of the 10 most common barriers identified are perceptions and not actual barriers. These include the perception of higher costs, lenient building regulations and the uncertainty and risks of innovations, among others. Additionally, study outcomes revealed the preference of the business as usual approach, a general lack of awareness and information dissemination as the three overarching barriers that potentially justify the gap between policy formulation and implementation in practice. Therefore, the study calls for innovation in information dissemination be it between policy and local practice or between housing professionals themselves. This would reduce the revealed dyssynchronisation between policy developments and the knowledge and awareness within local practice thus contributing to closing the gap between the development of policies and their implementation.

Study 3: The demand for small, low-carbon, zero-energy, timber dwellings: A study of consumers' stated housing preferences

In this study, the social dimension is addressed again by investigating the human factor on the demand side of the housing market. From the housing market perspective, small, low-carbon, (near) zero-energy dwellings are being proposed as a solution based on the assumption that housing preferences are leaning towards smaller dwellings due to the increasing number of smaller, elderly, and lower-income households. Recalling the importance of accounting for individuals as actors and not recipients in the process of change, this study follows the stance of shaping supply through adopting a bottom-up approach in its investigation. As such, this study tests this assumption by gauging consumers' housing expectations and aspirations in their demand for housing through the evaluation of their current housing preferences and answers the following research sub-question:

- **To what extent do smaller, low-carbon and zero-energy dwellings fulfil current housing preferences?**

A quantitative methodological approach was adopted through the distribution of a uniquely tailored housing preferences questionnaire in Flanders, Belgium and in Almere, the Netherlands. The Multi-Attribute Utility theory (MAUT) method was used to gauge housing preferences and potential trade-offs pertaining to the following specific housing characteristics: dwelling type, dwelling location, dwelling size, number of bedrooms, and building materials. Through the MAUT method, complete dwelling profiles were composed and scored based on respondents' ratings thus gauging the extent to which small, low-carbon, (near) zero-energy dwelling fulfil current housing preferences. Overall, the findings indicated that there is no demand for the smallest timber dwellings of less than 50 m^2, as they scored below the average level of attractiveness in both research areas. This implies that they do not align with the current housing preferences of consumers. However, the smaller timber dwellings of 50 to 80 m^2, scored just around the average level of attractiveness. This suggests that there is potential for timber dwellings in the size range of 50 to 80 m^2 to meet consumer preferences. Additionally, results refuted the assumption that preferences are leaning towards smaller dwellings due to the increase of smaller, elderly, and/or lower income households considering the only characteristic affecting preferences around dwelling size was revealed to be the consumers' current residential area.

Study 4: The assessment of downsizing and the use of timber as embodied carbon reduction strategies for new-build housing

In this study, the technical dimension presented in the conceptual framework is addressed. The normalization of a zero-operational energy performance significantly increased the relevance of a dwelling's embodied energy performance. The reduction of embodied carbon has regained traction and is now at the top priority level of environmental policies and programmes. For this reason, this research chooses to focus on the embodied carbon of small, low-carbon, (near) zero-energy dwellings in its investigation. Furthermore, keeping in mind that sustainability strategies now call for the prioritization of the avoidance of energy demand and materials, the focus of embodied carbon reduction strategies is no longer restricted to the use of more sustainable, low-carbon building materials. It rather becomes crucial to simultaneously decrease quantities through downsizing and limiting embodied carbon emissions at an early stage prior to any application. Accordingly, this study answers the following research sub-question:

— What is the impact of downsizing and the use of timber on the embodied carbon of a new-build dwelling?

A quantitative methodological approach was adopted through conducting a partial life cycle assessment (LCA) of the small, low-carbon, (near) zero-energy dwellings using TOTEM: The Tool to Optimize the Total Environmental Impact of Materials. The material impact of three housing scenarios was computed: the Small House (45 m^2), the Medium House (76 m^2), and the Large House (104 m^2). For each scenario, two different construction approaches were simulated. These approaches compared a modular timber design with a traditional concrete design. The three selected dwellings were among the H4.0E dwellings built in Almere. The results revealed that the total embodied carbon emissions ranged from 42,608 to 70,384 KgCO2eq for the timber designs and 54,681 to 91,270 KgCO2eq for the concrete designs. Downsizing alone led to a 40% material impact reduction. When downsizing was combined with the use of timber as the primary building material, it achieved even more significant carbon savings, amounting to 53%. Additionally, this study demonstrated a hierarchical approach that enables practitioners to utilize data at the level of building elements and components to make informed decisions during the early stages of design. Examples are decisions regarding secondary design choices such as roofing, flooring and coating. This approach ultimately led to further embodied carbon reductions amounting to 29% thus demonstrating how unnecessary embodied carbon emissions can be prevented at the early design stages. Lastly, when contextualizing the findings of this study within the existing body of literature, it became evident that there is a lack of consistency in life cycle assessment (LCA) studies. This lack of comparability hinders a comprehensive understanding of outcomes, underscoring the need for common guidelines around the implementation and documentation of LCA, both within the industry and the scientific community.

Overall conclusion

By adopting a holistic and multidimensional outlook as was set out in the conceptual framework, this research sheds light on the complexity of the subject at hand, demonstrating that the answer to the main research question is far from straightforward. While downsizing to dwellings smaller than 50 m^2 leads to the most significant reduction in embodied carbon and minimizes the material impact, this dwelling size may not align with current housing preferences and could potentially reduce the comfort and satisfaction levels of residents in the studied areas. Furthermore, while there is a need for current established housing policies, design requirements and financial incentives to be adjusted to facilitate upscaling, there is a simultaneous need for the latest developments to be effectively communicated to local authorities and housing professionals to accelerate the shift towards small, low-carbon, (near) zero-energy dwellings.

It is also important to highlight that, while the inclusion of three different study contexts provided valuable insights and underlined the importance of contextual peculiarities and their impact on study outcomes, especially in the exploratory examination of institutional barriers, this also presented a limitation. Although these contextual variations did not hinder the aim of achieving a holistic and multidimensional understanding of small, low-carbon, and (near) zero-energy housing, they did pose challenges in generating generalizable conclusions. Consequently, the geographical representativeness of this research was constrained.

In terms of future research, this thesis laid the groundwork for adopting a multidimensional outlook in the evaluation of the implementation and uptake of small, low-carbon, (near) zero-energy dwellings in practice. Looking forward, future research can build upon this foundation by conducting similar investigations with more extensive and diverse samples of housing professionals and consumers across various contextual settings. Future research can delve deeper into the nuances of housing preferences by implementing innovative evaluation methods that better simulate real life decision making and capture the dynamic nature of the housing market. Also, such studies can be conducted within all types of residential areas for a more comprehensive understanding of the interplay between location and dwelling size preferences. There is also ample room to broaden the scope of including the human factor in the study through conducting post-occupancy evaluations. From a technical perspective, future research should strive for comprehensive life cycle assessments that offer a more precise and complete depiction of dwellings' carbon footprints. A particular focus should be placed on standardizing the process of accounting for embodied carbon in building services, sanitary elements, and furniture. Additionally, a comparative analysis of different life cycle assessment tools would help identify potential disparities in results arising from distinct assumptions made by each tool. This analysis would enable a more accurate interpretation of life cycle assessment outcomes, promoting a better understanding of their implications.

Lastly, future research can extend the scope of this study by delving into the economic dimension. Conducting an analysis of the affordability of small, low-carbon, and (near) zero-energy housing designs would offer valuable insights into their practical feasibility as a housing solution, especially when compared to more conventional housing options. In that way, this would also address specific institutional barriers identified by housing professionals such as concerns related to higher initial costs, payback periods and return on investment. Such an analysis would complement the multidimensional approach adopted in this research and lead to a more comprehensive perspective on the viability and potential adoption of these innovative dwelling designs in different contexts. By incorporating this dimension, future research can contribute to an even broader understanding of the potential of small, low-carbon, (near) zero-energy dwellings as a housing solution in North-West Europe.

Samenvatting

Samenvatting Nederlands

Het is algemeen erkend dat de wereldwijde inspanningen om de gevolgen van klimaatverandering te beperken en de vastgestelde duurzaamheidsdoelstellingen te bereiken, aanzienlijke uitdagingen hebben ondervonden. Op dit moment is duidelijk geworden dat geleidelijke veranderingen niet langer voldoende zijn en dat de reactie op de dreiging van klimaatverandering moet worden versterkt en drastisch versneld. Daarom heeft de EU zich als doel gesteld om in 2050 klimaatneutraal te zijn. De gebouwde omgeving staat bekend als een belangrijke bijdrager aan klimaatverandering en is verantwoordelijk voor bijna 40% van de mondiale broeikasgasemissies. Aangezien de residentiële sector met name 75% van het Europese gebouwenbestand uitmaakt, kunnen we stellen dat huisvesting op zichzelf een aanzienlijke bijdrager is aan klimaatverandering.

Tegelijkertijd hebben verschillende demografische, maatschappelijke en economische ontwikkelingen de vraag naar huisvesting veranderd. Deze ontwikkelingen hebben geleid tot een groeiend tekort aan huisvesting in de meeste Europese landen, wat de bouw van nieuwe woningen dringend noodzakelijk maakt. Hoewel er vanuit duurzaamheidsperspectief steeds meer druk op de woningsector staat om extra uitstoot van broeikasgassen te voorkomen, is de bouw van nieuwbouwwoningen onvermijdelijk gezien de gelijktijdige druk vanuit het perspectief van de woningmarkt om in te spelen op het groeiende woningtekort. Als reactie op deze tweeledige uitdaging, zijn de laatste ontwikkelingen in het energiebeleid gericht op strengere regelgeving. In verschillende Europese landen is een nul-op-de-meter operationele energieprestatie nu verplicht en de politieke focus is verschoven naar een levenscyclusperspectief waarbij de vermindering van de CO_2 uitstoot gedurende de levenscyclus van gebouwen prioriteit heeft gekregen. Bovendien wordt in de meest recente milieuprogramma's het vermijden van de vraag naar energie en materialen gepromoot als de belangrijkste nieuwe duurzaamheidsstrategie. Binnen de residentiële sector leidt deze nieuwe strategie, in combinatie met de sterk groeiende behoefte aan nieuwe woningen, tot een vermindering van materiaalverbruik door een grotere nadruk op het bouwen van kleinere woningen.

Onderzoekdoel

Tegen deze achtergrond worden kleine, koolstofarme, (bijna) energieneutrale woningen voorgesteld als een huisvestingsoplossing die zowel tegemoet komt aan duurzaamheidseisen als het groeiende huisvestingstekort in Europa. Als onderdeel van het project *Housing 4.0 Energy: Affordable & Sustainable Housing through Digitization* (Nederlands: Housing 4.0 Energie: Betaalbare en duurzame huisvesting door digitalisering), gefinancierd door Interreg Noord-West Europa, is het doel van dit onderzoek om de implementatie van kleine, koolstofarme, (bijna) energieneutrale woningenin de praktijk te onderzoeken en hun potentieel als huisvestingsoplossing te beoordelen. Dienovereenkomstig is de volgende hoofd onderzoeksvraag geformuleerd:

- **In hoeverre zijn kleine, koolstofarme, (bijna) energieneutrale woningen een huisvestingsoplossing in Noordwest-Europa?**

Dit onderzoek bouwt voort op bestaande theoretische kaders binnen de energieliteratuur, op basis waarvan een eigen conceptueel kader is geformuleerd. Dit kader is ontworpen om de hoofd-onderzoeksvraag te beantwoorden vanuit een multidimensionaal perspectief die de institutionele, sociale en technische aspecten omvat die verband houden met kleine, koolstofarme (bijna) energieneutrale woningen. Daarbij combineert dit onderzoek een top-down evaluatie van bestaande beleidsmaatregelen met een aanvullende bottom-up benadering. Het onderzoek erkent de cruciale rol van de menselijke factor in het veranderingsproces, zowel aan de aanbod- als aan de vraagzijde van de woningmarkt, terwijl het tegelijkertijd de materiële impact van de innovatieve woningontwerpen uit het H4.0E-project in beschouwing neemt.

Dit onderzoek maakt gebruik van bevindingen uit het H4.0E-project en haalt onder meer gegevens uit drie pilotprojecten in België, Ierland en Nederland. Uit het geformuleerde conceptuele kader komen vier onderzoeksvragen voort, die worden beantwoord in vier afzonderlijke studies, zoals hieronder samengevat.

Studie 1: Institutionele barrières voor (bijna) energieneutrale huisvesting: een context specifieke benadering

In deze studie wordt de institutionele dimensie rond kleine, koolstofarme, (bijna) energieneutrale woningen behandeld. Vanuit het belang van een stimulerend beleid voor een effectievere implementatie en acceptatie van duurzaamheidsmaatregelen, wordt vanuit een top-down perspectief gekeken naar het potentiële effect van bestaande beleidsmaatregelen en vervolgens wordt onderzocht welke potentiële institutionele barrières er bestaan voor de realisatie van kleine, koolstofarme, (bijna) energieneutrale woningen. Aangezien het onderzoek naar barrières één van de belangrijkste en fundamentele acties is om de implementatie van nieuwe duurzaamheidsmaatregelen te evalueren, beantwoordt deze studie de volgende onderzoeksvragen:

- **Wat zijn de institutionele barrières voor de realisatie van koolstofstofarme, (bijna) energieneutrale woningen? Welke inzichten kunnen worden verkregen uit het onderzoek naar en de identificatie van deze institutionele barrières en hoe kunnen ze het beleid informeren?**

Barrières voor de implementatie van duurzaamheidsmaatregelen, waaronder (bijna) energieneutrale woningen/-gebouwen, zijn uitgebreid onderzocht in de academische literatuur. Ondanks variaties in onderzoeksgebieden, perspectieven, locaties en periode, zijn eerdere studies consequent tot vergelijkbare conclusies uitgekomen. Deze studie betoogt dat, hoewel dit kan worden geïnterpreteerd als een bevestiging van de uitkomsten, het ook een beperking zou kunnen aankaarten die voortvloeit uit analyses op een algemeen, niet context specifiek niveau. Daarom wil deze studie bijdragen aan de voortdurende discussie door een context specifieke benadering te kiezen in het onderzoek naar barrières. Er wordt een kwalitatieve benadering gehanteerd en de gegevens zijn verzameld via focusgroep discussies met woningprofessionals in Leuven (België), Kilkenny (Ierland) en Almere (Nederland). Bij het analyseren van de resultaten kwamen de bevindingen van de studie in eerste instantie overeen met de resultaten van eerder onderzoek. Bij een meer gedetailleerde analyse werden 21 extra contextuele barrières geïdentificeerd, wat de formulering van meer specifieke beleidsaanbevelingen mogelijk maakte, elk met een andere toewijzing van prioriteit, afgestemd op de specifieke context in kwestie.

Studie 2: Ervaren barrières voor (bijna) energieneutrale huisvesting: empirisch bewijs uit Kilkenny, Ierland

In deze studie wordt de sociale dimensie rond de realisatie van kleine, koolstofarme , (bijna) energieneutrale woningen behandeld, met de nadruk op de aanbodzijde van de woningmarkt. Tegenwoordig wordt erkend dat een succesvolle implementatie en acceptatie van duurzaamheidsmaatregelen sociale veranderingen vereist, evenzeer als technische veranderingen. Zodoende moet het onderzoek rekening houden met het potentiële effect van de menselijke factor. Ondanks dat het belang van de menselijke factor in energie- en bouwkundig onderzoek steeds meer wordt erkend, heeft de focus vooralsnog voornamelijk gelegen op het onderzoeken van eindgebruikers. Daarbij zijn eindgebruikers voornamelijk opgenomen als ontvangers van verandering in plaats van actoren bij verandering. Met andere woorden, onderzoek heeft zich minder gericht op het onderzoeken van de menselijke factor bij de uitvoering van duurzaamheidsmaatregelen. Door individuen op te nemen als ontvangers van verandering, heeft het ook de potentie van hun acties over het hoofd gezien. Als reactie op het beperkte onderzoek naar woningprofessionals en hun percepties als actoren in het veranderingsproces, onderzoekt deze studie de menselijke factor aan de aanbodzijde van de woningmarkt en plaatst de ervaringen van woningprofessionals centraal in het onderzoek naar institutionele barrières voor de implementatie en acceptatie van kleine, koolstofarme, (bijna) energieneutrale woningen. Daarom is de volgende onderzoeksvraag geformuleerd

— **In hoeverre beïnvloeden de percepties van woningprofessionals de identificatie van barrières voor de realisatie van (bijna) energieneutrale woningen?**

Voor dit onderzoek werd een kwalitatieve methodologische benadering gehanteerd en de gegevens werden verzameld via een focusgroep en semi-gestructureerde interviews met woningprofessionals in Kilkenny, Ierland. Door een iteratief onderzoeksproces is in deze studie onderscheid gemaakt tussen daadwerkelijke en ervaren barrières die zijn geïdentificeerd door woningprofessionals. Uit de uitgevoerde analyses bleek dat 6 van de 10 meest genoemde barrières gepercipieerde barrierès zijn en geen daadwerkelijke barrières. Deze omvatten onder andere de perceptie van hogere kosten, soepelere bouwvoorschriften en onzekerheid en risico's van innovaties. Bovendien onthulden de resultaten van de studie de voorkeur voor de 'business as usual' benadering, een algemeen gebrek aan bewustzijn en een tekort schietende informatieverstrekking als de drie overkoepelende barrières die de kloof tussen beleidsvorming en implementatie in de praktijk mogelijk verklaren. Daarom pleit de studie voor innovatie in informatieverspreiding, of het nu gaat om de informatie-uitwisseling tussen beleid en lokale praktijk of tussen woningprofessionals onderling. Dit zou de geconstateerde kloof tussen beleidsontwikkelingen en de kennis en het bewustzijn binnen lokale praktijken verminderen en zo bijdragen aan het dichten van de kloof tussen de ontwikkeling van beleid en de implementatie ervan.

Studie 3: De vraag naar kleine, koolstofarme, (bijna) energieneutrale, houten woningen: een studie naar de woonvoorkeuren van consumenten

In deze studie staat de sociale dimensie opnieuw centraal, maar nu door de menselijke factor aan de vraagzijde van de woningmarkt te onderzoeken. Vanuit het perspectief van de woningmarkt worden kleine, koolstofarme , (bijna) energieneutrale woningen voorgesteld als een oplossing vanuit de veronderstelling dat woonvoorkeuren meer gericht zijn op kleinere woningen vanwege het groeiende aantal kleinere, oudere en lagere inkomenshuishoudens. Gezien het belang van het rekening houden met individuen als actoren en niet als ontvangers in het veranderingsproces, volgt deze studie een bottom-up benadering om het gewenste aanbod in kaart te brengen. Als zodanig test deze studie de veronderstelling dat de vraag naar kleine woningen toeneemt door de huidige woonvoorkeuren van van consumenten in kaart te brengen. Hieruit ontstaat de volgende onderzoeksvraag:

- **In hoeverre voldoen kleinere, koolstofarme en (bijna) energieneutrale woningen aan de huidige woonvoorkeuren?**

Er is een kwantitatieve methodologische benadering gevolgd door de verspreiding van een op maat gemaakte vragenlijst over woonvoorkeuren in Vlaanderen (België) en Almere (Nederland). De Multi-Attribute Utility Theory (MAUT)-methode werd gebruikt om de woonvoorkeuren met betrekking tot de volgende specifieke woningkenmerken te meten: woningtype, woninglocatie, woninggrootte, aantal slaapkamers en bouwmaterialen. Door de MAUT-methode werden complete profielen van woningen samengesteld en beoordeeld op basis van de beoordelingen van de respondenten, waardoor de mate waarin kleine, koolstofarme, (bijna) energieneutrale woningen aan de huidige woonvoorkeuren voldoen, kon worden gemeten. Over het algemeen gaven de bevindingen aan dat er geen vraag is naar de kleinste houten woningen van minder dan 50 m^2, omdat ze onder het gemiddelde aantrekkelijkheidsniveau scoorden in beide onderzoeksgebieden. Dit impliceert dat ze niet overeenkomen met de huidige woonvoorkeuren van consumenten. De kleinere houten woningen van 50 tot 80 m^2 scoorden echter net rond het gemiddelde aantrekkelijkheidsniveau. Dit suggereert dat er potentieel is voor houten woningen in de maatrange van 50 tot 80 m^2 om aan de woonvoorkeuren van consumenten te voldoen. Tot slot, de resultaten weerlegden de eerdere veronderstelling dat voorkeuren neigen naar kleinere woningen vanwege het toenemende aantal kleinere, oudere en/of lagere inkomenshuishoudens, aangezien het enige kenmerk dat van invloed is op voorkeuren met betrekking tot woninggrootte, het huidige woongebied van de consumenten bleek te zijn.

Studie 4: De evaluatie van kleinere woningen en het gebruik van houtbouw als strategieën voor de vermindering van het in nieuwe woningen opgeslagen koolstof

In deze studie wordt de technische dimensie uit het conceptuele kader behandeld. De verplichting om in de nieuwbouw (bijna) energieneutrale woningen te realiseren, heeft de relevantie van de in de woning opgeslagen koolstof aanzienlijk vergroot. De vermindering van in de woning opgeslagen koolstof staat nu op het hoogste prioriteitsniveau van milieubeleidsmaatregelen en -programma's. Om deze reden is ervoor gekozen om in dit onderzoek de focus te leggen op de in de woning opgeslagen koolstof van kleine, (bijna) energieneutrale woningen. Bovendien, met inachtneming van het feit dat duurzaamheidsstrategieën nu oproepen tot het verminderen van de energievraag en het materiaalgebruik, is de focus niet langer beperkt tot het gebruik van duurzamere, koolstofarme bouwmaterialen. Het wordt cruciaal om tegelijkertijd de hoeveelheid gebruikte bouwmaterialen te verminderen door kleinere woningen te realiseren en zo de uitstoot van ingesloten koolstof in een vroeg stadium, voorafgaand aan enige toepassing, te beperken. Daarom beantwoordt deze studie de volgende onderzoeksvraag:

- **Wat is het effect van kleinere woningen en het gebruik van houtbouw op de in nieuwe woningen opgeslagen koolstof?**

Er werd een kwantitatieve methodologische benadering gevolgd door het uitvoeren van een gedeeltelijke levenscyclusanalyse (LCA) van de kleine, koolstofarme , (bijna) energieneutrale woningen met behulp van het TOTEM programma, ofwel de Tool to Optimize the Total Environmental Impact of Materials. De materiaalimpact van drie huisvestingsscenario's werd berekend: een klein huis (45 m^2), een middelgroot huis (76 m^2) en een groot huis (104 m^2). Voor elk scenario werden twee verschillende bouwtechnieken gesimuleerd. Deze benaderingen vergeleken een modulair houten ontwerp met een traditioneel beton en baksteen ontwerp. De drie geselecteerde woningen behoorden tot de H4.0E-woningen die in Almere werden gebouwd. De resultaten toonden aan dat de totale hoeveelheid in de woningen opgeslagen koolstof varieerde van 42.608 tot 70.384 KgCO2eq voor de houten ontwerpen en van 54.681 tot 91.270 KgCO2eq voor de betonnen ontwerpen. Enkel een verkleining van een woning leidde tot een vermindering van de materiaalimpact met 40%. Wanneer verkleining werd gecombineerd met het gebruik van hout als het belangrijkste bouwmateriaal, werden nog significantere uitstootbesparingen bereikt, tot 53%. Bovendien demonstreerde deze studie een hiërarchische benadering die professionals in staat stelt gegevens te gebruiken op het niveau van bouwelementen en componenten om goed geïnformeerde ontwerpbesluiten te kunnen nemen in de vroege ontwerpfase. Voorbeelden zijn beslissingen met betrekking tot secundaire ontwerpkeuzes zoals dakbedekking, vloeren en bekleding. Deze benadering leidde uiteindelijk tot verdere theoretische vermindering van de in de woningen opgeslagen koolstof tot 29%, waardoor werd aangetoond hoe onnodige uitstoot van ingesloten koolstof in de vroege ontwerpfase kan worden voorkomen. Ten slotte werd bij het positioneren van de resultaten uit deze studie binnen de uitkomsten in de bestaande literatuur duidelijk dat er een gebrek is aan consistentie in levenscyclusbeoordeling (LCA) -studies. Dit gebrek aan vergelijkbaarheid belemmert een alomvattende interpretatie van resultaten en benadrukt de noodzaak van gemeenschappelijke richtlijnen voor de uitvoering en documentatie van LCA, zowel binnen de sector als in de wetenschappelijke gemeenschap.

Algemene conclusie

Door een holistische en multidimensionale benadering te hanteren, zoals uiteengezet in het conceptuele kader, werpt dit onderzoek licht op de complexiteit van het onderwerp, waarbij wordt aangetoond dat het antwoord op de hoofdonderzoeksvraag verre van eenvoudig is. Hoewel verkleining tot woningen kleiner dan 50 m^2 leidt tot de meest significante vermindering van embodied carbon en de materiaalimpact minimaliseert, komen woningen op deze schaal mogelijk niet overeen met de huidige woonvoorkeuren en kunnen deze het comfort en de tevredenheid van bewoners in de bestudeerde gebieden mogelijk verminderen. Bovendien, hoewel er behoefte is aan aanpassing van het huidige huisvestingsbeleid, de ontwerpeisen en financiële randvoorwaarden om opschaling te vergemakkelijken, is er tegelijkertijd behoefte aan effectieve communicatie van de recente (beleids) ontwikkelingen naar lokale autoriteiten en woningprofessionals om de transitie naar kleine, koolstofarme, (bijna) energieneutrale woningen te versnellen.

Het is ook belangrijk om op te merken dat, hoewel de inclusie van drie verschillende onderzoekscontexten waardevolle inzichten heeft opgeleverd en het belang van contextuele eigenschappen en hun invloed op onderzoeksresultaten heeft benadrukt, met name in het verkennende onderzoek naar institutionele barrières, dit ook een beperking heeft opgeleverd. Hoewel deze contextuele variaties het doel om een holistisch en multidimensionaal begrip van kleine, koolstofarme en (bijna) energieneutrale woningen te bereiken niet hebben gehinderd, hebben ze geleid tot kanttekeningen bij het genereren van algemene conclusies. Als gevolg hiervan was de geografische representativiteit van dit onderzoek beperkt.

Wat betreft toekomstig onderzoek heeft dit proefschrift de basis gelegd voor het volgen van een multidimensionale methode bij de evaluatie van de implementatie en acceptatie van kleine, koolstofarme, (bijna) energieneutrale woningen in de praktijk.

In de toekomst kan verder onderzoek voortbouwen op deze basis door vergelijkbare onderzoeken uit te voeren met uitgebreidere en meer diverse steekproeven van professionals en consumenten in verschillende contexten. Toekomstig onderzoek kan dieper ingaan op de nuances van woonvoorkeuren door innovatieve evaluatiemethoden toe te passen die realistische besluitvorming beter simuleren en meer rekening houden met de dynamische aard van de woningmarkt. Dergelijke onderzoeken kunnen ook worden uitgevoerd in meerdere soorten woongebieden voor een beter begrip van de interactie tussen locatie en woonvoorkeuren qua woninggrootte. Er is ook voldoende ruimte om de menselijke factor in het onderzoek uit te breiden door gebruiker-evaluaties uit te voeren. Vanuit technisch oogpunt moet toekomstig onderzoek streven naar uitgebreide levenscyclusbeoordelingen die een nauwkeuriger en completer beeld geven van de embodied carbon footprint van woningen. Een speciale focus moet worden gelegd op het standaardiseren van het proces om rekening te houden met embodied carbon in bouwinstallaties, sanitaire elementen en meubilair. Daarnaast zou een vergelijkende analyse van verschillende levenscyclusbeoordelingstools helpen bij het identificeren van mogelijke verschillen in resultaten als gevolg van afzonderlijke aannames van elke tool. Deze analyse zou moeten leiden tot een nauwkeuriger interpretatie van de resultaten van levenscyclusbeoordelingen, wat op haar beurt een beter begrip van hun implicaties zou bevorderen.

Tot slot kan toekomstig onderzoek de reikwijdte van deze studie verbreden door de economische dimensie toe te voegen. Een analyse van de betaalbaarheid van kleine, koolstofarme en (bijna) energieneutrale ontwerpen zou waardevolle inzichten bieden in hun praktische haalbaarheid als woonoplossing, vooral in vergelijking met meer gangbare huisvestingsopties. Dit zou ook enkele specifieke institutionele barrières aanpakken die zijn aangekaart door woningprofessionals, zoals zorgen over hogere aanvangskosten, terugverdientijden en return on investment. Een dergelijke analyse zou de multidimensionale benadering die in dit onderzoek is aangenomen, aanvullen en zal leiden tot een breder perspectief op de levensvatbaarheid en potentiële acceptatie van deze innovatieve woningontwerpen in verschillende contexten. Door deze dimensie op te nemen, kan toekomstig onderzoek bijdragen aan een nog breder begrip van de potentiële van kleine, koolstofarme, (bijna) energieneutrale woningen als woonoplossing in Noordwest-Europa.

The construction of a Wikihouse in Almere in the Netherlands as part of the Housing 4.0 Energy (H4.0E) project funded by Interreg North-West Europe. Copyright: Wikihouse.

PART 1 Introduction

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1 Introduction

In light of the urgency of climate action to achieve the decarbonization goals set for 2050 coupled with the growing housing shortage in Europe, smaller, low-carbon, (near) zero-energy dwellings are being proposed as a solution fulfilling both sustainability challenges and housing market needs. As such, this research aims to assess the potential of these dwellings being a solution by investigating their implementation in practice as part of the European project entitled Housing 4.0 Energy (H4.0E): Affordable and Sustainable Housing through Digitization funded by Interreg North-West Europe.

With that in mind, this introduction begins by outlining the comprehensive background within which this research is situated. Starting with a broad view, section 1.1.1. establishes climate change as a global threat that requires radical rather than incremental change in the implementation of mitigation strategies. Section 1.1.2. highlights the role of the built environment, including that of the residential sector, as a significant contributor. Narrowing down to the European housing market, section 1.1.3. describes the latest developments that changed households' trajectories and led up to the growing housing shortage explained in section 1.1.4.

When the urgency of climate action is met with a need for new-build housing, strict energy policies and regulations are needed to meet 2050 decarbonisation goals. This directs us to the more specific research context which describes the developments of energy performance policies within the built environment. Accordingly, section 1.2.1. outlines the progression from a (near) zero operational energy performance (NZEB) to a net zero-energy performance (ZEB). Section 1.2.2. sheds light on the latest political shift pushing for adopting a life cycle approach in the evaluation of energy performance and underlining the growing importance of embodied carbon as we approach a zero operational energy performance. In fact, this political shift does not stop at the importance of accounting for embodied carbon. Latest developments highlight the need to start prioritizing the avoidance of the demand for both energy and materials. In the context of housing this translates into downsizing as the new mitigation strategy which is described in section 1.2.3. As such, the H4.0E project proposed smaller, low-carbon, (near) zero-energy dwellings with the aim to provide a housing solution fulfilling both sustainability challenges and the growing housing shortage which is elaborated on in section 1.2.4.

Within this specific context, the aim of this research is to investigate the implementation of the proposed dwellings in practice. In addressing the research aim, the theoretical backdrop is laid out, providing the foundation for the subsequent analysis and investigation. Section 1.4.1. starts by underlining the importance of adopting a holistic multidimensional outlook in investigating the implementation of sustainability outcomes to achieve more impact and long-term change. Accordingly, Section 1.4.2. highlights the growing importance of the social dimension and the human factor to be included in energy research. This translates into adopting a bottom-up approach and the application of social science theories to energy research which is presented in Section 1.4.3. Having established the importance of the incorporating the social dimension, section 1.4.4. emphasizes on the need to maintain the link with stakeholders and policy makers. This translates into having the bottom-up approach meet the top-down by investigating the institutional context for a holistic understanding of the implementation of a sustainability outcome. As such, multidimensional frameworks such as the Energy Culture framework are needed where the technical, social and institutional dimensions complement each other as described in section 1.4.5. Building on the Energy Culture framework, this research's conceptual framework is explained in section 1.4.6.

Figure 1.1 provides a visual representation of this introduction's outline. Based on the conceptual framework, the research sub-questions are formulated followed by a description of the methods implemented. Lastly, the relevance of this body of work is explained on both the societal and scientific fronts and the introduction ends with the presentation of the thesis outline

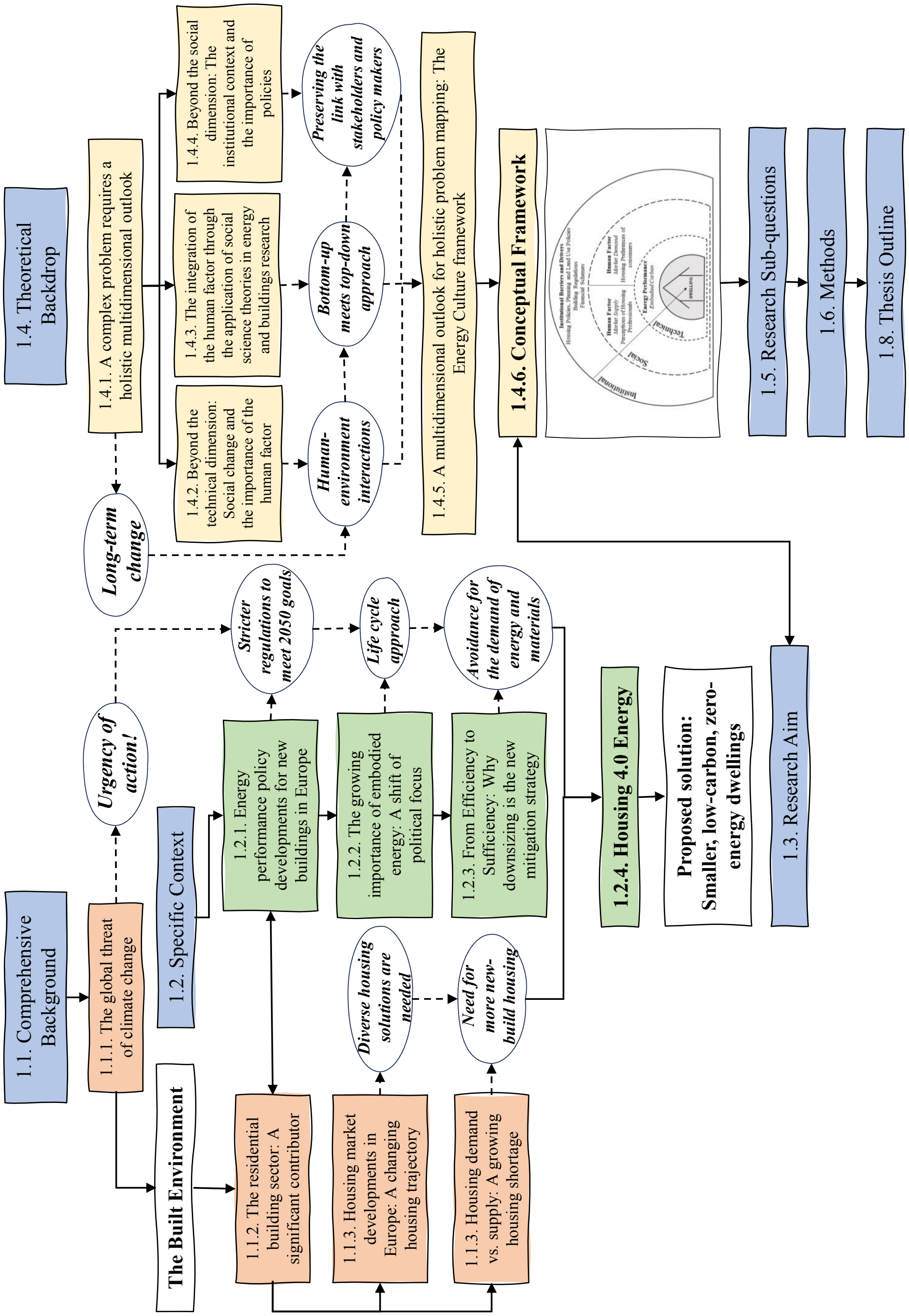

FIG. 1.1 Introduction outline

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1.1 Comprehensive Background

1.1.1 The global threat of climate change

Consequences of climate change and global warming on natural and human systems have been observed all around the world (IPCC, 2022). Numerous countries have already experienced changes in their weather patterns, including shifts in precipitation patterns and extreme temperatures that have led to more frequent and intense extreme weather events. These include hurricanes, droughts, and heatwaves which in turn led to an increase in climate related fatalities (Masson-Delmotte et al., 2018). One of the main agreements reached at the Paris Climate Conference held in December 2015 involved limiting global warming to 2°C and if possible below or equal to 1.5°C (European Commission, 2021b). However, seven years later, during the most recent climate conference COP27, it was acknowledged that the commitments put in place to limit global warming were not held by the leading carbon emitters (European Commission, 2022). In fact, the United Nations Environment Programme's (UNEP) latest report, investigating the gap between promised and needed global emission reductions, painted a rather grim picture of the world's progress so far. The report explains that even when nationally determined contributions are implemented unconditionally, this would lead to a global warming of 2.4 ºC thus already exceeding the much dreaded 2ºC (United Nations Environment Programme, 2022a). The observed consequences of climate change underscore the urgency for action in the implementation of mitigation and adaptation strategies and the report comes to the overarching conclusion that incremental change is no longer an option (United Nations Environment Programme, 2022a). The global response to the threat of climate change needs to be strengthened and the only way to halt this rapid progression is to radically accelerate and increase the implementation of climate change mitigations.

1.1.2 The residential building sector: A significant contributor to climate change

Despite an unprecedented drop of CO_2 emissions globally during the COVID-19 pandemic, the built environment witnessed a rebound as soon as the world resumed its pre-pandemic state. The latest Global Status Report for Buildings and Construction stated that the building sector was back to being

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responsible for 34% of global energy demand and around 37% of global energy and process related CO_2 emissions (IEA, 2022). The residential building sector in particular was found to be responsible for 21% of the energy demand and 17% of the energy and process related CO_2 emissions globally (Global Alliance for Buildings and Construction, 2019). In fact, globally, direct and indirect emissions particularly from the residential building sector increased by about 50% since 1990 (IPCC, 2022). In Europe, the building sector is responsible for an even higher share representing 40% of its energy demand and making it one of its most significant climate change contributors (UN environment programme, 2022). More specifically, the residential sector constitutes 75% of the European building stock and housing was demonstrated to be responsible for 22% of a European household's carbon footprint (Ivanova et al., 2017). This translates into a registered average of 700.6 of kilograms per capita of greenhouse gas emissions for heating and cooling in 2020 with the most significant contributors such as Luxembourg, Ireland, Belgium and Germany exceeding 1000 kg and the Netherlands falling closely behind with 911.7 kg (eurostat, 2022a). Thus, considering the residential sector takes up the largest part of the European building sector and taking into account the related greenhouse gas emissions, it is safe to say that housing in particular is an important factor and significant contributor to climate change in Europe (BPIE, 2011).

1.1.3 Housing market developments in Europe: A changing housing trajectory

Significant demographic, societal and economic developments in Europe are said to have changed the nature of housing demand and contributed to a gap between housing demand and supply (Beer, Faulkner, Paris, & Clower, 2011). On the demographic front, Europe witnessed an increase of almost 4% in one-person households between 2007 and 2017. This resulted in the number of one-person households exceeding 33% of the total number of EU households making them the most common household type. Together with two-persons households, covering approximately 32% of the total number of EU households, these two categories make up nearly two thirds of the EU-28 population (eurostat, 2023). On the societal front, lower fertility rates and longer life expectancies, among other changes in habits, all contributed in changing the composition of EU households (Beer et al., 2011). In fact, the percentage of couples living together with children decreased by 3.4% during that time period while the percentage of couples living alone without children rose by 9.3% (eurostat, 2023). Single adults households increased by 30.7% from 2009 to 2022 and the percentage of single senior adults of 65 years and above increased of almost 60% for men and more than 20% for women. On the economic front, the 2008 crisis already had a significant impact on income distribution within the European population whereby the gap between income classes increased. However, the latest unforeseen crises, namely the invasion of Ukraine and the COVID-19 pandemic, have led to exceptional circumstances that are rapidly developing into a genuine cost of living crisis (Housing Europe, 2023). The increasingly difficult economic conditions significantly affected housing affordability and homeownership has become inaccessible to a larger group of the population. Smaller households can no longer afford the traditional single-family dwelling be it starting young adults, single parents, and/or senior residents among other small household compositions. Taking into account all of the abovementioned factors, one's housing trajectory can no longer be considered straightforward going from living with parents to outright homeownership (Beer et al., 2011). Housing trajectories have changed and become much more complex and there is a growing need for more diverse housing solutions that would fulfil the needs of increasingly diverse household compositions.

1.1.4 Housing demand versus housing supply: A growing housing shortage

Despite the abovementioned housing market developments, housing supply in the EU appears to have remained constant, if not falling behind. It is important to highlight that there are different ways to address a housing shortage. One is through a more efficient use of the current building stock, be it through transformation or reallocation for instance, and another is through new construction. When it comes to new construction in particular, in the study of the state of housing over the years, Housing Europe frequently reported that multiple European countries are facing a structural housing shortage due to the slow rate of new construction that is constantly outpaced by demand (Housing Europe, 2017, 2021, 2023). Selected countries for which data was available to trace the increasing housing shortage throughout the years are the Netherlands and Ireland. In 2017, Housing Europe reported that the expected housing demand in the Netherlands will be 73,000 new dwellings per year between 2015 and 2019 while average supply was at an average of 62,000 new dwellings per year. Conclusively, the report warned that there is an emerging housing gap that needs to be addressed. Similarly, in 2017 in Ireland, housing demand was estimated at 25,000 new dwellings per year while housing supply was 65% lower and the report also concluded that there was a housing shortage in light of current and future housing needs (Housing Europe, 2017). In 2021, the updated study of the state of housing in Europe reported that, in the Netherlands, the unmet housing needs amounted to 331,000 dwellings while the average annual delivery between 2017 and 2019 was just above 87,000 housing units. In Ireland, the unmet housing needs grew to reach 165,000 housing units while supply amounted to 25,300 units. Thus, again, the report concluded that the housing shortage in both countries will continue to worsen in light of the population growth in the Netherlands and the consistent shortfall of new construction in Ireland (Housing Europe, 2021). While the complete report of the state of housing in 2023 has yet to be published, Housing Europe already announced that the situation has not improved considering that, in addition to previous years, people have to cope with the difficulties caused by the invasion of Ukraine and the pandemic (Housing Europe, 2023). Considering that housing shortages automatically lead to the increase in housing prices, what is more important to note is that the rate at which housing prices are increasing is significantly faster than that of new constructions. This by itself increases even more the demand for affordable housing. In this manner, a self-perpetuating cycle is established, whereby the increase in housing prices increases the demand for housing, further exacerbating the challenge for construction to keep pace. That is to say that, on the long run, what could make a big difference in terms of closing the gap between demand and supply will be the capacity of the sector to provide a sufficient number of new-build dwellings rendering them more affordable (Housing Europe, 2023). As such, it is safe to conclude that overall housing was, is, and will remain a significant contributor to climate change considering the construction of new-build dwellings is much needed and inevitable taking into account the growing housing shortage.

1.2 Specific Context

1.2.1 Energy performance policy developments for new buildings in Europe

Being a significant contributor is also an indication of where change is most needed. The Intergovernmental Panel on Climate Change (IPCC) repeatedly reported, with high confidence, the potential that lies within the building sector when it comes to opportunities to reduce greenhouse gas emissions and achieve the decarbonisation goal set out for 2050 (IPCC, 2022). This was translated into the development of several policies that addressed the limitation of carbon emissions within the building sector including the residential sector. Initially, within the context of new-build, the political focus was on designing to decrease energy demand throughout a building’s operation phase (Pomponi & Moncaster, 2018). The European Energy Performance of Buildings Directive (EPBD) was a key catalyst with the launch of NZEB: Near(ly) Zero-Energy Building back in 2010 requiring all new-buildings to be NZEB by the end of 2020 (European Commission, 2016). Consequently, research followed suit and soon enough, the NZEB concept developed into ZEB denoting Net-Zero-Energy Buildings where operational energy demand is fully off-set by on-site energy generated from renewables (Grinham et al., 2022). This was taken even further and ZEB evolved into 'energy plus' buildings where the building generates more energy from renewables than it consumes throughout a year (Rodriguez-Ubinas et al., 2014). Currently, a near zero operational energy performance is mandatory for all new-build dwellings. However, the commission is pushing for ZEB to be made mandatory as of January 1 2030 whereby a very low amount of energy still required is fully covered by energy from renewable sources and without on-site carbon emissions from fossil fuels (European Commission, 2021a). That is to say that, while a (near) zero operational energy has been normalized and represents the current mandatory goal for new-build dwellings in Europe, stricter regulations can be expected in the near future.

1.2.2 The growing importance of embodied energy: A shift of political focus

A dwelling's environmental impact is not restricted to the operational energy consumed throughout its use-stage. A total environmental impact also includes the energy consumed throughout a dwelling's production, construction, and end-of-life stages. Greenhouse gas emissions released throughout these stages are known as embodied energy. Put differently, embodied energy includes greenhouse gas emissions released throughout the raw material extraction, transportation, manufacturing, construction, maintenance, repair and/or replacement, deconstruction or demolition and disposal of a dwelling (Chastas, Theodosiou, Bikas, & Kontoleon, 2017; Lützkendorf, Foliente, Balouktsi, & Wiberg, 2015; Robati & Oldfield, 2022). That said, from a lifecycle perspective, the definition of a near (NZEB) or zero-energy building (ZEB) becomes incomplete as it is not representative of the total environmental impact of a dwelling and study boundaries are not extended to include embodied energy (Lützkendorf et al., 2015). Consequently, research has introduced net-zero carbon emissions buildings (ZCB) that account for both operational and embodied carbon emissions by adopting a life cycle approach in the assessment of a dwelling's energy performance (Grinham et al., 2022) (Figure 1.2).

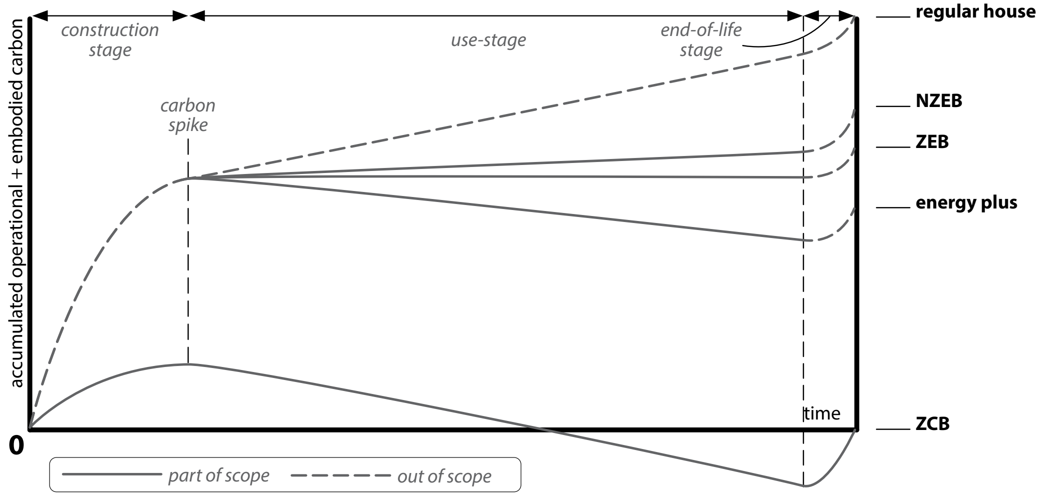

FIG. 1.2 The development of the definition of zero-energy buildings

In theory, with a zero operational energy performance, embodied energy makes up 100% of a dwelling's carbon footprint (Balouktsi & Lützkendorf, 2016). It becomes the only source of greenhouse gas emissions, hence, the most significant and influential one (Röck et al., 2020). In practice, this translates into the increase of the share of embodied energy with the decrease of operational energy (Kristjansdottir, Heeren, Andresen, & Brattebø, 2018; Li, Foliente, Seo, Rismanchi, & Aye, 2021). Indeed, it is said that there is a trade-off between operational and embodied energy (Carcassi Olga Beatrice, 2022). Studies argued that emissions saved throughout the use-stage of a dwelling can be partly lost if not totally off-set by emissions released in the other stages due to the need for extra building materials and/or technical systems to achieve a zero operational energy performance (Röck et al., 2020). This concept was later referred to as the 'carbon spike' effect indicating the high carbon investment that occurs at the initial stages of a life cycle, hence a relatively shorter amount of time, risking the dwelling's overall consumption budget (Carcassi Olga Beatrice, 2022; Maierhofer, Röck, Saade, Hoxha, & Passer, 2022). All in all, the normalization of a zero operational energy performance through building regulations significantly increased the relevance of embodied energy (Robati & Oldfield, 2022). The increasing contribution of embodied energy is reinforced further when taking into account the future decarbonisation of the energy grids as part of the 2050 climate goals (Grinham et al., 2022; Robati & Oldfield, 2022; Röck et al., 2020). Overall, this has forced a shift of the current political focus. While the European Commission does not enforce a zero carbon energy performance yet, it does require the disclosure of life cycle global warming potential through its

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proposal to switch to ZEB by 2030 (European Commission, 2021a). As such, the reduction of embodied carbon in buildings has regained traction and reached the top priority levels of the latest environmental programs (Global Alliance for Buildings and Construction, 2019; United Nations Environment Programme, 2022a, 2022b; World Green Building Council, 2022).

1.2.3 From efficiency to sufficiency: Why downsizing is the new mitigation strategy

On account of the numerous initiatives led by EU governments to enhance the energy performance of the built environment, it is safe to say that efficiency strategies aimed at improving both the operational and embodied energy of buildings, including dwellings, are well-known by now. Common examples include, the use of energy efficient appliances, the enhancement of indoor temperature through ensuring air-tightness and using better insulation, the integration of renewable energy sources through solar panels, implementing passive design principles, and overall using more sustainable materials. Yet, on an overarching level, the latest status report on buildings produced by the International Energy Agency concludes that countries are off-track in terms of achieving the zero carbon target for 2050 (IEA, 2022). This was reiterated in the latest Global Status report for buildings and construction highlighting a widening gap between the observed performance of the building stock and the desired pathway towards a zero carbon target in 2050 (United Nations Environment Programme, 2022b).

Consequently, recalling the need for a radical increase and acceleration of climate action, intergovernmental and European organizations are going back to prioritizing 'Avoidance', the fundamental and most effective energy reduction strategy (Andrews, 2014). Indeed, in the sixth assessment report, the IPCC reintroduced the hierarchical framework known as *Sufficiency, Efficiency, and Renewables* (SER). In this framework, the emphasis is placed on sufficiency as the main principal promoting primarily the avoidance of "demand for energy and materials over the life cycle of buildings and goods" (p.7 lines 43-44) (Cabeza, 2022). When sufficiency is confronted with an alarming growing need for new-build housing, it translates into building less and becomes "adjusting the size of buildings to the evolving needs of households by downsizing dwellings" (p.4 lines 29-30) (Cabeza, 2022). It was based on the assumption that SER policies are to be properly implemented that the IPCC reported, with high confidence, the potential of buildings to achieve the net zero emissions goals for 2050 in their modelling of global scenarios (IPCC, 2022). Minimizing excess floor area is actually also one of the necessary shifts listed

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by the Energy Transitions Commission to reduce emissions form the building sector (Energy Transitions Commission, 2023). Considering both operational and embodied energy are directly related to floor area through heating, cooling, building materials among others, it was argued that reducing a dwelling's floor area to the amount necessary to meet basic needs would have a significantly reductive impact on the sector's energy consumption. Even more so considering that, according to the European Union Statistics on Income and Living Conditions, the average living space per person in Europe has increased reaching 1.7 rooms per person in 2022 despite the fact that demographic changes resulted in smaller household sizes (eurostat, 2022b). Overall, a distinction between energy efficiency strategies and energy sufficiency strategies arises, be it for operational or for embodied energy performance. Considering the urgency of climate action, the time has come to implement sufficiency strategies prior to and as a complement to efficiency strategies. Within the context of new-build housing, downsizing regains priority in addition to achieving a zero operational energy and using more sustainable materials for a lower embodied energy.

1.2.4 Housing 4.0 Energy: Affordable and Sustainable Housing through Digitization

As part of the presented background, the *Housing 4.0 Energy: Sustainable & Affordable Housing through Digitization* (H4.0E) project funded by the Interreg North-West Europe was established to provide new housing solutions that would help reduce future GHG emissions within the housing sector and close the existing gap between housing supply and demand. Accordingly, the H4.0E project proposed smaller, low-carbon, (near) zero-energy dwellings as a solution that potentially addresses the needs of the growing group of smaller households composed of one to two persons. Designs would incorporate both sufficiency and efficiency strategies through smaller floor areas, implementing modular construction methods, using more sustainable building materials, ensuring a good thermal envelope with proper insulation and glazing, and integrating renewable energy among others. Accordingly, a total of 44 dwellings were designed and built in Almere in the Netherlands, Huldenberg in Belgium, and in Kilkenny, Wexford and Carlow in Ireland (NWEurope, 2021). Project details and dwelling designs slightly differ per pilot location. For instance, in the Netherlands, the concept of self-building was explored while in Belgium the focus was directed towards modular construction and in Ireland the use of sustainable versus traditional materials was compared. In that way, the project also addressed the need for more diverse housing solutions.

Table 1.1 provides a summary of project and dwelling characteristics in every pilot location.

TABLE 1.1 H4.0E pilot characteristics

Characteristic	Netherlands	Belgium	Ireland
Dwelling type	Detached, semi-detached	Detached, semi-detached	Detached, semi-detached, apartment
Dwelling size (NFA)	45 to 104 m^2	46 to 63 m^2	61 to 110 m^2
Main building material	Timber	Timber	GGBS concrete
Ownership	Owner occupation	Private	Local authority
Tenure type	Ownership	Rental	Rental
Target group	Self-builders	Social letting agency	Social housing
Housing sector	Private	Private, partially subsidized	Social

1.3 Research Aim and Main Research Question

Having established this background that encompasses and links climate change to the state of housing in Europe and the latest energy performance policy developments, it becomes clear that the matter of housing provision is multilayered and complex. The housing market is no longer responsible to simply address and answer to the growing shortage. It must do so while taking into account on the one hand the increasing complexity of housing trajectories and the diversified households compositions and on the other the increasingly strict energy performance regulations where embodied energy has regained importance and sufficiency policies have regained priority.

With this in mind, the **aim** of this research is to **achieve meaningful impact by investigating the implementation of small, low-carbon, (near) zero-energy dwellings in practice and assessing their potential as a solution** to the complex and multilayered situation the housing market finds itself in. Accordingly, as part of the H4.0E project, it addresses the following main research question:

- **To what extent are small, low-carbon, (near) zero-energy dwellings a housing solution in North-West Europe?**

Recalling the urgency of climate action and the need to switch from incremental change to long-term sustainable solutions, this research aims to do so by not restricting itself to the technical feasibility of the implementation of such dwelling designs and their corresponding performance but going beyond that and exploring the potential that lies in their uptake.

1.4 Theoretical Backdrop

1.4.1 A complex problem requires a holistic multidimensional outlook

Climate change is a multifaceted phenomenon and its consequences reverberate across diverse dimensions. Having an impact on the ecological, social, and economic conditions of countries across the world, this global challenge has been at the centre of the political, social and economic discourse in the last decades (Petts, Owens, & Bulkeley, 2008; Schmidt & Weigt, 2015). Expectedly, this inherit complexity is also reflected in the world's response to climate change, and in the diverse mitigation strategies formulated. Here, a holistic multidimensional outlook becomes necessary in the response to climate change as, it would enable the development of more intricate and effective measures on the one hand. On the other hand, it would allow a complete and more thorough understanding of how the diverse aspects of mitigations potentially interact with one another (Schmidt & Weigt, 2015). Within the realm of research, this is manifested as the need for experts and researchers from diverse disciplines to cooperate and combine their knowledge and integrate their different perspectives in answering emerging climate related questions (Ryan, Hebdon, & Dafoe, 2014; Schmidt & Weigt, 2015). While this may initially appear as self-evident, the implementation of a multidimensional approach in energy related research practice emerges as a difficult undertaking (Schmidt & Weigt, 2015). Indeed, the review of fifteen years of energy scholarship confirmed that the greater part of existing studies were conducted within a single discipline (Sovacool, 2014). Some argue that the lack of collaboration in energy research is due to clashes between the theoretical frameworks underpinning diverse disciplines (Schmidt & Weigt, 2015). Others claim that energy research has been focusing primarily on technological developments (Stern, 2014). Be it the former or the latter, what is certain is that climate action is needed on all fronts especially considering the less-than-optimistic trajectory of the world so far. Beyond short-term incremental solutions revolving around energy efficiency and technical innovations, there is a need for a multidimensional outlook towards solutions that would achieve long-term sustainable changes.

1.4.2 Beyond the technical dimension: Social change and the importance of the human factor

Within the scope of research in the built environment, it has been increasingly acknowledged that the successful implementation and uptake of technological innovations and energy efficiency strategies is not a matter restricted to achieving change within the technical dimension but is also dependent on achieving change within the social dimension (Janet Stephenson et al., 2010). From a technical perspective, energy performance research moved so rapidly that the NZEB concept was developed into ZEB, followed by 'energy plus' buildings and the focus now is on improving energy performance from a life cycle perspective with ZCB. That is to say that research directed towards technical solutions has been on-going for years. From today's point of view the challenge is no longer as much in finding technical solutions but it has shifted towards their proper implementation and uptake. It is actually the observed gap between the predicted and actual energy demand of buildings otherwise known as the energy performance gap that led to the recognition of the importance of the human factor in energy research in the built environment (Pelsmakers, 2019). This is what Stern referred to as 'the second environmental science' of 'human-environment interactions' in his call for the 'development of an […] integrative science of human interactions with energy and energy systems' (p.1) (Stern, 2014). As such, considering the implementation and uptake of technical innovations requires human interactions, taking into account the human factor in the study becomes crucial for a more complete understanding of the sustainability outcome (McKague, Lawson, Scott, & Wooliscroft, 2016; J. Stephenson, 2018).
It is worth mentioning that, what is referred herein as the human factor has been labelled differently in previous literature. For instance, the human factor was referred to as a non-building-bound factor together with household characteristics and the energy related behaviour affecting the performance of a building as opposed to building-bound factors that include the insulation, ventilation, lighting, and renewable energy of the building (van der Grijp et al., 2019). Another example is in

the final report of the International Energy Agency (IEA) Annex 53 where the human factor was considered an internal driving force together with the psychological, socio-economic, and socio-demographic characteristics of occupancy as opposed to external driving forces that include the technical characteristics of the building (Alam, Bao, Zou, & Sanjayan, 2017). Regardless of how it manifests itself, the social dimension is emerging into prominence. Albeit slow and gradual, the recognition of the importance of the human factor is growing and human-environment interactions have been gaining attention within energy and buildings research.

1.4.3 The integration of the human factor through the application of social science theories in energy and buildings research

The growing recognition of the importance of the human factor in energy research led to the increase of studies covering both the technical and social dimensions in their research approach. The greater part of these existing studies focus on merging social science theories in the study of the technological innovation. Common examples are the Actor-Network theory (ANT) and the theory of Planned Behavior (TPB) (Ajzen, 1991; Pellegrino & Musy, 2017; Wong, 2016). While these theories were initially referred to with the aim to include and better understand the human factor in energy research, they differ in terms of study focus, aim, and end-goal. For instance, the focus of study of the ANT framework is the innovation as a system of social and material entities. Its aim is to investigate why and how one innovation is more successful than the other and its end goal is to prevent the failure of that innovation (Wong, 2016). In the context of housing, this would include occupancy and its interaction with the dwelling. The study focus of the TBD is people’s behavior within specific contexts. Its aim is to predict or explain that behavior and its end goal is to understand it enough to promote behavioral change (Ajzen, 1991). In the context of housing this revolves around occupancy behavior and the underlying attitudes, social norms, beliefs, and intentions. Be it through the study of interactions within a network, or the behavior itself, both theories allow, one way or another, the inclusion of the human factor in the investigation of the implementation and uptake of a technical innovation. Yet, regardless of the differences and commonalities of these approaches, it must be said that these approaches remain two-dimensional as they focus on the occupant and the technical innovation. Extrapolating from this premise to the context of housing research, this would translate into a bottom-up approach. While undeniably effective and insightful, a parallel top-down outlook is still necessary. Put differently, considering that the overarching aim of this research is to achieve meaningful impact in its investigation, a bottom-up approach needs to meet the top institutional context in place for a holistic and complete understanding of a sustainability outcome.

1.4.4 Beyond the social dimension: The institutional context and the importance of policies

A top-down outlook entails recognizing the importance of the policies established around the technical innovation and integrating their potential impact in the analysis of the process of change. Although the study of policies and policy instruments around the implementation and uptake of technical innovations has had a fair amount of attention in energy and buildings research, the inclusion of the institutional dimension in the investigation remains essential for a holistic understanding of the sustainability outcome (J. Stephenson et al., 2015). It is known that the effective implementation and uptake of a technical innovation requires an encouraging policy environment just as much as a learning society (Rechkemmer, 2010). The literature does argue that studies investigating the policy dimension outnumber the ones that investigate the social dimension. However, it is important to highlight that these studies in question were restricted to the boundaries of that one dimension (Sovacool, 2014). While the human factor has indeed been generally undermined and downplayed in previous literature (Rechkemmer, 2010; Sovacool, 2014), preserving a simultaneous link with policy makers and stakeholders is still essential if not crucial for the production of relevant outcomes that can be used. Indeed, the mismatch between what is produced by energy researchers and what is relevant to policy makers and stakeholders had been already flagged as an issue by previous studies (Sovacool, 2014). Overall, that is to say that when the aim is to reach real world solutions that address real world problems, it can be said that the successful implementation and uptake of a sustainability outcome is dependent on the convergence of the technical, social and institutional dimensions (Sovacool, 2014). Long-term change can only be achieved through the study of the entire system surrounding the technical innovation and equal attention must be given to all three entities that make up this system. Accordingly, it is important for energy research to adopt a multidimensional rather than two-dimensional approach that incorporates the institutional context (Golubchikov & Deda, 2012).

1.4.5 A multidimensional outlook for a holistic problem mapping: The Energy Culture Framework

It has been argued that creating a new framework could achieve a better reflection of a multidimensional approach (J. Stephenson et al., 2015). An example of a created theoretical framework with a holistic approach in energy research is the Energy Cultures (EC) framework (Janet Stephenson et al., 2010). The core aim behind the conception of the EC framework is to understand why outcomes related to energy and sustainability are being achieved or not. Being an actor-centred approach, its study focus is the occupant and their energy consumption and the emphasis leans more towards understanding cultural change rather than mere replication of behaviours within the energy context (J. Stephenson, 2018). Cultural changes entail people actively changing their habits, practices and ways of life, and focusing on that would provide more insight into how habits form and how to change them in a more sustainable direction (J. Stephenson, 2018; J. Stephenson et al., 2015). To that end, the EC framework combines established social theories that allow for the understanding of the system surrounding the actor, in all its properties, attributes, and interactions (Hopkins & Stephenson, 2014). As such, the system surrounding the actor comprises four main entities: norms, practices, material culture and exogenous factors (Figure 1.3). Norms comprise people's expectations and aspirations (J. Stephenson et al., 2015). Put differently, how people live considering their current circumstances and how they think they should be living (Hopkins & Stephenson, 2014). Practices originally stem from the practice theory, where they consist mainly of an individual's or household's repetitive daily actions related to energy consumption. However, within the EC framework, practices also include less frequent actions related to energy consumption such as the purchase of energy-efficient appliances (J. Stephenson et al., 2015). Material culture consists of the concrete aspects surrounding an actor that could have an impact on energy performance and consumption. Last but not least, exogenous factors are the ones that are out of the actor's control but still have an impact on their energy consumption. They are categorized into transactional factors which are the ones that have a direct impact or contextual referring to factors the actor has to adapt to (J. Stephenson et al., 2015). In that way, the EC framework facilitates the establishment of a conceptual representation of the complex system around the sustainability outcome in question, an activity otherwise known as problem mapping (Schmidt & Weigt, 2015). With that in mind, the following section elaborates on the aspects within the EC framework that deviate from the aim of this work.

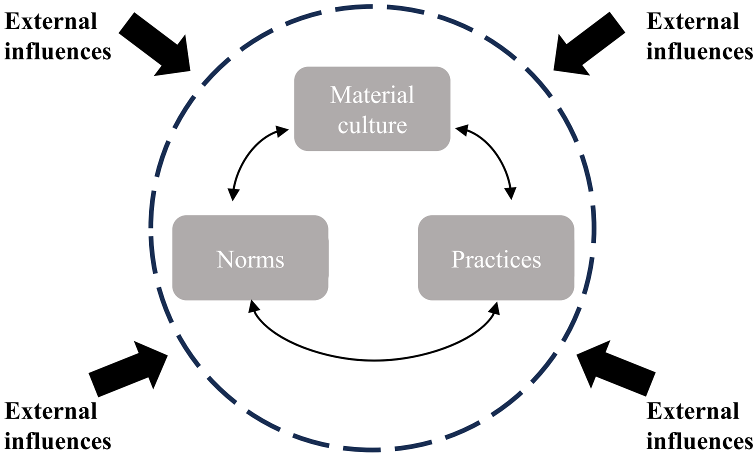

FIG. 1.3 The Energy Culture Framework illustrated (J. Stephenson et al., 2015)

1.4.6 Conceptual framework

Recalling that the aim of this research is to investigate **small, low-carbon, (near) zero-energy dwellings as a solution** to the complex and multilayered situation laid out in the contextual background, this work builds upon the theoretical backdrop presented herein to establish its own conceptual framework in addressing its main research question. Figure 1.4. provides a visual representation of this work's conceptual framework.

Just like the EC framework, the intention is to use problem mapping to visually represent and structure the complex and multifaceted environment where small, low-carbon, (near) zero-energy dwellings would be implemented and adopted. Laying out this space for this sustainability outcome would help identify the different challenges and potential bottlenecks this uptake would be facing and enable a better understanding of how these challenges are interrelated for a more comprehensive study of the matter at hand. However, other aspects of the EC framework do not align with the aim of this research.

First, although the EC framework adopts a multidimensional approach and investigates the social, technical and institutional aspects, it remains an actor-centred approach. Within the context of housing studies, this indicates that the EC framework gives priority to a bottom-up approach in its study of sustainability outcomes. Considering that this research focuses on the uptake of small, low-carbon, (near) zero-energy dwellings just as much as on their implementation, striking a balance between a bottom-up and a top-down approach is of major relevance. Bearing in mind the important role the institutional dimension can have on the effective uptake of the sustainability outcome in this research, incorporating both by shifting the focal point to the dwellings in question and having the bottom-up and top-down approaches meet would lead to better insight and a more holistic understanding of the situation at hand.

Second, having end-users and their energy consumption as the study focus, the EC framework accounts for the human factor but restricts the study of human-environment interactions to the demand side. In this manner, the EC framework complies to the most common and investigated way to integrate the human factor which has been through the end-users and the study of their behaviour as consumers. While the importance of the human factor is recognized in this research, and it is agreed that practices and norms should be accounted for in the investigation of a sustainability outcome, this work aspires to extend its scope to include the human factor as an actor with a role that is as important and as significant on the supply side. As such, the human-environment interactions investigated would extend to the provision of housing rather than just demand for and consumption of housing. In that way, the participation of stakeholders and policy makers is ensured and the link between a bottom-up and top-down approach is preserved.

Third, in their focus on energy consumption and energy behaviour, previous applications of the EC framework indicate that the operational energy of a dwelling was prioritized. This does not come as a surprise considering that the political focus was on bringing operational energy consumption to zero. However, at this point in time when this work is being conducted, a (near) zero operational energy is mandatory. The current political focus has shifted and is now looking at energy consumption from a life cycle perspective which entails that achieving a low embodied energy has regained priority. Bearing that in mind, in its cover of the technical dimension, this research pays particular attention to the embodied energy of the dwellings being investigated.

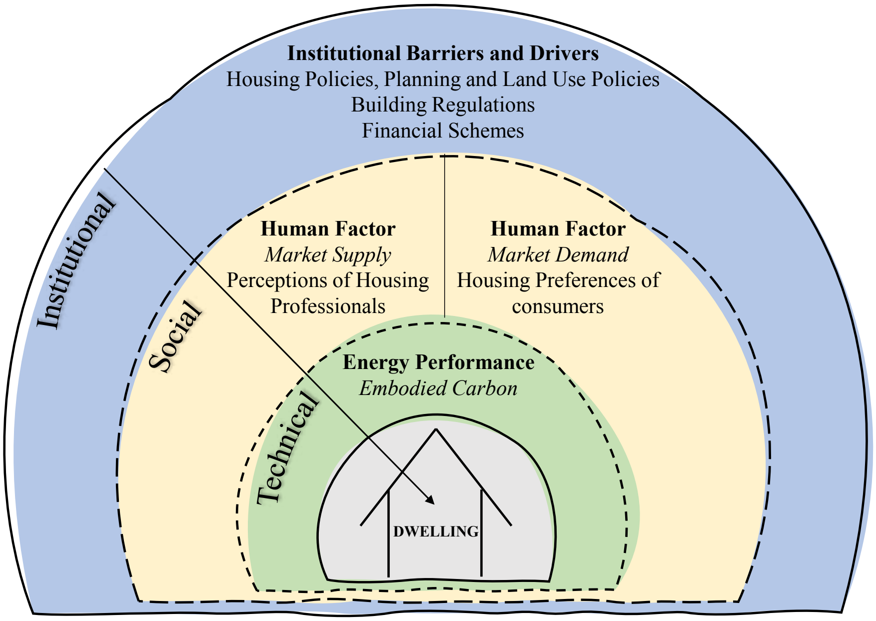

FIG. 1.4 Conceptual framework

1.5 Research Questions

Within this established conceptual framework, the research addresses its main question: *To what extent are small, low-carbon, (near) zero-energy dwellings a housing solution in North-West Europe?* By posing the following four objectives and corresponding research sub-questions.

First, it has been established throughout this introduction that, preserving the link with policy makers and stakeholders is essential if not crucial in the investigation of the implementation of a sustainability measure as previous literature already highlighted a mismatch between what is being produced by energy research and what is relevant to policy makers and stakeholders. Moreover, recalling the importance of having an encouraging policy environment for a more effective implementation and uptake of sustainability measure, the intention here is to adopt

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a top-down outlook that recognizes the potential impact of established policies for a more holistic understanding. That being said, this research addresses the institutional dimension by exploring current established contextual policies through the investigation of potential institutional barriers and drivers to the implementation and uptake of small, low-carbon, (near) zero-energy dwellings. The investigation of barriers and drivers is one of the primary and foundational actions taken to evaluate the implementation of new measures for an overall effective market response. Considering the investigation of institutional barriers is conducted in collaboration with policy makers and stakeholders, the link between energy research and decision makers is preserved for overall more specific and relevant policy recommendations. Accordingly, this first stage answers to following sub-question:

- **What are the institutional barriers to the implementation and uptake NZEBs? What insights can be gained from the investigation and identification of these institutional barriers and how can they inform policy?**

Second, as argued throughout the introduction, sustainability transitions and the successful implementation and uptake of innovations entail social changes just as much as technical changes. Accordingly, the scope of energy research needs to go beyond the technical feasibility of a sustainability measure and account for the potential impact of human-environment interactions, also referred to as the human factor, in the investigation. While the recognition of the importance of the human factor has been increasing in energy and buildings research, the focus has been directed mostly on investigating end-users as the human factor obstructing change. Moreover, end-users have predominantly been included as *recipients of change* rather than *actors for change*. In other words, not only has research focused less on investigating the human factor in the provision of sustainability measures but, by including individuals as recipients of change, it has also overlooked the potentially significant impact of their actions, underpinned by their perceptions in the process of change. As such, in this research, the social dimension is addressed by examining the human factor on both the supply and demand side of the housing market and by opting a reversed approach where individuals are accounted for as actors whether they are housing professionals or consumers seeing as both could play a pivotal role within the housing provision process. That being said, with the overarching aim to unravel the potential impact of the human factor in the provision of small, low-carbon, (near) zero-energy housing, this research starts with the investigation of the established perceptions of housing professionals involved in the provision of housing and addresses the following research sub-question:

- **To what extent do the perceptions of housing professionals affect the identification of barriers to the implementation of NZEBs?**

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After having accounted for the human factor on the supply end of the housing market, this research proceeds by looking at the human factor on the demand end of the housing market. As explained throughout the introduction, smaller, low-carbon, (near) zero-energy dwellings are being proposed as a solution that would answer to both sustainability concerns and housing market challenges. From the sustainability perspective, this was based on the newly prioritized avoidance and sufficiency strategies that translate into downsizing within the context of housing and the built environment. From the housing market perspective, this was based on the need for new housing solutions that would fulfil the needs of increasingly diverse household compositions as previously highlighted in this introduction. Put differently, within the context of the housing market, it was assumed that preferences are also leaning towards smaller housing due to the increasing number of smaller households composed of one to two persons, of elderly households and empty nesters, and lower-income households. That being said, the intention of this research at this stage is to test this assumption by gauging consumers' housing expectations and aspirations in their demand for housing through the evaluation of their current housing preferences. Recalling the importance of accounting for individuals as actors and not mere recipients in the process of change, this research follows the stance of shaping supply through adopting a bottom-up approach in its investigation. Accordingly, in the second part of this second stage addressing the social dimension, this research answers to the following research sub-question:

— **To what extent do smaller, low-carbon and zero-energy dwellings fulfil current housing preferences?**

Third, the last stage of this research addresses the technical dimension around small, low-carbon, (near) zero-energy housing. As explained throughout this introduction, from the technical perspective, the focus has predominantly been on reducing a dwelling's operational energy. To the point that a (near) zero-operational energy represents the current mandatory goal for new-build dwellings in several countries around Europe. However, a dwelling's life cycle is not restricted to its operational energy but also includes embodied energy. It is said that there is a trade-off between the operational and embodied energy of a dwelling seeing as, theoretically, with a zero-operational performance, embodied energy makes up 100% of a dwelling's carbon footprint. That is to say that, the normalization of a zero-operational energy performance significantly increased the relevance of a dwelling's embodied energy performance. Considering the urgency of climate action together with the significant role of the housing sector and the inevitable growing need for new-build housing, there has been a shift of political focus. The reduction of embodied carbon has regained traction and is now at the top priority level of environmental policies and programmes. For this reason, this research chooses to focus on the embodied carbon of small, low-carbon, (near) zero-energy dwellings in its investigation of the technical dimension. Furthermore, keeping in mind that sustainability strategies now call for the prioritization of the avoidance of energy demand and materials, the focus of embodied carbon reduction strategies is no longer restricted to the use of more sustainable, low-carbon building materials. It rather becomes crucial to simultaneously decrease quantities through downsizing and limit embodied carbon emissions at an early stage prior to any application. Accordingly, this research addresses the technical dimension of small, low-carbon, (near) zero-energy dwellings by investigating their embodied carbon and focusing on both the use of more sustainable building materials and downsizing as embodied carbon reduction strategies. As such, this third stage answers to the following research sub-question:

— **What is the impact of downsizing and the use of timber on the embodied carbon of a new-build dwelling?**

1.6 Research Methods

This study implemented mixed methods for its data collection and a combination of qualitative and quantitative data was collected through desk studies, focus groups, questionnaires, semi-structured interviews, and embodied carbon modelling. Following the structure of its adapted theoretical framework, the methods implemented are described in three main stages.

1.6.1 Stage 1: The Institutional Dimension

This stage addresses the first research sub-question:

— **What are the institutional barriers to the implementation and uptake NZEBs? What insights can be gained from the investigation and identification of these institutional barriers and how can they inform policy?**

This stage revolved around investigating the different institutional backgrounds where small, low-carbon, (near) zero-energy are to be built: Belgium, Ireland, and the Netherlands. Institutional barriers to the implementation and uptake of such dwellings were investigated to identify potential peculiarities within each context. More specifically, financial, technical, cultural, and legislative barriers were addressed through financial schemes, building standards and regulations, housing policies, planning and land use policies, and cultural perceptions, habits, and practices. Since the aim at this stage was to conduct in-depth evaluations to gather country-specific information, a qualitative methodological approach was adopted. Through the H4.0E project, the data was collected in the form of a series of focus group discussions organized with housing professionals in each of the three contexts. Participants included housing professionals, housing providers, decision makers in the field, and local and regional authorities.

1.6.2 Stage 2: The Social Dimension – Market supply

This stage addresses the second research sub-question:

- **To what extent do the perceptions of housing professionals affect the identification of barriers to the implementation of NZEBs?**

This step revolved around investigating the human factor in the supply end of the market through exploring the perceptions of housing professionals within each project location. Throughout the investigation of challenges obstructing the implementation and uptake of small, low-carbon, (near) zero-energy dwellings, a distinction was made between actual and perceived barriers. First, through a series of follow-up semi-structured interviews with housing professionals involved in the H4.0E projects, data collected from the focus groups were validated and/or complemented. Second, a desk study of policy documents and government publications enabled the cross-referencing of identified barriers with current regulatory situation in each context.

1.6.3 Stage 2: The Social Dimension – Market demand

This stage addresses the third research sub-question:

- **To what extent do smaller, low-carbon and zero-energy dwellings fulfil current housing preferences?**

This step revolved around investigating the human factor in the demand end of the market through exploring the housing preferences of potential households in Flanders and in Almere. A quantitative methodological approach was adopted through the distribution of a uniquely tailored questionnaire. The Multi-Attribute Utility theory (MAUT) method was used to gauge housing preferences and potential trade-offs pertaining to the following specific housing characteristics: dwelling type, dwelling location, dwelling size, number of bedrooms, and building materials (Jansen, 2011). Through the MAUT method, respondents rated individual housing characteristics based on their level of importance and their preferences. Based on these individual ratings, complete dwelling profiles were composed and scored thus gauging the extent to which small, low-carbon, (near) zero-energy dwelling fulfil current housing preferences.

1.6.4 Stage 3: The Technical Dimension

This stage addresses the fourth research sub-question

- **What is the impact of downsizing and the use of timber on the embodied carbon of a new-build dwelling?**

This stage revolved around investigating the technical dimension of small, low-carbon, (near) zero-energy dwellings with a particular focus on embodied carbon being the growing most influential factor on carbon emissions. A quantitative methodological approach was adopted through conducting a partial life cycle assessment (LCA) of H4.0E modular timber designs using TOTEM: The Tool to Optimize the Total Environmental Impact of Materials (TOTEM, 2022). The embodied carbon reduction strategies of downsizing and the use of timber as the main construction material were explored through a two-way comparative analysis. On the one hand H4.0E dwelling models of varying dwelling sizes were compared with each other. On the other hand, H4.0E dwelling models were compared with theoretical, baseline dwelling designs based on traditional construction methods and common construction materials.

1.7 Research Relevance

1.7.1 Scientific relevance

On a higher level of enquiry, the originality of this work stems from its study outlook whereby a broad perspective is adopted and small, low-carbon, (near) zero-energy dwellings are investigated from a multidimensional approach covering the institutional, social and technical dimensions simultaneously. In tailoring its conceptual framework, this work taps into sustainability transition studies and consults previously established frameworks based on social science theories, a field of research that is growing but is far from being exhausted and has yet to become the norm (J. Stephenson et al., 2015). Accordingly, this research builds on the Energy Culture framework and on the growing argument that adopting a social lens in energy research provides more insight into how change can be achieved in a more sustainable direction. Although the need for such an approach in the investigation of climate related mitigation strategies has been increasingly recognized in past literature, research output has not progressed rapidly (Stern, 2014). The overwhelming majority of research on (near) zero-energy dwellings focuses on the technical dimension through the evaluation of the dwellings' energy performance (Sovacool, 2014) and genuine multidimensional studies are not as common as one would expect (Petts et al., 2008).

On a more specific level of enquiry, this research answers four main knowledge gaps. First, this work expands its approach by including the institutional dimension and assigning an equal level of importance to the role of policies. In that way, it strikes a balance between bottom-up and a top-down approach for a more holistic outlook of the context where small, low-carbon, (near) zero-energy dwellings are implemented and adopted. Second, in its evaluation of the human factor, this research does not restrict its analysis to the perspective of consumers, which has been the most investigated role (Stern, 2014). It also investigates the role of professionals on the supply end of the market and includes them as actors either facilitating or obstructing the sustainability outcome (Pellegrino & Musy, 2017). This perspective is not as consistently covered by previous studies around energy behaviours. Second, from the perspective of housing trajectories, this research tests the assumption stating that smaller households would prefer smaller dwellings and investigates the potential of downsizing in fulfilling the current housing preferences of consumers. In that way, this research bridges housing supply to demand and ensures housing provision is informed by housing consumption (Boumeester, 2011; Jansen, Coolen, & Goetgeluk, 2011; Mulliner & Algrnas, 2018; Opit et al., 2020). Third, from the technical perspective, this research builds on the regained timeliness of embodied carbon and investigates the dwellings' energy performance by focusing on their embodied carbon consumption (Global Alliance for Buildings and Construction, 2019; United Nations Environment Programme, 2022a, 2022b; World Green Building Council, 2022). In light of avoidance and sufficiency strategies it investigates both downsizing and the use of more sustainable materials as embodied carbon reduction strategies.

Overall, by bringing all these perspectives together, through holistic problem mapping, this body of work allows the identification of challenges and opportunities that might have been previously overlooked in single-disciplinary studies. This in turn led to a more comprehensive evaluation of the study focus gaining insight in the course of action needed at the institutional, the social and the technical levels.

1.7.2 Societal relevance

Whether in the immediate future or over the long term, the European population is currently and will continue to experience the impacts of the growing housing shortage. In the immediate future, from the housing market perspective, a growing housing shortage increases dwelling prices which in turn increases demand only to reinforce this housing shortage (Housing Europe, 2023). The lack of affordable housing translates to housing inequality and the inability to enter the housing market (Beer et al., 2011). This leads to social exclusion seeing as lower income households are forced to live outside cities, which in turn could reduce their work opportunities thus reinforcing income instability (Pittini et al., 2017). In that way, the investigation of smaller, low-carbon, (near) zero-energy dwellings, and more specifically their implementation in practice, helps formulate a better understanding around their uptake and potential as a housing solution answering to growing affordability issues. On the long term, form the sustainability perspective, urban, suburban and/or rural areas can be considered the most vulnerable areas to the effects of climate change due to the concentration of people, buildings, infrastructures, and economic activities (UNEP, 2018). From that angle, achieving the decarbonization goals set for 2050 is not optional but rather crucial as it would help make the built environment and the communities within more resilient to the potential consequences of climate change (Golubchikov & Deda, 2012). Within this context, not only is the investigation of small, low-carbon, (near) zero-energy dwellings relevant but necessary as it would enable an understanding of the factors underpinning their implementation and uptake as a sustainability outcome. Overall, gained insights can be translated into policy recommendations that would, on the one hand, work towards preventing the fraying of social cohesion, ensuring accessibility to all, and maintaining social equality and social cohesion. On the other hand, it would lead to a course of action that pins down what is needed to encourage a radical shift towards small, low-carbon, (near) zero-energy dwellings seeing as incremental changes are no longer enough to reach decarbonization goals in time. In that way, this research would be contributing to sustainable development goal (SDG) 11: Sustainable cities and communities, and on a higher level, to SDG 13: Climate action (United Nations, 2023).

1.8 Thesis Outline

This research consists of three stages that answer the main aim of the study, which is to investigate the extent to which small, low-carbon and (near) zero-energy dwellings could be a housing solution in North-West Europe. The thesis structure follows its adapted theoretical framework linking the research aim to the four study objectives: investigating the institutional dimension presented in Chapter 2, evaluating the social dimension from the perspective of housing professionals presented in Chapter 3, and from the perspective of the consumer presented in Chapter 4 and assessing the technical dimension through modelling the embodied carbon performance presented in Chapter 5. Together, these chapters answer the main research question and build up the map of outcomes that visualizes the gained insight at the institutional, the social and the technical levels which is presented in Chapter 6, the last part of this thesis. The thesis outline is illustrated in Figure 1.5.

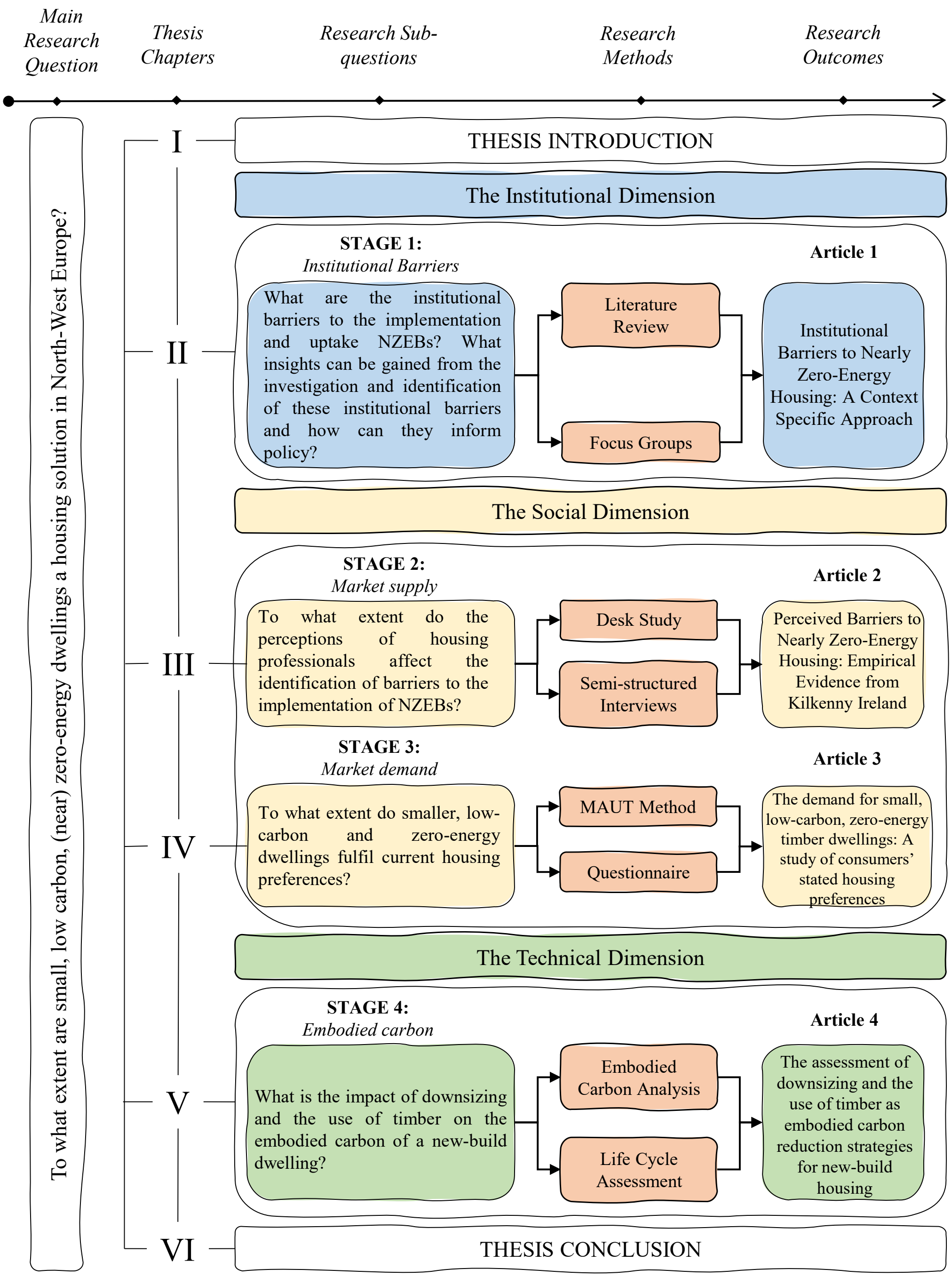

FIG. 1.5 Thesis outline

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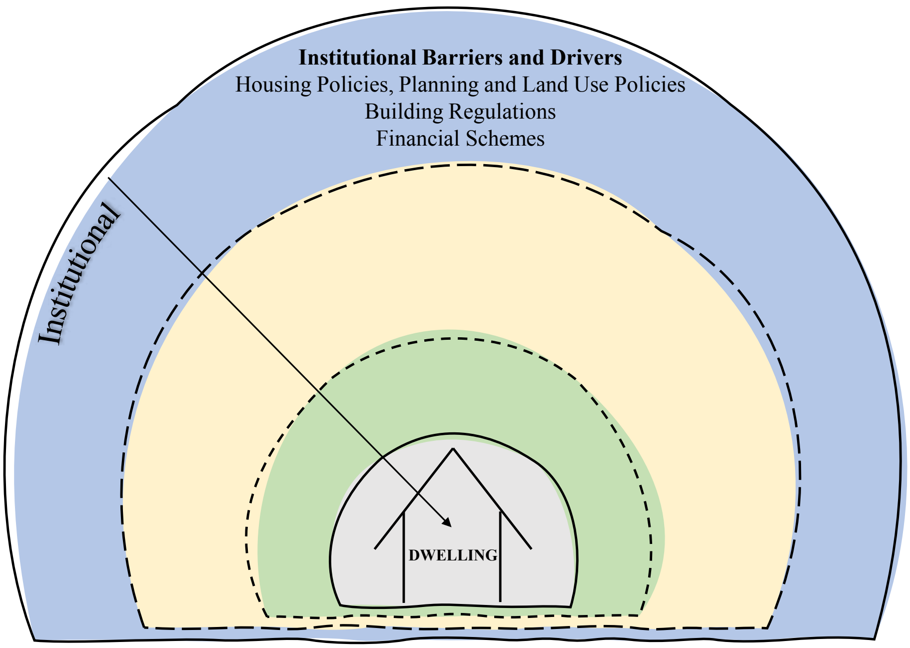
The construction of a Wikihouse in Almere in the Netherlands as part of the Housing 4.0 Energy (H4.0E) project funded by Interreg North-West Europe. Copyright: Wikihouse.

PART 2

STAGE I Institutional Dimension


Institutional Barriers and Drivers
Housing Policies, Planning and Land Use Policies
Building Regulations
Financial Schemes
Institutional
DWELLING

2 Institutional Barriers to Nearly Zero-Energy Housing

A Context Specific Approach

First published as: Souaid, C., van der Heijden, H., & Elsinga, M. (2021). Institutional Barriers to Near Zero-Energy Housing: A Context Specific Approach. *Sustainability*, *13*(13), 7135.

** Aside from layout changes and minor textual changes, this paper has not been amended for uptake in this dissertation.*

This dissertation investigates small, low-carbon, (near) zero-energy dwellings as a solution that would both address sustainability challenges and answer to the growing housing shortage in in North-West Europe. Unlike the majority of studies around NZEB, this research adopts a multidimensional approach in its investigation where the institutional and the social aspects surrounding the dwellings are investigated in addition to the technical aspect. As per the conceptual framework laid out in the introduction, this chapter starts with the investigation of the institutional dimension surrounding small, low-carbon NZEB dwellings. Through the conduction of focus groups with housing professionals in Belgium, Ireland and the Netherlands, general and context specific barriers to the implementation and uptake of the dwellings are identified in this chapter. Four main categories of barriers were investigated and results are presented in the form of legislative, financial, technical, and cultural barriers. Accordingly, recommendations are formulated in the form of legislative, financial, technical and cultural policy suggestions thus concluding this chapter.

The chapter starts off with an introduction highlighting the stagnating transition to nearly zero-energy housing in section 2.1. It then gives an overview of past literature on challenges to the implementation of nearly zero-energy housing in section 2.2 by highlighting the most common barriers previously identified in section 2.2.1, defining them in section 2.2.2 and categorizing them in section 2.2.3, leading up to the importance of adopting a context specific approach discussed in section 2.2.4. The methods implemented for both data collection and data analysis are outlined in detail in section 2.3. Results are presented in section 2.4 where recurrent barriers are distinguished from newly identified barriers in sections 2.4.1 and 2.4.2. Results are then discussed in section 2.5 where corresponding policy suggestions are proposed in section 2.5.2. Concluding remarks are made in section 2.6.

ABSTRACT After more than ten years since the introduction of Nearly Zero-Energy Buildings (NZEBs), the transition towards a zero-energy new built environment can still be considered slow despite European Member States' various efforts to facilitate, promote and accelerate their implementation and uptake. The barriers to sustainability measures in general and NZEBs in particular have been extensively explored by academic literature and despite different research scopes, perspectives, locations and times, previous studies have reached similar outcomes. Similar barriers were perceived by different housing professionals in different geographic contexts and these same barriers also persisted through time. This study argues that while this could be interpreted as a validation of outcomes, it also underlines a limitation resulting from a general level of analysis. Thus, this study contributes to the discussion by adopting a context-specific approach in its investigation of barriers to nearly zero-energy housing in small towns in Flanders, Ireland and the Netherlands. The data was collected from a series of focus groups with housing professionals in Leuven, Kilkenny and Almere. Through descriptive coding, this study's outcomes echoed previous research findings. However, a closer look through inferential coding resulted in the identification of 21 new contextual barriers leading to the formulation of more specific policy suggestions with a different allocation of precedence that depends on every context.

KEYWORDS NZEB; nearly zero-energy housing; new-build housing; institutional barriers; upscaling; policy suggestions

2.1 Introduction

It has been more than 10 years since the European Parliament published the Energy Performance of Buildings Directive (EPBD) 2010/31/EU which included Article 9(1) stating that all new-buildings are to be nearly zero-energy as of January 2021 [1]. In 2014, ZEBRA 2020's evaluation of the distribution of newly constructed dwellings showed that, out of 14 European Member States (MS), France was the only European country where the definition of NZEB matched the actual building regulations, thus making it the only country that has been actually building NZEBs since 2013 [2]. In 2016, the Directive published a synthesis report comprising the analysis of European MS national action plans which formed the basis of their recommendations and guide-lines on the promotion of NZEB [3]. The report highlighted that, despite their noticeable efforts, all MS, with the exception of Slovenia and the Netherlands, did not include quantitative intermediate targets for the implementation of NZEBs by 2015 [3]. Instead, the targets mentioned were mostly qualitative and extremely variable from one MS to the other, making a progress assessment less tangible and a comparative analysis more difficult. Consequently, the importance of setting quantitative intermediate targets was stressed again and repeated throughout the synthesis report, and one of the Directive's main summary recommendations was for European MS to accelerate their efforts in promoting the uptake of NZEBs and to ensure meeting these quantitative set target dates [4]. However, in 2018, the New Buildings and NZEBs central team under the Concerted Action EPBD reported that 24% of European MS still did not have a de-tailed definition of NZEB stated in legal documents [5]. The submission of National Action Plans in 2019 was another nudge for European MS [6]; however, it is fair to say that the transition towards the implementation and uptake of NZEB has been slow while the urgency and importance to achieve this transition is growing. Even more so now considering the European Green Deal that aims to make Europe the first cli-mate-neutral continent by 2050 [7].

So, what are the factors obstructing or delaying this transition? Although innovation is key in achieving zero-energy designs, an effective transition to a zero-energy built environment requires a successful uptake and upscale of such designs [8]. In fact, one of the common running arguments around sustainability or energy transitions is that they are societal and cultural changes as much as they are technical. It is based on this fundamental argument that the Energy Cultures (EC) framework was conceptualized. The EC framework adopts an actor-centred approach where it recognizes the importance of technology through the study of an actor's material surrounding as one of its study entities. However, it also recognizes the societal and cultural aspects of change by broadening its scope to include as its other study entities the study of practices, norms and external transactional or contextual factors that could have a direct or indirect impact on the actor [9,10]. The foundational definition of institutions is any set of guidelines used to organize any form of human interaction. Any form of institution and combinations of institutions or guidelines will affect actions and outcomes [11]. The EC framework recognizes the complexity of these intra and interrelations and their significance or impact on achieving change by broadening its concept of culture to include external factors such as policies and regulations, in addition to habits and values, and materials and technology [9,10]. The identification of contextual factors and the determination of what is 'external' is dependent on the nature of the actor in the study [10]. When it comes to NZEB, whether the actor is the resident or the NZEB itself, external factors, in other words the institutional context, around the supply and uptake of NZEBs is the same. Thus, the question becomes: *What are the institutional barriers to the implementation and uptake of NZEBs?* Then more explicitly: *What insights can be gained from the investigation and identification of these institutional barriers and how can they inform policy?*

Section 2.2 of this paper explores the literature on barriers to the implementation and uptake of sustainability or energy efficiency measures, technologies or designs including NZEBs. Considering this is an explorative study focusing on (near) zero-energy, low-carbon, small and affordable housing, the literature reviewed involves a combination of the concepts of sustainability, housing, policy, and energy performance. This review establishes the basis for this study's methodological approach consisting of a series of focus groups, which is described in Section 2.3. Section 2.4 presents the results by differentiating between barriers that persisted in 2019 and new contextual barriers. Section 2.5 presents the discussion of findings where the importance of a context-specific investigation is highlighted and potential policy suggestions are formulated accordingly. Finally, Section 2.6 concludes the paper by highlighting its contribution and limitations leading to direction for future research.

2.2 Literature Review

2.2.1 Barriers to the implementation of sustainability measures including NZEBs

One of the primary or foundational policy actions taken to evaluate the implementation of new measures is the investigation of barriers and drivers for an effective overall market response [12]. Consequently, be it explicitly or implicitly, the challenges to the implementation and uptake of new measures, designs or technologies within the built environment have been widely covered in sustainability and energy efficiency literature over the past years [13–18]. Considering the momentum gained by NZEBs since 2010, the barriers and opportunities to their implementation and uptake have al-so been thoroughly explored by academic literature [19–26].

These studies were conducted at different times and expanded over different lo-cations. They varied in scope ranging from general such as the barriers to sustainable building to specific such as the barriers to zero-carbon homes or NZEBs in particular. The barriers were explored from different angles of stakeholders be it policy makers, housing experts or professionals in the construction industry and the subjects of investigations were also different since they included energy efficient housing, low-carbon housing or prefabricated affordable housing apart from NZEBs. The distinction be-tween the studies evaluating barriers to sustainability measures in general and studies evaluating barriers to NZEBs in particular is important as it underlines the development of barriers through a change of scope. Even within NZEB focused studies, although the scope of the research is now narrower, the studies reviewed still differed in their points in time, the methods implemented, the perspectives taken and their geo-graphic contexts. Yet, despite these differences, the outcomes with regards to the barriers to sustainability measures and NZEBs revealed significant similarities and overlaps. Table 2.1 summarizes these outcomes and highlights the similarities by listing them in a descending order starting with the most common barriers with the highest number of references. It also highlights the overlaps in its listing by making a distinction between mentions that occurred in studies around sustainability measures in general and mentions that occurred in studies around NZEBs in particular.

TABLE 2.1 List of overall barriers to the implementation and uptake of sustainability measures including NZEBs

Code	Barrier	Sustainability	NZEB	Overall Mentions	Rank
LRB01	Higher costs	[13,14,16–18]	[20,22–26]	11	1
LRB02	Lenient building regulations	[14,16–18]	[19,22–26]	10	2
LRB03	Shortage of skills	[13–15,18]	[20–24,26]	10	2
LRB04	Lack of awareness	[14–16,18]	[21–26]	10	2
LRB05	Unclear or conflicting policies	[13,14,17]	[19,21–25]	9	3
LRB06	Uncertainty and risks of innovation	[14–18]	[20,23–25]	9	3
LRB07	Lack of adequate financial incentives	[13–16]	[19,24–26]	8	4
LRB08	Lack of expertise and experience	[15,16,18]	[21,23,24,26]	7	5
LRB09	Cultural preferences	[16,17]	[20,23–26]	7	5
LRB10	Lack of knowledge	[14,16,18]	[20,23–25]	7	5
LRB11	Payback period and return on investment	[14,16,17]	[22–25]	7	5
LRB12	Limited authority	[13,14,16,18]	[24,25]	6	6
LRB13	Lack of communication and coordination	[13,14,16]	[20,21,23]	6	6
LRB14	Access to technology	[14,18]	[20,23,24]	5	7
LRB15	Inadequate policy	[13,14,18]	[20,25]	5	7
LRB16	Business as usual approach	[18]	[22,23,25,26]	5	7
LRB17	Lack of priority and trade-offs	[14–16,18]	[22]	5	7
LRB18	Access to land	[13,14]	[23]	3	8
LRB19	Insufficient investment	[13,15]	[22]	3	8
LRB20	Poor management and maintenance	[13,16]	-	2	9
LRB21	Information asymmetry (supply/demand)	[13,16]	-	2	9
LRB22	Lack of involvement	[18]	[26]	2	9
LRB23	Split incentive	[16]	[24]	2	9
LRB24	Community opposition	[13]	-	1	10
LRB25	Lengthy governmental approval process	[13]	-	1	10
LRB26	Climate and geography	-	[21]	1	10
LRB27	Design methodology	-	[21]	1	10

2.2.2 Definitions of most recurrent barriers

This subsection elaborates on the definitions of the barriers that reoccurred in at least six previous studies. In other words, it defines the barriers, ranking from 1 to 6.

The first most recurrent barrier was revealed to be higher costs. Higher costs comprise any additional costs associated with the implementation of sustainability measures, technologies and/or materials compared to standard construction and/or the typical measures imposed by current policy and regulations. However, higher costs are not restricted to the initial stage of construction. They also apply to the maintenance and conservation of innovative sustainability measures.

The second most recurrent barriers are lenient building regulations, the shortage of skills and the lack of awareness. Lenient building regulations are perceived as a barrier mainly when current or established regulations are less stringent than the sustainability measures or designs in question. The shortage of skills mostly applies to the implementation of sustainability measures within the construction sector and includes the lack of training for it. The definition of the lack of awareness is quite broad but it can be manifested through market demand. When purchasers or end-users do not realize the magnitude of climate change consequences and the urgency of action, they do not demand sustainability measures or designs.

The third most recurrent barriers are the unclear or conflicting policies and the uncertainty and risks of innovations. Under unclear and conflicting policies, conflicts can occur between different policy areas as well as between the policies of local authorities and those of the central government. Uncertainty and risks of innovations describe the general reluctance to use new materials and technologies or adopt new methods and designs. These are usually perceived as unreliable due to the insufficient testing and the lack of experience when it comes to their implementation, maintenance and management.

The lack of financial incentives is the fourth most recurrent barrier. After the economic crisis in Europe, financial institutions were more reluctant to loan, which results in the absence of adequate and supporting schemes. The barrier of the lack of financial incentives is interrelated with the barrier of uncertainty and risk of innovations as the latter accentuates the former.

It is also closely linked to one of the fifth most recurrent barriers: the long payback periods and return on investments. The barriers of lack of experience and expertise, lack of knowledge, and cultural preferences are the other fifth most recurrent barriers. The definition of the lack of expertise and experience is closely related to the shortage of skills as it implies a lack of information to implement sustainability measures and designs. However, it also applies to other professionals such as designers and engineers. The lack of knowledge is associated to a lack of interest in sustainability leading to the non-consideration of sustainability measures that go beyond existing policies and regulations. Cultural preferences of traditional methods can be linked to both supply and demand through the business as usual barrier and the community opposition barrier especially when it comes to affordable housing developments since their foundational essence is one: the reluctance or resistance to change one's habits.

The limited authority and the lack of communication and coordination are the sixth most common barriers. In the absence of governmental support, the barrier of limited authority is raised. It can occur when the stakeholders involved do not have the authority or adequate leadership and support to implement sustainability measures. It can also apply to local authorities in the case of high interference from the central government. Last but not least, the lack of communication and coordination applies to the channels between local authorities and central governments as much as those between different policy areas and departments or different design and construction disciplines.

2.2.3 Categorization of most recurrent barriers

Whether studies focused on sustainability measures in general or NZEBs in particular, the identification of barriers always led to a certain categorization. In 2009, the feasibility of zero-carbon homes was investigated from the perspective of home builders in England [25]. Identified barriers were categorized into legislative, financial, technical and cultural barriers, thus covering all the potential aspects of constraints. In 2011, low-carbon housing refurbishments in England were evaluated this time from the perspective of architects and the same categorization was adopted [22]. Some research resulted in fewer groups such as a study evaluating the environmental legislation barriers and drivers to energy conservation and building design where legislative, financial and design barriers were identified [14]. Others opted for more groups as for example a study evaluating zero-carbon homes from the perspective of the construction industry in the UK that assigned skills and knowledge and industry their own categories of barriers in addition to economic, cultural and legislative barriers [23]. Overall, aside from the slight differences between these categorizations, the most recurrent distinctions made are between financial, cultural, technical and legislative barriers. The combination of all four can be considered to provide an institutional overview of barriers to NZEBs. However, it is

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important to highlight that the assignment of barriers to corresponding categories is not a straightforward process. One must recognize that they are all interrelated and that any change in one will most certainly affect another (Figure 2.1).

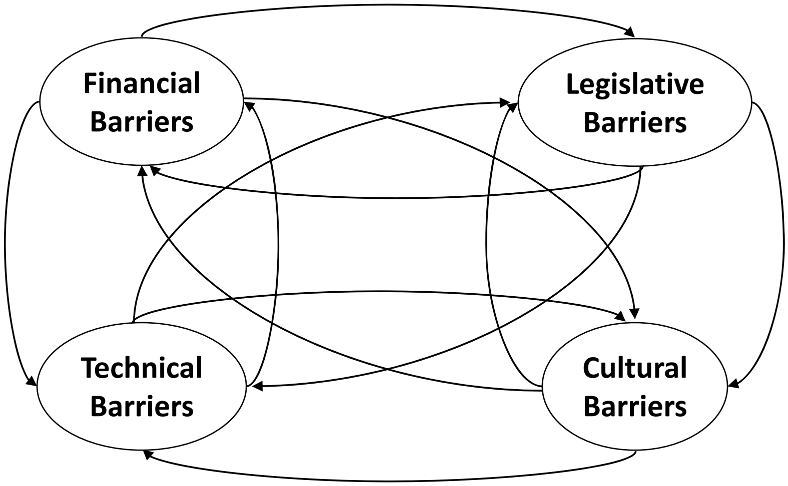

FIG. 2.1 Common categories of institutional barriers

Recalling the foundational definition of institutions being any set of guidelines used to organize any form of human interaction, each category is a form of institution and combinations of institutions or guidelines will affect actions and outcomes [11]. Moreover, some of the barriers identified such as the lack of communication and coordination could apply or fall under any of the four categories. Thus, to avoid repetition, a fifth category of 'overarching barriers' was created. In line with that reasoning, Figure 2.2 illustrates the most common barriers to the implementation and uptake of NZEBs according to these five categories. The numbers accompanying the arrows indicate the number of mentions of these most common barriers in previous studies. The dashed arrows highlight the overlap of the lack of communication and coordination barrier that resulted in the creation of the fifth category of overarching barriers.

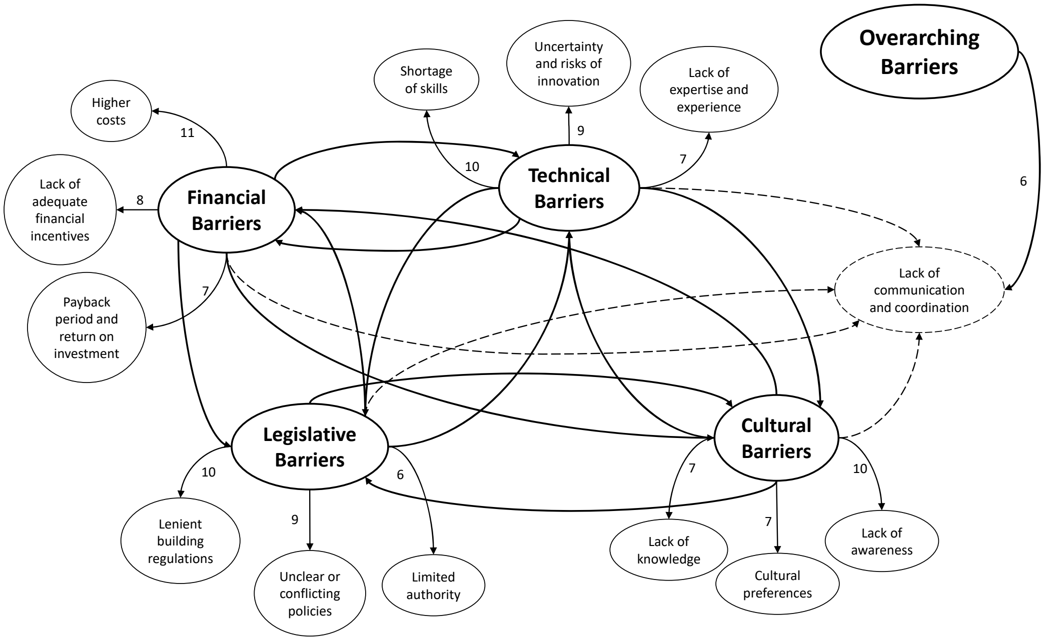

FIG. 2.2 Categorization of most common barriers

2.2.4 The importance of context and NZEB related policies

The review of studies on sustainability measures in general followed by a review of studies on barriers to NZEBs in particular, shed light on the fact that the barriers identified in these studies remained the same despite different research scopes, perspectives and geographic locations. This indicates that these stated constraints are applicable to any type of sustainability measure and that they are perceived by most professionals involved in the provision of these measures. Additionally, underlining the fact that the studies reviewed were conducted at different points in time singles out the persistence of these identified barriers through time. Academically, this can be interpreted as a validation of research outcomes and conclusions. However, in practice, this underlines a significant limitation. It raises the question of how these constraints have been addressed and why they have been recurring over time despite the formulation of recommendations and measures to overcome them.

A possible explanation to the persistence of similar results is the general level of analysis. While reaching generalizable outcomes and having a holistic view on challenges to the uptake of innovations is helpful, a more context-specific level of analysis could help identify more context relevant challenges leading to better and more precise recommendations. It is well known that energy commitments, legislative structures, traditions and practices, and building regulations all vary from one country (i.e., context) to another [16,19]. In fact, a closer look into a certain context often generates new and more specific outcomes, in this case, barriers. For instance, a study on future challenges to NZEBs in Southern Europe identified the different geography and climate of Southern European countries as one of the main barriers to the successful implementation of NZEBs (Table 2, LRB26). Hot summers and recurrent heat waves are a few of the climatic conditions leading to poor NZEB designs and a significant energy performance gap. This is also linked to the second context-specific barrier identified in this study, which is a poor design methodology (Table 2, LRB27). It is argued that due to these different geographic and climate conditions, rules of thumb and steady state simulation tools are not enough to achieve a successful design. Thus, in Southern European countries, there is a need for design requirements based on field measurements and real performance monitoring data [21]. In Northern European countries this approach has already been in place [5,19,24].

The recognition of changing conditions due to different climates and locations is exactly why the EPBD did not provide specific, harmonized minimum or maximum requirements to European MS in their definition of a nearly zero-energy building. In fact each MS was required to determine their own requirements tailored to the peculiarities of their contexts [3]. This also resulted in MS having individual action plans. First, the growing imperative of NZEBs entailed the submission of nearly zero-energy buildings national plans [27]. Then, following the Paris Agreement, each MS had to submit its own National Climate and Energy Plans [6]. European MS even have their own national action plans such as the Dutch Climate Agreement [28], the Irish Climate Action Plan [29] and the corresponding progress report [30]. That is to say the importance of contextual characteristics and their acknowledgment as influencing factors is manifested in policy and government reports. Yet, in academia, there is still a need for context-specific investigation and studies exploring in detail the challenges and opportunities to the implementation and uptake of NZEBs while taking into account local peculiarities.

As part of a larger project funded by Interreg North-West Europe entitled Housing 4.0 Energy: Affordable and Sustainable Housing through Digitization (H4.0E), this research aims to contribute to this discussion by conducting a more context-specific investigation of barriers to the successful implementation and uptake of nearly zero-energy housing in Belgium, Ireland and the Netherlands from the perspective of professionals involved in the commissioning, design, construction and regulation of housing. Through the H4.0E, a number of small and affordable (near) zero-energy dwellings will be designed and built in the three different northern European countries. In particular, the dwellings are divided into three pilot projects: one in Huldenberg in Belgium, another in Kilkenny, Wexford, and Carlow in Ireland, and a third in Almere in the Netherlands. The overarching project aim is not only to provide new and affordable housing solutions for small, low to middle-income households composed of one to two persons but also to explore and facilitate the uptake of these dwellings within Flanders, Ireland, and the Netherlands [31]. This paper is the initial stage of a larger study that will investigate, with reference to the EC framework, the norms, practices and materials surrounding H4.0E dwellings and their occupants.

2.3 Materials and Methods

This study followed an iterative approach in its implementation, alternating between desk research, qualitative data collection and qualitative data analysis as illustrated in Figure 2.3. The desk research mainly covered secondary sources such as academic articles, textbooks, government proceedings, government reports and websites. The qualitative data was collected through focus groups. The qualitative data analysis is described below.

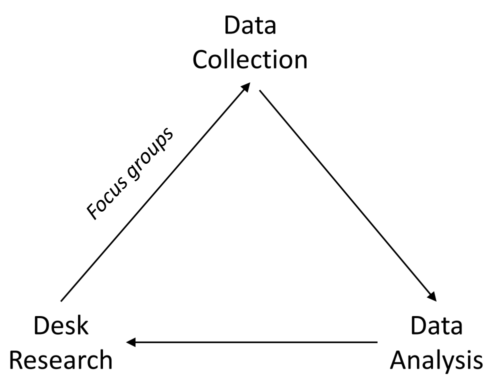

FIG. 2.3 Iterative methodological approach

2.3.1 Focus group content

The explorative review of studies on barriers to sustainability measures in general and to NZEBs in particular was foundational to the design of the focus group discussions in two ways. First, it allowed the identification of the main categories of barriers for an overall institutional overview: legislative, financial, technical, cultural and overarching barriers. Second, in most of the studies reviewed the categorization of barriers followed the data analysis. In this study, these categories were taken as a starting point to the focus group discussions. In other words, main keywords were determined under each category, which led to the formulation of the explorative and engaging questions that guided the focus group discussions. Keyword examples would be: housing policy, planning and land use policy, energy policy, building regulations, building standards, financial schemes, tax reductions, subsidies, and cultural habits and preferences. A distinction between implementation and uptake was ensured through the division of focus group discussions into two rounds. The first round focused on the current challenges to the actual implementation of H4.0E dwellings and the second round focused on potential challenges to their uptake to a wider scale.

2.3.2 Focus group participants

One focus group was conducted per each pilot between the months of April and June 2019. The focus groups gathered housing designers, technical experts, housing providers and decision makers in the field as well as local and regional authorities for a balanced composition of people representing all parties involved in the field of housing. In fact, the focus group method was selected specifically to have an open discussion amongst the different parties involved in housing provision. The participants were recruited by nomination [32]. The number of participants per focus group did not exceed the recommended maximum of 15 as 9 housing professionals were present in Almere and Kilkenny and 12 in Leuven [33]. The discussions were guided by a moderator and an assistant-moderator and took place in English and in Dutch depending on the location. With the participants' consent, the discussions were recorded then transcribed into detailed reports. The reports were then shared with the H4.0E pilot representatives and the housing professionals who participated in the study for their comments and feedback. The input received was taken into account during the qualitative data analysis described in more detail below.

2.3.3 Pilot characteristics

One of the ways the importance of context was included in this study was through the different pilot projects' characteristics. Each H4.0E pilot project had a different ownership, tenure type, target group, income range and housing sector as can be seen in Table 2.2. The Flemish and Irish pilots have similar project characteristics and they are significantly different from the Dutch pilot characteristics. While the first two focus on providing affordable NZEBs to low-income households on waiting lists through either social housing or partial subsidization, the Dutch pilot targets low to middle-income households within the private housing sector looking to become owners and willing to self-build their dwelling [31]. Thus, the importance of a context-specific investigation could be tested through the comparison of focus group outcomes between the Dutch, Flemish and Irish pilot projects considering all three have different geographic contexts but the latter two have similar project characteristics.

TABLE 2.2 H4.0E pilot project characteristics

Country	Belgium	Ireland	Netherlands
Pilot location	Huldenberg	Wexford, Carlow, Kilkenny	Almere
Ownership	Private	Local Authority	Private
Tenure Type	Rental	Rental	Owner Occupied
Target Group	Waiting list	Social housing waiting list	Self-builders
Income Range	Low-income	Low-income	Low/Middle-income
Sector	Private, Partially subsidized	Social Housing	Private

2.3.4 Qualitative data analysis

The qualitative data collected was analyzed directly from the transcribed reports. An initial screening of focus group outcomes amongst the three pilots projects allowed the underlining of barriers that have been identified by previous studies yet reoccurred in this study. Having the pre-determined barrier categories and the pre-identified barriers serving as the main thematic groupings, the data was coded into these key categories and barriers—otherwise known as *descriptive coding*. Secondary and tertiary screenings allowed the highlighting of the importance of a context-specific investigation through the identification of new context-specific barriers—otherwise known as *inferential coding* [34]. Inferential coding was crucial to the qualitative data analysis also because of the intra and interrelations of the institutional barriers. Although the focus group discussions were structured in a way that directly allows the identification of barriers within the five different categories—financial, legislative, technical, cultural and overarching—the interrelation of these barriers prevailed and at several instances the statements of focus group participants (FP) covered several barriers at once be it explicitly or implicitly. An example would be:

"You are expected to meet building regulations, you can exceed them but this becomes like any other project [...] based on an individual basis. You do not get funding for exceeding the building regulations."
(Statement 1, Kilkenny)

Through this statement, we are able to identify first the lenient building regulations barrier (LRB02) that describes current building regulations as more lenient than NZEB requirements. Second, we can extract the insufficient investment barrier (LRB19) describing the lack of government funding allocated to support the construction of NZEBs. This is underlined by a perception of higher costs (LRB01) that is automatically associated with NZEB design and construction regardless of the accuracy or validity of this perception. Third, we can sense the lack of priority and trade-off barrier that is about having to choose between affordability over zero-energy performance and not being able to achieve both (LRB17).

In other statements, the implicit indications of barriers are dominating. For instance:

"I think that the need for housing at the moment is pushing everything on at a particular speed and the urgency to get houses built and to get people into houses."
(Statement 2, Kilkenny)

The statement above is an indication of the lack of awareness (LRB04) considering the participant's perception of urgency is misplaced. In that statement, the imperative of all new dwellings to be nearly zero-energy is dismissed by the urgency to simply provide housing. When referring to the Irish Climate Action Plan 2019 and the detailed actions within, it becomes clear that this is not the case [29].

2.4 Results

The data analysis of this study mirrors the approach taken in the literature review as it followed a gradual process that started with a general overview of barriers to the implementation of H4.0E dwellings followed by a more detailed investigation of barriers within each context. Thus, the first part of this section lists the focus group outcomes that have been identified in previous studies and the second part introduces and defines the new barriers that were identified in the focus groups. This presentation of results sheds light on known factors that were still perceived as challenging to the implementation of NZEBs in 2019 in addition to generating new outcomes.

2.4.1 Barriers that persisted in 2019

As mentioned above, this section highlights the similarities between this study's focus group outcomes and the barriers to sustainability measures and NZEBs identified from previous literature. The outcomes are grouped as per the five categories previously determined. Thus, Table 2.3 lists the overlapping financial barriers, Table 2.4 lists the overlapping legislative barriers, Table 2.5 lists the overlapping technical barriers, Table 2.6 lists the overlapping cultural barriers and Table 2.7 lists the overlapping overarching barriers. The tables list the barriers with the corresponding supporting statements from the focus group discussions depending on the location where they are applicable. All barriers listed have been identified in at least one of the three different study contexts. Places of non-occurrence are indicated by '**X**'. As can be seen in Tables 2.4 through 2.7, all the most recurrent barriers previously mentioned in Figure 2.2 and defined in Section 2.2.2 also reappeared in the focus group outcomes of this study. However, 10 out of the 14 other barriers that were not as frequently mentioned in previous studies were also identified in this study's focus group outcomes. These are the insufficient investment, the lack of priority and trade-off or the split incentive barriers under financial barriers; the inadequate policy, access to land or lengthy governmental approval process under legislative barriers; the climate and geography barrier under technical barriers; the business as usual approach and community opposition barriers under cultural barriers; and the lack of involvement barrier under overarching barriers.

TABLE 2.3 Financial barriers that persisted in 2019

Code	Barrier	Kilkenny	Leuven	Almere
LRB01	Higher costs	"[…] you do not get funding for exceeding building regulations […]."	"People do not want to use wooden cladding because of the higher maintenance costs."	"[…] the closer you get to zero (energy) then some of your costs really go up and then it starts affecting (affordability)."
LRB07	Lack of adequate financial incentives	"We cannot give money upfront unless the architect or engineer signed off and works have been completed."	"The reason why social landlords in Flanders are less focused on the realization of energy-neutral homes is the cost […]."	"Now […] the bank (is) saying […] we want a guarantee that the house will be finished so what happens if someone […] breaks his arm […] the actual costs if you use a professional for this are higher because then you will have to pay these and then suddenly someone doesn't have enough income anymore."
LRB11	Payback period and return on investment	"If the first thing they learn is that the value of their security will be 0 in 15 years that will have a big bearing on their willingness to lend against the property."	X	"You need to show that you have enough income, you need to show that the house will have enough values […] so your loan to value is valid."
LRB19	Insufficient investment	"[…] you do not get funding for exceeding building regulations […]."	X	X
LRB17	Lack of priority and trade-offs	"[…] the answer will always be well if we could house 6 families instead of 4 families if that makes economic sense then that's what they will go with […]."	"It is established that there is a constant trade-off between economy and energy efficiency. This trade-off is traditionally made at the level of the initial investment."	X
LRB23	Split incentive	X	"In the (social) rental sector it is generally the case that the landlord invests and the tenants has lower energy costs."	X

TABLE 2.4 Legislative barriers that persisted in 2019

Code	Barrier	Kilkenny	Leuven	Almere
LRB02	Lenient building regulations	“You are expected to meet building regulations, you can exceed them but this becomes like any other project […] based on an individual basis [...].”	“Low-carbon building is not yet part of the applicable standards within social housing. There are no specific guidelines for the use of materials.”	X
LRB12	Limited authority	“(The) likelihood is the building is already pre-determined and pre-designed to a certain standard anyway.”	“A problem that the social housing companies are confronted with is that they are tied to government contracts: public procurement.”	X
LRB05	Unclear or conflicting policies	“It (similar designs) still doesn’t get you away from your application for DAC (or) fire certification. They’re all individual schemes it’s not something you can pre-certify.”	“There is still no clear framework within which to work. If this framework exists and it is incorporated into spatial implementation plans, developments can proceed quickly.”	X
LRB15	Inadequate policy	“When you do have land, you’re working with local authorities on what the need is for the area.”	“The realization of affordable housing should be a reason for municipalities to make semi-public and public land available in the form of long-term leases instead of selling the land to project developers.”	“There is no land and it is not organized enough by national or local government to make available plots for self-build.”
LRB18	Access to land	“[…] there is not land out there or the access to land to take complete control of it.”	“The realization of affordable housing should be a reason for municipalities to make semi-public and public land available in the form of long-term leases instead of selling the land to project developers.”	“It is difficult to realize such a project in urban areas. It is easier here because you have large lots.” “Land price was one of the obstacles. There were difficult negotiations.”
LRB25	Lengthy governmental approval process	“Something that should take 3 months takes 2 years and you go back there and you are re-applying and…”	X	“This (land-value determination) discussion took 2 years in this case […].”

TABLE 2.5 Technical barriers that persisted in 2019

<table>
<tr><th>Code</th><th>Barrier</th><th>Kilkenny</th><th>Leuven</th><th>Almere</th></tr>
<tr><td>LRB06</td><td>Uncertainty and risks of innovation</td><td>“New innovative technologies and techniques means unforeseen issues.”</td><td>“To be able to make a good investment a client should […] have insight into the initial investment [...] A lot of data is needed for this and unfortunately it is not always available.”</td><td>“We had to do a lot of tests to showcase that the type of construction is strong enough to fit (building regulations).”</td></tr>
<tr><td>LRB03</td><td>Shortage of skills</td><td>“After the last downturn, we lost a lot of skills.”</td><td rowspan="2">“If the tender is specifically aimed at prefab construction there is a risk that there will not be enough tenders, few companies specialize in this.”</td><td>X</td></tr>
<tr><td>LRB08</td><td>Lack of expertise and experience</td><td>“It’s also about the expertise […] you see discrepancies (and) differences from one developer to another […] this is a new enough system and the problems will manifest themselves a few years later […].”</td><td>X</td></tr>
<tr><td>LRB26</td><td>Climate and geography</td><td>“An Irish problem has always been damp walls.”</td><td>X</td><td>“[…] the floor downstairs […] the whole thing is floating a bit above ground to keep it all dry.”</td></tr>
</table>

TABLE 2.6 Cultural barriers that persisted in 2019

Code	Barrier	Kilkenny	Leuven	Almere
LRB04	Lack of awareness	"I think that the need for housing at the moment is pushing everything on at a particular speed and the urgency to get houses built and to get people into houses."	"Society has to make the switch."	X
LRB10	Lack of knowledge	"Lack of knowledge about how the system works makes people frustrated and pushes them to play around with switches not knowing how it affects the performance of the house."	"New technologies (such as underfloor heating) are no longer much more expensive, but the residents must be able and willing to deal with them."	"[…] this is different and far away from the standards and how we do things normally, can't be bothered."
LRB09	Cultural preferences	"[…] there is a mindset about timber frame in this country."	"The new techniques must be socially accepted."	"90% of the houses in Holland are built with concrete and bricks and that's what we are used to so suddenly starting to use wood is a bit different."
LRB16	Business as usual approach	"The department of housing in the government is more focused on traditional construction."	The social rental sector in Flanders has traditionally focused on building spacious traditionally built homes.	"Within the council, generally if you want to do an innovative project that does things a bit differently let's say 10% of the organization absolutely loves that and the other 90% thinks […] this is different and far away from the standards and how we do things normally, can't be bothered."
LRB24	Community opposition	"It's not necessarily the local authority it's the neighbors. *Not in my backyard* sort of mindset […] Even if the objections are trivial you will have councilors looking into it."	X	X

TABLE 2.7 Overarching barriers that persisted in 2019

Code	Barrier	Kilkenny	Leuven	Almere
LRB13	Lack of communication and coordination	"You just have to (recognize) how nobody talks to each other […] the big issue at the moment is between design and operation […] sharing information is the most important thing and ultimately lowers costs and improves building performance […] but it all comes back to everybody working together and that is the biggest issue in the construction sector."	"A framework and a vision are provided from the housing policy but it is very important that this is taken up locally."	X
LRB22	Lack of involvement	"A lot of Approved Housing Bodies now are working with developers and turnkeys."	X	X

2.4.2 New focus group barriers

The focus group discussions led to the identification of several new barriers per different context. Table 2.8 lists these barriers to the implementation and uptake of H4.0E dwellings by distinguishing between categories and countries. The listing within the four categories does not follow any particular order. Place of occurrence is indicated with a 'Y'.

TABLE 2.8 Summary of focus group barriers to the implementation and uptake of H4.0E dwellings

Category	Code	Barrier	Kilkenny	Leuven	Almere
Financial	FGB01	Inconsistent financial schemes benchmarks	Y		
	FGB02	Cost of certification	Y		
	FGB03	Self-build mortgage scheme	Y		Y
	FGB04	Loan to security scheme	Y		
	FGB05	Residual counting			Y
	FGB06	Profit maximization		Y	
Legislative	FGB07	Individual certification schemes	Y		
	FGB08	Local authority design requirements	Y	Y	Y
	FGB09	Long period of testing and development			Y
	FGB10	Social housing design requirements		Y	
	FGB11	Restrictions on small dwellings		Y	
	FGB12	Restrictions on compact construction		Y	
Technical	FGB13	Lack of standards	Y	Y	
	FGB14	Dwelling lifespan	Y		
Cultural	FGB15	Thermal comfort perception	Y		
	FGB16	Societal daily habits	Y	Y	
	FGB17	Lack of information		Y	Y
	FGB18	Perception of timber dwellings	Y		Y
	FGB19	Perception of small dwellings		Y	
	FGB20	Perception of self-build			Y
	FGB21	Reluctance to move		Y	

Focus group financial barriers to H4.0E dwellings

The contextual financial barrier of inconsistent benchmarks for green financing (FGB01) applicable to Ireland describes, as its name implies, the lack of consistency between different financial institutions when it comes to their benchmarks around the implementation of sustainability measures. In a way, this barrier was perceived to reflect the institutions' willingness to lend underlining the interrelation with the lack of financial incentives barrier (LRB07). The cost of certification barrier (FGB02) also applicable to Ireland entails the cost implications of certification applications needed for a design's approval. In Ireland, certification applications entail both designer and consultant fees. Consultant fees are perceived to be higher than designer fees. This was identified as obstructive to the uptake of H4.0E dwellings because even when dwelling designs are being replicated, certification costs would still be high due to these consultant fees. In other words, these fees could potentially counter the cost savings that would be achieved through the replication of H4.0E dwelling designs. The contextual financial barrier of self-build mortgage scheme (FGB03) is applicable to both the Irish and Dutch contexts. Currently, mortgage schemes are obstructive for low to middle-income households interested in building their own small, low-carbon and (near) zero-energy home as mortgage requirements in both contexts contest the affordability and innovation of the project. Within the Irish private sector, to avoid potential risks, the established financial schemes are set in a way that does not necessarily encourage innovation. The process of obtaining a mortgage requires most of the works to be completed and signed off by an architect and/or an engineer. Funds cannot be released otherwise, thus making it more difficult for individuals to obtain the necessary support to build their own H4.0E dwelling. In Almere, current financial schemes within the private sector also require a project completion guarantee from self-builders in case of injuries. This challenges the affordability aspect of self-building since it automatically changes the income brackets for applicants that would qualify for the scheme (Statement 3). This recalls the established loan to security scheme highlighted by participants in Kilkenny (FGB04) that was linked to the reluctance of financial institutions to lend (LRB07) under the assumption that the value of the security would depreciate faster because these dwellings have shorter lifespans compared to traditionally built dwellings (FGB21).

"[…] the bank (is) saying […] we want a guarantee that the house will be finished so what happens if someone […] breaks his arm […] the actual costs if you use a professional for this are higher because then you will have to pay these and then suddenly someone doesn't have enough income anymore."
(Statement 3, Almere)

The next contextual financial barrier identified in Almere is interrelated to policy and concerns the land price determination. In theory, land price is determined based on residual counting (FGB05) where building costs are subtracted from the market value. This was perceived as obstructive because a decrease in building costs would lead to higher land costs and contest the savings made through self-building depending on the municipalities' standardized land quotas. Last but not least, participants in Flanders perceived the established economic model as an overarching barrier to the provision of affordable housing in general. It was highlighted that as long as profit maximization (FGB06) is the main goal, successfully implementing and upscaling affordable and zero-energy housing is challenging.

Focus group legislative barriers to H4.0E dwellings

Under legislative barriers, the focus group discussion in Ireland identified the individual certification scheme (FGB07) as significantly challenging to the rapid uptake of H4.0E dwellings. The scheme requires an individual application for each certification needed per dwelling. Among these certifications are the Disability Access Certificate (DAC) or the Fire Certificate and the pre-certification of dwellings for those is not possible. Therefore, regardless of whether or not the dwelling designs have been replicated, the length of process stays the same. The next barrier applicable to the Irish context is also applicable to the Flemish and Dutch contexts and involves local authorities' design requirements (FGB08). In some instances these can be limiting and restrictive. In Flanders, these design requirements were perceived to be particularly restrictive to small-scale living (FGB11). Participants highlighted that although minimum living area requirements differ from one municipality to another, most of them exceed the largest H4.0E dwellings design living area. In the Netherlands, H4.0E dwelling designs also need to comply with the land use plan but this was not perceived as constraining as the long period of testing and development to pass building regulations which is the only other legislative barrier identified in Almere (FGB09). In Flanders, design requirements were also perceived as constraining within the social housing sector where they aim for universality of design to facilitate the allocation process (FGB10). Participants described these requirements as traditional and outdated in a way that encourages spacious dwellings. They were also perceived as too prescriptive to the extent of being obstructive especially when it comes to the adoption of energy-efficient technologies and innovative designs like small-scale living. Within land subdivision policies, participants in Leuven identified a restriction to compact construction (FGB12). It was highlighted that in Flanders, it is often the case to assign not more than one dwelling per a relatively large plot of land and this was perceived as inefficient and preventive of the provision of dwellings (Statement 4).

“The discussion should not really be about the realization of a small residential unit on a building plot but about the realization of a number of units on a plot.”
(Statement 4, Leuven)

Focus group technical barriers to H4.0E dwellings

With regard to aiming for a low embodied carbon, the lack of standards (FGB13) was identified as a barrier in both Kilkenny and Leuven. Participants perceived the absence of clear guidelines on the use of materials as challenging to the design of a low embodied H4.0E dwelling let alone its uptake. Additionally, participants in Leuven pointed out the absence of standards on modular construction which was also perceived as constraining to the uptake of H4.0E dwellings (Statement 6). In Kilkenny, the dwelling’s shorter lifespan (FGB14) was perceived as potentially constraining and as mentioned above this barrier is interrelated to others like the financial barrier of willingness to lend.

“Low-carbon building is not yet part of the applicable standards within social housing. There are no specific guidelines for the use of materials.”
(Statement 6, Leuven)

Focus group cultural barriers to H4.0E dwellings

According to FP in Kilkenny, a combination of occupants’ perception of thermal comfort (FGB15) and their daily habits (FGB16) can result in their reluctance to change energy sources (Statement 5).

“As a society, we decide if the room is warm enough by touching the radiator. […] because the hand on the radiator is not warm enough even though the actual temperature in the room is 21 degrees they would say the heating system is not working.”
(Statement 5, Kilkenny)

Participants pointed out that traditional heating systems like radiators have been around long enough for people to make use of them in different indispensable ways. For instance in summer Irish occupants use radiators to dry clothes and that cannot be replaced by new systems like mechanical ventilation. This opinion was shared by participants in Leuven who claimed that occupants are used to traditional heating and ventilation systems to a point that they would still choose them over new systems regardless of the fact that they have been made more affordable. The barrier of lack of information (FGB17) also concerns potential occupants. In Leuven, the lack of information was linked to the incorrect use and operation of innovative technologies which could have a significant impact on the overall energy efficiency and performance. In Almere, the lack of information was linked to the uncertainty that revolves around the performance of a self-built dwelling considering this is still a new practice. This is an underlying barrier to the barrier of ‘perception of self-build’ (FGB20). Other H4.0E dwelling characteristics that provoke a negative perception are the timber frame (FGB18) and the small size of the dwelling (FGB19). In Kilkenny and Almere, participants highlighted that people do not perceive timber framed dwellings as robust and durable or resistant to water respectively. Participants in Leuven pointed out that people in Flanders tend to link small dwellings to tiny houses or ‘container’ homes that are usually found in gardens, orchards or nature. This negative perception only reinforces people’s reluctance to move (FGB21) from their larger family homes which is another cultural barrier that was identified in Leuven.

2.5 Discussion

2.5.1 A context specific investigation

The importance of a context-specific investigation was repeatedly manifested throughout this study. In the first instance, it was demonstrated through the distinction between general barriers that had been previously identified by literature and persisted in 2019 and the other focus group barriers specific to the H4.0E dwellings. The barriers that persisted in 2019 are the ones that were identified in previous studies and identified again by this study’s focus group participants. They are the barriers that persisted despite different research scopes, times, methods or geographic contexts. Examples of barriers that persisted in 2019 and that are common to all three contexts are the perception of higher initial costs, inadequate policy, access to land, lack of financial incentives, uncertainty and risks of innovation, cultural preferences and the business-as-usual mindset. Other examples of barriers that persisted in 2019 and that are common to at least two of the three contexts are the lack of awareness, the lack of knowledge, the lack of communication and coordination, the shortage of skills, the lack of expertise and experience, the loose building regulations, the unclear and conflicting policies, the limited authority, the lack of priority and trade-offs and the long payback periods and return on investment. The second manifestation is through the inclusion of three pilot projects, out of which two have similar project characteristics. Both the Irish and Flemish pilot projects are focused on delivering dwellings for low-income households on waiting lists within the social housing sector whereas the Dutch pilot project is focused on assisting low to middle-income households in the private housing sector in self-building their dwelling. Contrary to what would be expected, there were not as many commonalities between the Irish and the Flemish contexts in the identification of H4.0E specific barriers. The third instance where the importance of context can be demonstrated is when a closer analysis of participants' statements is conducted. This is when local peculiarities can be identified and precedence can be determined. A straightforward example would be occupants' perceptions of H4.0E dwellings. In the Irish and Dutch contexts the negative connotation and uncertainty concerned the timber frame of the dwellings, in the Flemish context the focus was on the small size of the dwelling. There is even a nuance in the perception of timber framed dwellings as participants in Kilkenny discussed the robustness of the structure, whereas participants in Almere mentioned the resistance to water over time. The distinction between contexts allows the allocation of precedence of the information distributed during the promotion of H4.0E dwellings. In other words, in the Irish context, precedence would be given to information on the strength and robustness of timber framed dwellings. In the Dutch context, the focus would be directed towards highlighting the durability and resistance of timber frames to water, and in the Flemish context, campaigns would focus on highlighting the benefits of living small. Another example would be the barrier of access to land. It is a barrier that was identified in previous studies and in all three focus groups so it would qualify as a general barrier. However, looking closer into each context, it becomes clear that the definition of access to land differs per pilot. In Kilkenny, access to land was linked to limited authority considering it is dependent on local authorities preferences and requirements. In Leuven, access to land was associated with regulations around the allowable number of dwellings to be built on a plot. Often it is limited to one house per a relatively large plot which was perceived to discourage the uptake of the smaller H4.0E dwellings. In Almere, apart from the non-availability of land in urban areas, land accessibility was linked to affordability and the determination of land value based on residual counting. Thus, branching out of the general barrier of land accessibility, three different context-specific barriers were identified through a closer look into context-specific data, thus leading to three different policy suggestions.

2.5.2 Policy suggestions

Having identified barriers to the implementation of H4.0E dwellings that are more specific to each of the three contexts, more relevant suggestions to overcome them can be formulated. Once again, considering each of the category of barriers as an institution on its own and recognizing the complexity of intra-relations within and interrelations with the other categories, one must recognize the potential impact of one policy suggestion under a certain category on one or several barriers in other categories. In line with that reasoning, while the categorization adopted throughout this paper is implemented to the policy suggestions, potential interrelations are also highlighted when applicable.

Financial policy suggestions

In Ireland, establishing common benchmarks for the financing of sustainability measures and ensuring consistency could facilitate the implementation and uptake of NZEBs. Revisiting the cost certification scheme by balancing out designer and consultant fees or potentially establishing a new scheme uniquely tailored for small, low-carbon, (near) zero-energy dwellings could help promote their uptake. Financial institutions could redirect their established schemes—or tailor new ones—towards encouraging new designs and the implementation of measures that exceed basic regulations especially boosting low to middle-income individuals in the private sector. Additionally, providing financial institutions with information around the dwelling designs, their lifecycle analysis and costs and keeping them informed about design developments could add reassurance with regard to the loan to security scheme and make up for the absence of a business model. The provision of this type of detailed information on NZEB designs could also help improve the engrained profit maximization drive of financial institutions in Flanders. In the Dutch context, revisiting the completion guarantee requirement would encourage self-builders with lower incomes. When it comes to the land price determination, in practice municipalities work with standardized land quotas. In the case these quotas are computed based on traditional construction methods, then savings can still result from the implementation of innovative construction methods including self-building. Thus, establishing this balance between building costs and land price by ensuring the capitalization on savings from self-building could be more encouraging for lower-income self-builders.

Legislative policy suggestions

The individual certification scheme barrier specific to the Irish context is a manifestation of the interrelations between barrier categories as it was also identified as a barrier under the contextual legislative barriers. Revisiting the established individual certification scheme in Ireland with a focus on the Disability Access Certificate and the Fire Certificate especially for small, low-carbon, and (near) zero-energy dwellings could accelerate the process of design approval leading to the promotion of their uptake. In the Dutch context, a potential solution to go around the long design testing and development process that preceded the implementation of H4.0E dwellings would be to standardize such small, low-carbon, and (near) zero-energy dwelling designs. In 2016, the EPBD's recommendation report had already stated that European MS policies are rather vague when it comes to the specific support of NZEB and their contribution to achieving NZEB targets. Consequently, a recommendation for a stronger connection between NZEB, MS policies and their corresponding measures had already been made in 2016. When it comes to the lack of standards in particular, the publication stated that more than two-thirds of EU MS already have measures in place to strengthen building regulations and energy performance certifications. In addition to that, a recommendation was made to establish a monitoring mechanism that verifies the fulfillment of NZEB requirements and consider setting up sanctions in case these requirements are not fulfilled [4].

The barrier of local authority design requirements that is common to all three contexts is also addressed, whether implicitly or explicitly, by the MS action plans. In the Dutch Climate Agreement, based on the recognition that an energy transition is not only a technical transition but also a social transition, a district-oriented approach is suggested. It entails the involvements of local residents in the decision-making process and the organization of potential interventions whether they are on a community level or on an individual dwelling level [28]. In the Irish Action Plan, several actions address the role of local authorities among which Action 65 aims to develop and establish a climate-action toolkit and audit framework for Local Authority development planning to drive the adoption of stronger climate action policies [29]. In the Flemish context, revisiting social housing design requirements that prioritize universality to facilitate tenant allocation and giving precedence to efficient designs rather than universality could help the uptake of H4.0E dwellings. Additionally, adopting a different approach in the subdivision of land giving precedence to area development rather than parcel-based could help lift the restrictions on small-scale living and compact construction. In fact, area development was incorporated into the measures listed in the Flemish NECP [35,36]. The fact that these barriers are still being identified despite previous recommendations and efforts to solve them could suggest an imbalance between policy and its implementation as one is moving ahead and the other is falling behind.

Technical policy suggestions

The technology supporting NZEB designs can no longer be considered risky or problematic in itself as it has been implemented and tested numerously in previous studies and projects. This is partly why this study only resulted in the identification of two contextual technical barriers to the implementation and uptake of H4.0E dwellings. The first being the lack of standards was addressed under the legislative policy suggestions highlighting yet another manifestation of the interrelations between the institutional categories. However, in the Flemish context the lack of standards was mentioned specifically regarding the low-embodied carbon and building materials. While a dwelling's embodied carbon has been gaining importance, going beyond guidelines and developing mandatory standards could encourage and facilitate the design, implementation and uptake of NZEB dwellings with a low embodied carbon. The second contextual technical barrier was raised from concerns around the H4.0E dwelling lifespans in comparison with the lifespans of traditionally designed and build houses. This contextual technical barrier can be linked to the foundational barrier of a lack of information around H4.0E designs. To really help the promotion of H4.0E dwellings it is important to make sure that the necessary information is made available to housing professionals. The provision of clear and detailed information around their designs and lifecycle analysis and costs could help overcome the perception that H4.0E or NZEB dwellings have shorter lifespans. Moreover, giving regular updates on design progress, performance and outcomes of similar projects could compensate the uncertainty that often comes with novelty.

Cultural policy suggestions

It is well recognized now that an energy transition or shift entails societal changes as much as it requires a technical one. Thus, the barriers associated with people's perceptions, habits and preferences, be it in a societal setting or a professional one, are some of the first and most common barriers identified in literature. Accordingly, the various measures to facilitate a cultural shift have also already been identified and are well known by now. In fact, the EPBD's 2016 recommendation report had already stated that more than two-thirds of EU MS have in place measures to increase awareness and education around NZEBs [4]. Raising awareness and changing mindsets through the education system is one of the measures listed in the Belgian NECP [35,36]. Similarly, the Irish Climate Action Plan dedicated numerous actions with the aim to increase the knowledge and awareness of people and shift their perceptions and preferences [29]. These include the encouragement and promotion of sustainable communities through the development of innovation champions [23,29]. In other words, champions are volunteers willing and motivated to adopt and promote change be it innovations in industry or new attitudes in society. They can be a source of information to their surroundings. They can set an example and provide constant support. They would be easier to reach and more available and capable of making on the ground impact. Increasing people's level of involvement and decision making power through the district oriented approach is the equivalent Dutch suggestion explained in their Climate agreement [28].

There are several reasons that could explain the fact these well-known cultural barriers persist despite the already established recommendations and measures to overcome them. One of them might be linked to the general approach to understanding and identifying people's reluctance to change. The context-specific cultural barriers identified in this study highlighted different nuances in people's perceptions that vary according to their location. Increasing people's exposure to new dwelling sizes, building materials, construction methods and energy systems is a well-known way to change the negative connotations they associate with small, timber-framed dwellings. However, redirecting the focus of publicity campaigns towards the robustness of timber in Ireland and its durability and resistance to water in the Netherlands could have a more significant impact on people. Promoting self-building is another campaign focus relevant to the Dutch context that could help increase their market uptake. In Flanders, publicity campaigns would focus on highlighting the benefits of small-scale living to contest their associations with container homes and reduce their reluctance to move. Moreover, providing information that highlights the various benefits of H4.0E dwelling designs such as their affordability, energy efficiency and all the resulting energy and cost savings could be a more effective approach complementing the information that focuses on the harm traditional designs and construction can do to the climate. Additionally, finding alternative solutions to people's social daily habits, like the use of the radiator for drying clothes in Ireland, could reduce their reluctance to change. Organizing workshops, trainings or demonstrations to tenants at an early stage to help them shift their established habits linked to traditional building systems and thermal comfort perceptions. Workshops provide tenants the necessary information around the operation of their new technologies. In that way, organizing workshops could prevent the misuse of these technologies and limit additional maintenance costs. This is a well-known measure and it is also being implemented throughout the H4.0E project [31]. Last but not least, organizing workshops on a neighbourhood level is less common but it is another way of keeping people informed, ensuring their involvement in the implementation process and increasing their cooperation on a community level.

2.6 Conclusion

This study's outcomes contribute to the discussion around barriers to NZEBs and nearly zero-energy housing by highlighting the importance of conducting context-specific investigations rather than reaching generalizable outcomes, especially considering that policies and regulations around NZEBs have significantly evolved over the years and are now more detailed and complex. This was done by first tracing the evolution of general barriers to NZEBs by distinguishing between barriers to sustainability measures, barriers to NZEBs and barriers to NZEBs that persisted in 2019. Then it captured the perceptions of the housing industry in three different contexts through its qualitative data collection and analysis leading to the identification of new contextual institutional barriers. Nuances and differences in precedence between the three pilot countries were highlighted, thus allowing the formulation of more specific and context relevant policy suggestions. The policy suggestions provided enable housing professionals including policy makers to tailor corresponding measures and action plans to overcome them.

To reach its outcomes, this study adopted a triangular methodological approach combining desk research, qualitative data collection and qualitative data analysis. Future research can contribute further to the analysis of outcomes and formulation of policy suggestions by complementing this approach and retracing the methodological steps taken through conducting a follow-up interaction with housing professionals. The outcomes presented herein can be foundational and used as a starting point to the structure of interviews or questionnaires. Through this application of the Delphi research method, contextual barriers and solutions can be explored and developed further to achieve effective policy implications. Additionally, while the aim of this study was to highlight the importance of a context-specific investigation hence to focus on its contextual outcomes, a second stage of research can focus on the other more general barriers identified, referred to herein as the barriers that persisted in 2019. The context-specific investigative approach introduced in this paper can be adopted to establish a detailed outline of the development of these general barriers through time in their corresponding contexts through a simultaneous detailed review of context-specific policy documents. The analysis of new contextual outcomes already highlighted a potential gap between policy and its implementation in industry. Adopting a context-specific approach to re-evaluate the barriers that persisted in 2019 would add new context-specific insight into the reasons behind this persistence despite previously formulated recommendations and implemented efforts to overcome them, thus closing the gap. Last but not least, it is worth mentioning that the COVID-19 pandemic happened during the same years the shift to NZEBs was meant to happen. In fact, the pandemic was identified as one of the main reasons behind delayed actions in the recent Irish progress reports. While the pandemic is an undeniable significant barrier to the implementation of H4.0E dwellings and uptake of NZEB, it was not taken into account in the analysis of this study's outcomes. The reason behind its exclusion is the fact that the focus groups that generated this study's data were conducted prior to the pandemic. Therefore, future research on barriers to NZEBs can focus solely on the ones caused by the pandemic to investigate the impact COVID-19 has had on the implementation and uptake of NZEBs.

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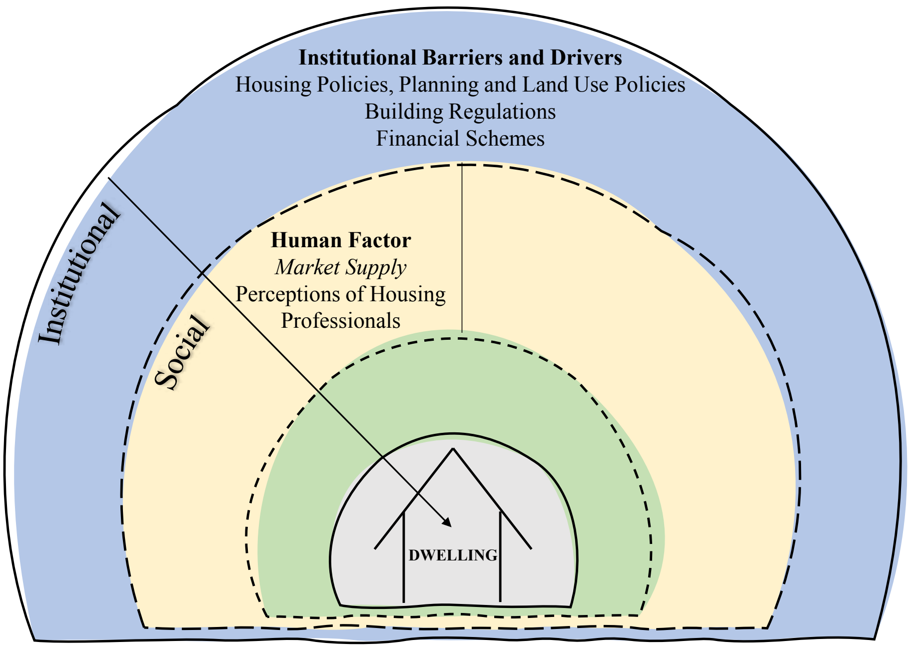
One of the dwellings built in Kilkenny, Ireland as part of the Housing 4.0 Energy (H4.0E) project funded by Interreg North-West Europe. Copyright: South East Energy Agency.

PART 3

STAGE II Social Dimension – Market supply

TOC


Institutional Barriers and Drivers
Housing Policies, Planning and Land Use Policies
Building Regulations
Financial Schemes
Institutional
Social
Human Factor
Market Supply
Perceptions of Housing
Professionals
DWELLING

3 Perceived Barriers to Nearly Zero-Energy Housing

Empirical Evidence from Kilkenny, Ireland

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** Aside from layout changes and minor textual changes, this paper has not been amended for uptake in this dissertation.*

In Chapter 2, the institutional dimension relevant to small, low-carbon, (near) zero-energy dwellings was investigated and both general and context specific legislative, financial, technical and cultural barriers were identified. This led to the formulation of policy suggestions to facilitate and accelerate both the implementation and uptake of said dwellings. Having investigated the institutional dimension, this chapter moves to the investigation of the social dimension, as per this research's conceptual framework. Energy transition studies have repeatedly highlighted the importance of addressing social change alongside technical change for an overall more effective shift to zero energy technologies. Yet, the majority of studies around NZEB have overlooked the potential impact of the human factor in the process of change even more so when it comes to professionals involved in the provision of the dwellings. Thus, this chapter tackles the social dimension relevant to small, low-carbon, (near) zero-energy dwellings by starting with the supply end of the market.

In the introduction section 3.1., the research gap related to the overlooking of the human factor in the provision end of the market is highlighted. In the background section 3.2., an overview of most common barriers to sustainability measures including NZEBs is provided and the factor of perceptions of housing professionals is addressed, both leading up to the study contribution. Section 3.3. presents a review of previous literature addressing the perceptions of professionals by distinguishing their inclusion on an empirical level and on a theoretical level. Section 3.4 explains the research process that allowed the distinction of the perceptions of housing professionals. The research methods section 3.5. explains in detail how through focus groups, follow-up semi structured interviews and a desk study covering governmental policy documentation, barriers identified in Chapter 2 were verified and validated with a focus on the Irish context. Data analysis and results section 3.6. demonstrates the descriptive and inferential coding of transcripts as well as the fact tracing that allowed the explicit distinction between perceived and actual barriers identified by professionals in Ireland. This resulted in a model shift where the perceptions of professionals constitute the obstacle and led to the identification of information dissemination and assimilation as the overarching hindrance impeding the implementation and uptake small, low-carbon (near) zero-energy dwellings which is discussed in section 3.7. This was the basis of further policy implications and recommendations concluding this chapter in section 3.8.

ABSTRACT In 2010, the Energy Performance of Buildings Directive announced that all new buildings are to be nearly zero-energy as of January 2021. Having reached year 2022, it can be said that the transition has proven to be slower than anticipated. Transition research has long acknowledged the potential impact of the human factor in the process of change. While there is a relative wealth of literature on end-users and their perceptions as recipients of change within the demand end of the market, research on professionals and their perceptions as actors in the process of change is limited. Thus, this study looks at the human factor in the supply end of the market by bringing professionals' perceptions to the forefront in its investigation of barriers to the implementation and uptake of nearly zero-energy housing in practice. As part of the project entitled Housing 4.0 Energy: Affordable and Sustainable Housing through Digitization, data were collected through a focus group and semi-structured interviews with housing professionals in Kilkenny, Ireland. Descriptive coding, inferential coding, and fact tracing revealed several identified barriers to be perceptions and not actual barriers to nearly zero-energy housing. Additionally, information dissemination and assimilation between policy and industry was identified as an overarching barrier. Therefore, the paper ends with recommendations to reduce delay factors at the supply end of the market, thus contributing to closing the gap between the development of policies and their implementation.

KEYWORDS nearly zero-energy housing; NZEB; barriers; perceptions; housing professionals; sustainability transition

3.1 Introduction

In 2010, the European Parliament announced through Article 9(1) of the Energy Performance of Buildings Directive (EPBD) 2010/31/EU that all new buildings are to be nearly zero-energy as of January 2021 [1]. Back then, it was assumed that a decade is enough time for policy, industry, and society to assimilate this change [2] and take necessary action to make the transition toward a (nearly) zero-energy built environment. To facilitate this transition, European Member States (MS) were required to submit National Action Plans on nearly zero-energy buildings (NZEBs) at an early stage and to include intermediate targets for 2015. The review of submitted action plans in 2013 already called attention to an initial potential delay in the transition process toward NZEBs [3]. Consequently, in a preventative effort, the Directive required of European MS “a minimum percentage of new buildings” to be NZEBs by 2015 in its publication of recommendations and guidelines on the promotion of NZEBs. The publication even clearly refers to the implementation of NZEBs as an “obligation” stating that “[…] citizens buying newly constructed buildings or apartments in 2021 would expect the market to have evolved in line with these targets and buildings to be NZEBs” (p.L208/51) [4]. Yet, by 2018, notwithstanding the added emphasis on the mandatory compliance and urgency of accelerated action, 24% of European MS still did not have a detailed definition of NZEBs stated in legal documents [5]. Thus, it may well be argued that the transition toward NZEBs has been slower than anticipated even after taking into account the latest required submission of updated National Action Plans in 2019 [6,7]. More importantly, this brings into question why the transition toward NZEBs has proven to be slower than anticipated despite the given decade for preparation and adjustment and the corresponding facilitating measures implemented throughout.

It has been argued and now recognized that energy or sustainability transitions entail societal and cultural changes just as much as technical changes [8-10]. This is reflected in transition research across disciplines where it has long been acknowledged that, to develop a proper understanding of the process of change, research needs to go beyond the particular subject of study and take into account the potential impact of people, otherwise known as the human factor, in their investigations [11,12]. This recognition of the human factor and the potential impact of characteristics such as perceptions, habits, and practices has particularly been growing in energy and sustainability transition research. Studies accounting for and investigating the interrelations between technological and social change are increasing. Within the context of NZEBs, after mono-disciplinary studies plateaued in the technical advancements around the performance of sustainability measures, research was directed namely to the investigation of end-users as the human factor obstructing change. End-users were approached as recipients of change, and studies centered around end-user behavior [9]. This underlines two main research gaps. First, while the assimilation of the role and importance of the human factor has become more common in NZEB research, the focus has been mainly on people on the receiving end, involved in the use of energy measures. Research has focused less on people on the delivering end, involved in the provision of energy measures within the overarching institutional context [9] resulting in fewer studies on the perceptions of professionals involved in the provision of NZEBs. Yet, the societal aspects of the institutional context where a sustainability measure is to be implemented are not restricted to market demand but also include market supply. That is to say, perceptions, habits, and practices are as impactful throughout the provision and implementation processes of sustainability measures as they are throughout their use [9-13]. In addition, it is important to establish a simultaneous understanding of the practices of both professionals and end-users in the study of change [9]. Second, interdisciplinary research argued that changing approaches and considering individuals as *actors* within a system, that is, their surroundings, would provide a better understanding of their practices within the mechanism toward change [13]. The distinction of individuals as *actors for change* from individuals *as recipients of change* maintains the importance of taking into account characteristics underpinning practices, such as perceptions, but it also allows the investigation of the potential impact one has on the other. Most importantly, this reversed approach purposely emphasizes the importance and potentially significant impact of people's actions, underpinned by their perceptions, in the process of change. This is equally applicable to professionals as it is to end-users considering they too could play a pivotal role within that process.

One of the primary and most common approaches to the evaluation of new policies and their implementation is the study of challenges or barriers [14]. In fact, one way to define a barrier is as an explanation for the reluctance to adopt change [12]. This makes the investigation of barriers particularly relevant to studies around energy or sustainability transitions. That said, with an overall aim to unravel the potential impact of the human factor within the provision of NZEBs, this study seeks to address the following main research question: *To what extent do the perceptions of housing professionals affect the identification of barriers to the implementation of NZEBs?*

Section 3.2 of this paper starts by setting the background around sustainability transitions by presenting the literature reviewed on barriers to the implementation and uptake of sustainability measures including NZEBs. It also highlights the predominant overlooking of professionals' perceptions in previous investigations of barriers. Section 3.3 traces the different ways perceptions were included in the few studies that did take them into account. Section 3.4 describes the iterative research process adopted in this study alternating between desk research, data collection, and data analysis. Section 3.5 then presents the research methods behind the qualitative data collection. Section 3.6 describes the different approaches within the data analysis while simultaneously presenting the study outcomes. Section 3.7 discusses these outcomes in relation to previous studies. Section 3.8 covers policy implications, introduces corresponding recommendations, and concludes the paper by highlighting its contribution, identifying its limitations, and providing suggestions for future research.

3.2 Background

3.2.1 General Barriers to Sustainability Measures Including NZEBs

To trace the development of the challenges faced in the implementation and uptake of sustainability measures in general including NZEBs in particular, the literature reviewed deliberately comprised research conducted at different points in time, spanning across different geographical contexts, covering different scopes, and adopting different perspectives (Table 10). With the exception of study number 5, all of these studies investigating barriers to the implementation and uptake of sustainability measures do so in consultation with a wide range of professionals. These include varying combinations of experts in regulation, social housing, local authorities and government agencies, architects, engineers, designers, consultants, developers, (sub)contractors, researchers, teachers, and policy makers. In other words, it can be said that the investigation of barriers to the implementation and uptake of sustainability measures including NZEBs has been extensively covered from all perspectives involved in their provision. What becomes noticeable then is that experts with different professional backgrounds identified a considerable number of similar barriers. Consequently, instead of tracing the development of challenges across time and across policy changes, what became evident through this combination of previous studies is actually the recurrence and persistence of a specific group of barriers despite the different professional perspectives adopted in their investigation. Table 3.1 lists the 10 most common barriers identified in previous literature. In this matrix, the most common barriers are entered as rows and the previous studies as columns (numbered 1 to 25, as they are listed in Table 3.2). An occurrence is marked by an "X" and the total number of occurrences is the addition of these marks. The barrier that has the highest number of occurrences is ranked 1, and the barrier that has the lowest number of occurrences is ranked, in this case, 5. When two barriers have the same number of occurrences, they are given the same rank.

TABLE 3.1 Summary list of studies in the literature review

Study Number	Publiction Year	Study Location	Research Keywords	Research Perspective	Research Methods	Reference
1	2013	Europe	Sustainability, European energy policy, Energy efficiency in buildings	Regulation experts working within academic institutions, private companies, and public authorities such as ministries and energy agencies	Questionnaire	[15]
2	2007	UK	Legislation, Building specifications	Experts within the Royal Institute of British Architects (RIBA) involved in architectural practices in the UK	Questionnaire	[16]
3	2015	Spain	Sustainable urban transformation, Low-carbon transitions	Stakeholders from different levels of decision making with authority or interest in energy matters	Q methodology, interviews, review of relevant literature	[17]
4	2019	Australia	Sustainability transition, Low carbon, Green buildings	Sustainability consultants and advocates, energy and sustainability assessors, architects, and experts involved in teaching and research	Focus groups	[18]
5	2013	Germany	Energy efficiency, Low and zero carbon technologies	Private homeowners of single and semi-detached homes who carried out refurbishment measures	Questionnaire	[19]
6	2019	Chile	Energy policy, Nearly zero energy building	Local experts within the construction industry and the Chilean state including building professionals and researchers [1]	Literature review and focus groups	[20]
7	2018	Interna-tional	Net zero energy buildings	Book—N/A	N/A	[21]
8	2014	Europe	Zero energy buildings	ZEBRA 2020 EU-funded project—N/A	N/A	[22]

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TABLE 3.1 Summary list of studies in the literature review

Study Number	Publiction Year	Study Location	Research Keywords	Research Perspective	Research Methods	Reference
9	2017	Southern Europe	Nearly zero energy building, Net zero energy building	Experts in national nearly zero-energy building regulations	Literature review and questionnaire	[23]
10	2021	Europe	Nearly zero energy buildings, European energy policy	Overview on the progress of the NZEB development in Europe—N/A	Desk study and literature review	[24]
11	2017	Interna-tional	Sustainability, Housing	Experts in the prefab industry including consultants, architects/engineers, builders/subcontractors, developers, and manufacturers/distributors [1]	Literature review and questionnaire	[25]
12	2019	Brighton, UK	Low-energy, Housing	Local and national policy makers, housing associations, researchers, and not-for-profit practitioners	Literature review and expert interviews	[26]
13	2015	Sweden	Low-energy buildings, Passive houses	Experts within construction companies that build low-energy buildings	Interviews	[10]
14	2012	UNECE Region	Low-carbon transitions, Residential buildings	Policy framework	N/A	[27]
15	2016	England and Wales, UK	Sustainability, Zero carbon, Homes,	Practitioners within the Home Builders Federation (HBF) particularly involved in the construction of houses	Literature review and questionnaire	[28]
16	2017	Interna-tional	Barriers to energy-efficient technologies, Building energy	Systematic literature review—N/A	Systematic literature review	[29]
17	2009	England, UK	Barriers, Zero carbon homes	Experts working within house building companies	Questionnaire and semi-structured interviews	[30]
18	2011	England, UK	Challenges, Low carbon, Housing refurbishment	Architects with housing refurbishment experience	Desk study, questionnaire, and semi-structured interviews	[31]

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TABLE 3.1 Summary list of studies in the literature review

Study Number	Publiction Year	Study Location	Research Keywords	Research Perspective	Research Methods	Reference
19	2015	UK	Barriers, Zero carbon homes	Developers, contractors, architecture and design consultants, experts within local authority and government agency with experience in low carbon homes	Semi-structured interviews	[32]
20	2007	England, UK	Barriers, Sustainability, Building	Experts in land use and planning regulations and in development and construction [2]	Literature review and interviews	[33]
21	2020	Interna-tional	Critical barriers, Sustainable housing	Experts in affordable and sustainable housing studies	Literature review and questionnaire	[34]
22	2002	Nether-lands	Institutional barriers, Sustainable construction	Institutions in the building and real estate sector	N/A	[35]
23	2018	Ghana	Barriers, Green building technologies	Engineers, architects, quantity surveyors, and project/contract managers with green building experience	Questionnaire	[36]
24	2017	Singapore	Barriers, Sustainable development	Project managers, consultants, quantity surveyors, design and facilities managers involved in green building projects (including residential projects)	Literature review, questionnaire, and follow-up interviews	[37]
25	2018	Chongqu-ing, China	Barriers, Prefabrication	Experts with experience in off-site construction including professors, contractors, engineer project managers, and design directors	Questionnaire	[7]

1 This study also included three European experts representing Germany, Spain, and Belgium (out of a total of 60 participants). 2 These studies also include end-users; however, the majority of the participants consulted remain experts involved in the field of study.

TABLE 3.2 Most common barriers identified in literature (adapted from [38]).

List of Barriers	Occurrence of Barrier in Previous Studies (Study Number)																									Total	Rank
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25		
Higher costs	X		X	X	X	X		X	X	X		X		X	X	X	X		X	X	X	X		X	X	19	1
Lack of awareness		X	X		X	X	X		X	X		X	X		X	X	X		X	X	X	X	X	X	X	19	1
Lenient building regulations			X		X	X			X			X	X	X	X	X	X	X	X	X	X				X	15	2
Shortage of skills	X	X		X		X	X			X		X	X			X	X		X	X		X		X	X	15	2
Cultural preferences	X		X		X	X			X		X		X	X	X		X		X		X	X		X		14	3
Lack of knowledge	X		X		X	X			X	X		X	X		X		X			X	X		X	X		14	3
Lack of adequate financial incentives		X	X	X		X		X	X	X					X			X	X	X	X	X		X		14	3
Business-as-usual mindset		X	X		X				X			X			X	X	X		X	X	X		X		X	13	4
Uncertainty and risks of innovation	X	X	X			X		X	X		X	X		X	X		X			X	X					13	4
Payback period and return on investment			X			X		X	X				X	X		X	X			X	X			X	X	12	5

3.2.2 The factor of perception

In previous studies on barriers to the implementation and uptake of sustainability measures including NZEBs, the terms perspective and perception are often used interchangeably. Lexically, a perspective is commonly defined as a way of thinking, an angle, or a viewpoint [39] while a perception is defined as a belief that is formulated based on impressions, appearances, and/or how things are seen [39-41]. Generally, perspective is more likely to influence perception. In other words, it can be assumed that individuals with different perspectives are more likely to have different perceptions of things. However, considering that perceptions are based on how things appear to be, the possibility for individuals with different perspectives to have similar perceptions cannot be dismissed. In the context of NZEBs, adopting the definition of perspective as a viewpoint can be translated into professionals constituting one perspective in comparison to end-users. Perspectives can also be more specific and the group of professionals itself can include different perspectives such as experts involved in housing policy, housing design, housing construction, or housing research among others. Distinctively, adopting the definition of perception as a belief that is based on how things appear, the identification of higher costs can constitute a perception in the context of NZEBs when it is based on an impression rather than a proper comparative investigation [26]. Accordingly, while current studies cover various perspectives through professionals with different expertise, the majority do not mention perceptions, and only a few focus on actually capturing the perceptions of professionals in their investigation. In other words, a possible explanation for the reaching similar outcomes despite adopting different perspectives could be the non-distinction between perceived identified barriers and actual identified barriers.

3.2.3 Study contribution

The fact that most of the studies on the barriers to sustainability measures including NZEBs consult professionals in their investigation makes professionals' input significantly deterministic of the recommendations and action plans these studies reach for better implementation and uptake. This only reinforces the importance of investigating and articulating professionals' perceptions in addition to adopting different perspectives. Recalling the importance of the human factor and characteristics such as perceptions in a transition process, a clear distinction must be drawn between the terms perspective and perception in the investigation of barriers to better gauge the latter and reach overall distinct outcomes. With that in mind, this study mainly questions why previous research predominantly undermined the potential impact of professionals' perceptions and has not dedicated a certain amount of attention to developing a proper understanding of them, especially within studies around the investigation of barriers. Considering the slower than anticipated transition toward a (nearly) zero-energy built environment, this paper aims to investigate and identify current barriers to the implementation and uptake of nearly zero-energy housing from the perspective of housing professionals. However, taking into account the role of professionals as actors and the potential impact of their perceptions in the process of change, this paper also aims to bring professionals' perceptions to the forefront throughout its process. It is not restricted to adopting different perspectives of professionals in its investigation but contributes to the discussion around barriers to NZEBs by going further and dedicating special attention to perceptions in the supply end of the market.

3.3 Professionals' Perceptions in Previous Studies

Acknowledging perceptions in the investigation of barriers can have different forms. Within the few past studies that did acknowledge perceptions in their investigations, some distinguished perceptions from perspectives when reporting their outcomes. Others recognized the importance of professionals' perceptions at an early stage, prior to gathering their data, and incorporated it into their methodology. Thus, this paper proceeds by identifying the different ways professionals' perceptions were included in previous studies on the barriers to sustainability measures including NZEBs. Two main categorizations were established, and studies were grouped accordingly.

3.3.1 Inclusion of perceptions on an empirical level

On an empirical level, the most common way perceptions were included in the investigation of barriers to sustainability measures is through an explicit concurrence. This is the case when studies pre-identify barriers at an initial stage of the research based on the existing literature. Then, professionals participate at a later stage where they are asked to rate and/or discuss the pre-identified barriers that are given to them. In these cases, the perceptions captured are mostly around the significance, criticality, and importance of existing barriers [17,18,27,28,35,42]. While it is important to identify the barriers that are perceived to be most obstructive to professionals, this approach can have a limiting effect as it potentially influences professionals' input by providing them with pre-identified barriers from the outset. In other words, issues that have already been identified and addressed by previous studies are being repetitively referred to when there is a need for research to investigate more closely the reasons why previously identified barriers persist and why their corresponding remedial measures have also persistently failed to redress the situation.

Another way of including perceptions on an empirical level is to consider all barriers identified by professionals as perceived. Here, very few studies follow up their data collection phase with a fact-tracing phase. The most common barriers that were linked to professionals' perceptions were higher costs and the risk and uncertainty that are linked to the implementation of novel designs and technologies. In other words, when reporting higher costs as a barrier, it was recognized that professionals identified this barrier based on their impression and not on a thorough investigation of actual costs [26,30,35,37]. More particularly, this was based on the belief that anything outside of business as usual would result in more expenses [26]. In fact, professionals' perception that the business-as-usual approach is adequate enough was identified as a barrier itself in previous research on the implementation and uptake of energy-efficient technologies [37].

3.3.2 Inclusion of perceptions on a theoretical level

On a more theoretical level of analysis, a study on the barriers and drivers to energy performance building labels recognized the potential impact of perceptions prior to their data collection and incorporated it into their methodology. Based on the diffusion of innovation theory, perceptions of housing professionals were linked to the rate of diffusion of the labels arguing that a successful diffusion depends on how advantageous it is perceived rather than on the actual objective advantages. The perceptions of professionals were then gauged through a questionnaire formulated based on this theoretically developed model [43,44]. A study on a city's low-carbon transition focused on professionals' perceptions of themselves in their investigation into the complexity of sustainability transitions and the role and interactions of professionals throughout. The study identified four different conceptual profiles of actors involved in the process of change: the follower, the visionary, the pragmatist, and the skeptic actors. It explained that while the follower believes change is more likely to be achieved following a top-down approach, the visionary believes that formal institutions are failing to address the urgent need for change and that a bottom-up approach supported by energy transition regulatory frameworks is more effective. The pragmatist recognizes the potential impact individuals have in the process of change; however, they accord a higher level of trust to public institutions and governance processes. Finally, the skeptic does not believe climate change is caused by human-related influences and is only driven by economic motives to achieve change. With these distinctions, the study highlighted the extent to which professionals who fall into the follower and skeptic discourse could obstruct others who fall into the visionary and pragmatist discourse and who are key to the initiation of change. Overall, through these four profiles, the study described how the perceptions professionals have of themselves could act as an incentive or as a deterrent to change [36]. Last but not least, an interdisciplinary categorization of theoretical barriers to energy efficiency that reflects the nested hierarchy of the model of socio-technical change repeatedly highlighted the potential impact of professionals' perceptions in the process of change. This impact was most prominent in the barriers that fall under the socio-technical regime category where outcomes are most influenced by the human actors and where the occurrence of change is the slowest. Particularly, the barrier of bounded rationality describes professionals as decision makers who overlook energy efficiency measures based on their embedded knowledge and previously established rules of thumb. Similarly, the barrier of inertia describes how professionals could actively oppose change by falling back on their habits and previously established routines in the workplace in an effort to avoid uncertainty and potential issues which could in turn result in the overlooking of adequate energy efficiency measures [12].

3.4 Research Process

Whether empirical or theoretical, having reviewed the different ways professionals' perceptions were included in previous research, this study engages in the discussion through several means. First, it prevents influencing professionals' contribution by purposely not adopting the explicit concurrence approach. It aims at initially seeking out the raw perceptions and knowledge of professionals around current barriers thus contributing to the need for research to investigate barriers more closely and gaining insight into the reasons behind their recurrence. Second, this study establishes a balance between empiricism and theory by recognizing perceptions throughout its process, from inception through to implementation and analysis of outcomes. Third, it adopts an iterative approach that alternates between desk research, data collection, and data analysis. The research process follows the initial explorative literature review and focus group with fact tracing and semi-structured interviews for the validation and finalization of outcomes. This is what enables the distinction of professionals' perceptions in its outcomes. This is of particular importance seeing as it is these implicit characteristics, namely perceptions, established habits, and embedded knowledge of professionals, that are the most difficult to identify and articulate and yet that could significantly disrupt the process of change [45]. Figure 3.1 depicts this iterative approach by illustrating how the study alternates between desk research, data collection, and data analysis through its different research stages along with a brief description of each stage. The following Section 3.5 describes in more detail the methods implemented throughout.

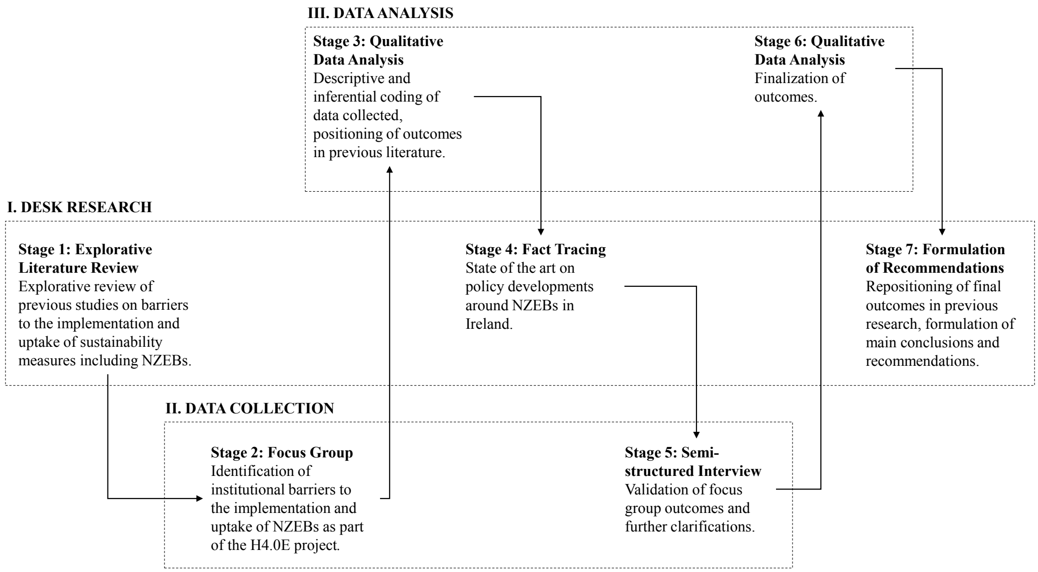

FIG. 3.1 Iterative methodological approach

3.5 Research Methods

3.5.1 Desk research

Overall, a wide range of documents were consulted in this study. In an initial stage, the desk research consisted of an explorative review of the literature to establish an understanding of the development of barriers to the implementation and uptake of NZEBs. For that, three main research concepts were used: institutional barriers, the built environment, and energy efficiency. The main keywords derived from these concepts and used in the search queries are as follows: challenges, obstacles, hindrances, together with building and/or housing and low-energy, low carbon, (near) zero-energy, zero-carbon. The main search engines consulted are Scopus, Google Scholar, and the Delft University of Technology search engine. The main sorting principle that determined whether or not an article was included in this study was the explicit address of barriers in its text. In other words, studies that did not explicitly address barriers in their text were discarded. This selection process resulted in 25 references ranging from academic journal articles and conference proceedings to textbooks. The outcomes of this initial explorative review are presented in Section 3.2.1, Table 3.1, where previous studies are listed according to their year of publication, study location, main keywords, research perspectives, and methods. Figure 3.2 depicts how the collection of keywords used in these 25 references falls within the research concepts of this study. At a later stage, the desk research revolved around establishing the state of the art on policy development around NZEB implementation in Ireland. To that end, different types of documents were consulted such as government publications, reports, and European projects' websites. In total, 7 main documents were referred to. These include the Irish Climate Action Plan, the Irish National Energy and Climate Action Plan, its following quarterly progress reports, the European Commission Assessment Report, and a report published by Ireland's Expert Group on Future Skills Needs.

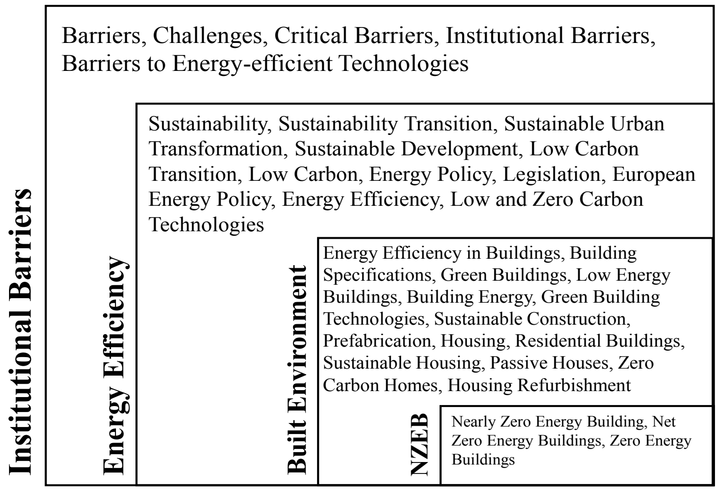

FIG. 3.2 Main research concepts and derived study keywords

3.5.2 Data collection

The qualitative data of this study were collected through the conduction of focus groups and semi-structured interviews as part of a larger ongoing research project entitled Housing 4.0 Energy: Affordable and Sustainable Housing through Digitization (H4.0E) funded by Interreg North-West Europe [46]. Data collection was conducted in Kilkenny, Ireland, and it was carried out between the months of April and December 2019.

Focus Group

Focus groups are recognized to enable the collection of data that are dense in content and rich in details, even more so when the topic addressed is complex and requires a nuanced and granulated understanding [47]. This is particularly valuable to this study where the aim is to capture professionals' perceptions, an implicit characteristic that was found difficult to pin down by previous research. Focus groups are also known to allow participants to openly discuss and share different views on the research topic [48], another aspect that is of value to this study where the aim is to make a clear distinction of perceptions amongst various perspectives.

Focus group participants were recruited by nomination [49] which allowed the selection to include experts representing housing associations, social housing, local and regional authorities, the governmental housing department, financial institutions, and researchers, engineers, and architects in the field. In other words, the focus group gathered decision makers involved in housing regulation, design, implementation, and local and regional provision thus ensuring an overall balanced and representative composition. In the end, a total of 9 housing professionals were present falling within the recommended average range of 8 to 12 participants and not exceeding the maximum of 15 [50]. Table 3.3 provides the different profiles of the focus group participants by listing them according to their expertise, years of experience, and the professional sector they represent. Due to cancellations, developers representing the private housing sector were missing which is recognized as a potential limitation to this study.

TABLE 3.3 Focus group participants

Participant Code	Expertise	Years of Experience	Professional Sector
FGP01	Retail management, Mortgage advisory	15 years	Financial Institution
FGP02	Engineering	12 years	Housing and Planning, Local Government
FGP03	Business management, EU projects officer	23 years	Regional Authority
FGP04	Engineering	Undisclosed	Local Authority
FGP05	Research and organizational development	13 years	Social Housing
FGP06	Architecture	30 years	Construction
FGP07	Property and project management, Building surveying	21 years	Social Housing
FGP08	Building information modeling training and certification	Undisclosed	Design Standards
FGP09	Engineering, energy, and sustainability management	10 years	Non-profit Energy Agency

As previously mentioned, this study did not provide participants with the previously established list of the most common barriers identified throughout the literature review. Both to avoid bias and to allow the generation of new insights, the focus group content consisted of open-ended, explorative, and engaging questions around the following key themes: housing policy, planning and land use policy, financial schemes, energy policy, building regulations and standards, and cultural habits and preferences (Table 3.4). Additionally, the focus group discussion was divided into two rounds. The first round explicitly addressed the current implementation of nearly zero-energy dwellings in Kilkenny. The second round addressed the general upscaling of nearly zero-energy housing within Ireland which entailed a change of location, ownership, tenure type, target group, and income range. With the participants' consent, the focus group discussion was recorded and transcribed, and a summary of preliminary outcomes was created.

TABLE 3.4 Focus group guiding questions

Category	Theme	Focus Group Open-Ended Questions
Institutional Barriers	Housing policy	What are the potential housing laws, regulations or policies that would prohibit/inhibit the realization of nearly zero-energy dwellings?
	Planning and land use policy	What are the planning or land use policies that would hinder/facilitate the realization of nearly zero-energy dwellings?
Financial Barriers	Financial schemes	Which economic policies or financial schemes could prohibit/inhibit the realization of nearly zero-energy dwellings?
Technical Barriers	Energy policy	What energy policies or standards are positively or negatively affecting the implementation of such projects?
	Building regulations and standards	What are the current general and technical building regulations prohibiting/inhibiting the realization of nearly zero-energy dwellings?
Cultural Barriers	Cultural habits and preferences	What are the cultural norms, habits or preferences that would prohibit/inhibit a successful implementation of nearly zero-energy dwellings?
Miscellaneous	N/A	What are the additional barriers or inhibitors faced in the upscaling of nearly zero-energy dwellings?

Semi-structured Interviews

After data were generated from the interactions of the different housing professionals, two follow-up semi-structured interviews were conducted with two H4.0E pilot representatives involved in the implementation of the H4.0E dwellings in Ireland (Table 3.5). Consulting pilot representatives after gathering initial data from external housing professionals explicitly opposed general input gained from industry to input gained based on an existing, ongoing project (H4.0E). This facilitated the distinction between actual barriers and perceived barriers. The interview proceedings enabled H4.0E pilot representatives to clarify and/or validate focus group data, provide more details on the design and construction of the H4.0E nearly zero-energy dwellings in Ireland, and elaborate more on the barriers that are being encountered in the process. The summary of preliminary outcomes was focal to the content of the interviews as the aim was, first, to prevent any misinterpretations and, second, to build upon the data that were collected during the focus group. Accordingly, interviewees were free to build the conversation and the list of interview questions was formulated thereafter, based on the validation or additional clarification of preliminary outcomes. Together with the summary of preliminary outcomes, it was shared two weeks prior giving interviewees enough time to prepare their feedback. The semi-structured interviews were organized in the form of online meetings followed by email exchanges, and with the interviewees' consent, exchanges were transcribed and documented for analysis.

TABLE 3.5 Interview participants' profiles

Participant Code	Expertise	Years of Experience	Professional Sector
SIP01	Energy Engineering	17 years	Non-profit energy agency
SIP02	Architectural Engineering	13 years	Non-profit energy agency

3.6 Data Analysis and Results

This section describes the different stages of the data analysis and gives detailed examples of the reasoning leading to the final study outcomes. It starts with descriptive and inferential coding which focuses on the analysis of the focus group discussion. It then moves to fact tracing where, through another desk study, focus group outcomes were cross-checked with the simultaneous policy developments. Lastly, it presents the validation and clarification of outcomes through the analysis of the follow-up semi-structured interview discussions.

3.6.1 Descriptive and inferential coding

The qualitative data analysis process mirrors this research's iterative approach alternating between data analysis, data collection, and desk research. At the outset, an initial screening of focus group outcomes allowed the recognition of the most common barriers that were pre-identified in the literature review and that recurred in this study. In that way, the pre-identified most common barriers listed in Table 3.1 served as the main thematic groupings throughout what is known to be the *descriptive coding* phase [51]. Descriptive coding was followed by *inferential coding* where second and third data screenings were conducted [51]. The implications of the inferential coding phase were twofold. First, it allowed the identification of barriers implicitly inferred in participants' statement. In some instances, implicit indications of barriers were dominant which is a direct manifestation of the density and high level of detail known to be characteristic of qualitative data [47]. Second, it also highlighted the extent to which barriers are intra- and interrelated to each other. Statement 1 demonstrates how both explicit and implicit barriers can be extracted out of one focus group participant statement.

"The other thing is, we are making houses more airtight, we are bringing mechanical forms of ventilation (but) it is still out there whether that is actually good for the person living in the property. […] I know you mentioned air quality and I don't know the question is out there for me." (FGP06, FG Statement 1)

This statement explicitly manifests an uncertainty and reluctance in the adoption of new technologies. Implicitly, this statement suggests an underlying preference for the business-as-usual approach. Overall, it does imply a potential lack of awareness with regard to the urgency of action when it comes to the implementation of measures to facilitate the transition toward a nearly zero-energy built environment. Following both descriptive and inferential coding, this initial phase of data analysis revealed that all the most common barriers listed in Table 3.1 recurred one way or another in the focus group outcomes. The codebook presented in Table 3.6 demonstrates how these pre-identified barriers extracted from past literature recurred in the focus group. It lists the barriers' codes, descriptions, and corresponding participants' statements. With regard to the number of occurrences, while some would argue that the most significant barriers are the ones that are mentioned the most [10], others state that importance does not go hand in hand with frequency. There are barriers that, although not as frequently mentioned, would lead to a significant obstruction to the implementation of a sustainability measure when they occur [26]. As such, significance is not attached nor restricted to frequency in this study. Nevertheless, the number of comments per barrier is included in Table 3.6. Overall, this presentation of results sheds light on the fact that previously known factors or challenges to the implementation of NZEBs were still perceived as challenging in 2019. More importantly, keeping in mind that the pre-identified list of barriers were not disclosed to participants, this supports the assumption that a possible explanation to the reaching similar outcomes could be the non-distinction between perspectives and perceptions of housing professionals.

TABLE 3.6 Codebook for the analysis of focus group transcripts (adapted from [38])

Barrier	Description	Example statement	Number of comments
Higher costs	Additional costs of implementing sustainability measures compared to standard construction and measures imposed by current policy and regulations (includes hidden, maintenance, and conservation costs).	"[…] you do not get funding for exceeding building regulations […]." (FGP03)	31
Lack of awareness	The event when people, be it end-users or professionals, do not realize the magnitude of climate change consequences and the urgency of action. It can be manifested as a lack of demand for sustainability measures.	"I think that the need for housing at the moment is pushing everything on at a particular speed and the urgency to get houses built and to get people into houses." (FGP02)	10
Lenient building regulations	Less stringent current regulations that do not require the sustainability measure in question.	"You are expected to meet building regulations, you can exceed them but this becomes like any other project […] based on an individual basis [...]." (FGP03)	5
Shortage of skills	Concerns the implementation of sustainability measures within the construction sector. Includes the lack of training.	"After the last downturn, we lost a lot of skills." (FGP06)	17
Cultural preferences	Unwillingness to stray away from traditional designs, technologies, or materials and accept or adopt new ones.	"[…] there is a mind-set about timber frame in this country." (FGP04)	17
Lack of knowledge	The non-consideration of sustainability measures that go beyond existing policies and regulations generally associated with a lack of interest in sustainability.	"We are building to building regulations as far as we're warranted [...]" (FGP07)	8
Business-as-usual approach	Applicable when the decision making is based on established rules of thumb due to the reluctance to go beyond what is already known or required by current policy and regulations.	"The department of housing in the government is more focused on traditional construction." (FGP02)	11
Uncertainty and risks of innovation	Reluctance to adopt new methods and designs and use new materials and technologies due to insufficient testing and lack of experience in implementation, maintenance, and management.	"New innovative technologies and techniques means unforeseen issues." (FGP05)	13
Lack of adequate financial incentives	Reluctance to loan partly reinforced by insufficient testing and lack of supporting evidence resulting in the absence of adequate and supporting schemes.	"We cannot give money upfront unless the architect or engineer signed off and works have been completed." (FGP01)	13
Payback period and return on investment	Specifically applicable to developers or investors including financial institutions.	"If the first thing they learn is that the value of their security will be 0 in 15 years that will have a big bearing on their willingness to lend against the property." (FGP03)	18

3.6.2 Fact tracing

At this stage of the study, it was important to establish an updated understanding of the state of the art with regard to the most recent policy developments around measures addressing the transition toward NZEBs. Accordingly, the descriptive and inferential coding phase was followed by a fact-tracing phase [21]. The particular focus of this second desk research was government proceedings, reports, and websites that are most relevant to the development of NZEBs within the Irish context [3,52-54]. Statement 2 demonstrates how focus group participants stated that current building regulations are not established as per a nearly zero-energy performance. This was identified as a potential barrier since aiming for zero energy is not mandatory.

“You are expected to meet building regulations, you can exceed them but this becomes like any other project it is assessed based on an individual basis.” (FGP03, FG Statement 2)

However, referring to governmental proceedings, the Irish National Energy and Climate Action Plan (NECP) states that, starting the first of November 2019, all new dwellings will be built to NZEB standards. The implementation of more stringent building regulations is mentioned again under existing measures [52]. Additionally, Action 56 of the Irish Climate Action Plan concerning the publication of “a methodology for compliance to NZEB in all new buildings” was reported as complete in the first progress report covering all actions within quarters 2 and 3 of 2019 [53]. Thus, it could be argued that this barrier is perceived rather than actual considering it contradicts the policy developments that were occurring simultaneously. In turn, this perception itself becomes the barrier to the implementation and uptake of NZEBs.

By adopting the same approach, the opposite can be said about the shortage of skills barrier as it can indeed be categorized as an actual barrier according to most recent policy documents (FG Statement 3).

“After the last downturn, we lost a lot of skills.” (FGP06, FG Statement 3)

Even though the shortage of skills has been addressed in the Irish Climate Action Plan and the Irish NECP [52,55], it was still recognized as constraining in the 2020 assessment report of the European Commission [56]. This was also confirmed by Ireland’s Expert Group on Future Skills Needs in 2020 which indicates that this barrier persists [57]. In that manner, fact tracing weighed in on the distinction between barriers that have already been addressed in policy documents and existing barriers that remain to be addressed. Accordingly,

Table 3.7 lists barriers that were addressed in Irish policy documents by providing the corresponding references and listing the policy action numbers where applicable. It also provides the justification such as an example of the corresponding policy measure to address the barrier in question. It states its latest policy status, where applicable, all leading to its final classification as a perceived or actual barrier. Considering the intra- and interrelations between all barriers, in some cases, there are several actions or measures that address a single barrier. In other words, the classification of barriers as actual or perceived is not a straightforward process as it entails a combination of measures acting together. However, this process still allows the formation of a preliminary understanding on the balance between housing professionals' perceptions and current policy developments.

TABLE 3.7 Perceived versus actual barriers addressed in Irish policy and other official documents

Barrier	Refs*	Action	Justification	Status **	Outcome
Higher costs	1–5	N/A	The European Commission requires the determination of NZEB regulations based on the cost optimization method. This requirement has been addressed in several EU MS action plans.	N/A	Perceived
Lack of awareness	6	68	Promote awareness and understanding of EPC [1] and provide Project Assistance Grants, training, and other support to public and private sector organizations to implement EPC projects.	Ongoing	Actual
Lenient building regulations	6	56	Measure: publish methodology for compliance with NZEB in all new buildings.	Complete	Perceived
Shortage of skills	6	50	Support relevant professional bodies in the development of training specifications/courses for the design of NZEB and deep retrofit buildings.	Ongoing	Actual
Uncertainty and risks of innovations	7 and 8	N/A	The technology behind NZEBs is available and proven. Technology is going even further, and the main focus now is shifting toward energy-plus buildings that contribute to energy generation rather than break even.	N/A	Perceived
Lack of adequate financial incentives	6	44, 54	Establish a Steering Committee and Working Group to design a new financing scheme to provide easier-to-access tailored finance for SMEs [2] and residential energy efficiency investment utilizing the European Commission's Smart Finance for Smart Buildings loan scheme.	Complete	Perceived
Payback period and return on investment	6	45	Develop a tool to deliver a roadmap to individual homes to achieve BER [3] B2, cost-optimal, and NZEB.	Complete	Perceived

** 1: [3], 2: [4], 3: [58], 4: [52], 5: [59], 6: [60], 7: [6], 8: [61]. ** The focus group was conducted in April 2019. Accordingly, the statuses of actions mentioned in this table were based on the progress reports published in 2019. 1 EPC: Energy Performance Contracting. 2 SME: Small and Medium Enterprise. 3 BER: Building Energy Rating.*

3.6.3 Validation and clarification of outcomes

As previously mentioned, interviewing H4.0E pilot representatives enabled input that is based on actual current experiences happening during the H4.0E project. Consequently, the data collected at this stage of the research process allowed a straightforward identification and/or confirmation of *actual* barriers. For example, interview statement 1 is an indication of the general lack of knowledge barrier amongst housing providers manifested through the non-consideration of sustainability measures that go beyond existing policies and regulations at the time. This renders the lack of knowledge an *actual* barrier to NZEBs. Implicitly, this statement also indicates a general lack of awareness on the urgent need to shift toward a zero-energy built environment that is manifested through that same lack of effort in exceeding the mandatory requirements. Thus, this reconfirms a lack of awareness as another *actual* barrier to NZEBs.

"In this Technical Guideline (TGD) is outlined a minimum standard that all buildings must comply with. Unfortunately, the LAs (local authorities) took and take this minimum requirement as a benchmark." (SIP01, IW Statement 1)

Other examples can be found in interview statement 2. On the one hand, this statement is an explicit example of the extent to which the reluctance to adopt innovative measures of design or construction obstructs and delays the project implementation. It is a direct manifestation of the perception of uncertainty and risks linked to innovation rendering this barrier a *perceived* barrier to NZEBs. On the other hand, it also exposes the business-as-usual approach and its potentially obstructive effect amongst individuals in the sector rendering it an *actual* barrier to the implementation and uptake of NZEBs.

" […] individuals do not want to be held responsible if a new type of design fails, so they are very cautious […]. Even it would be in their favour […]" (SIP02, IW Statement 2)

Overall, the iterative research process followed in this study and the combination of methods implemented succeeded in distinguishing the perceptions of housing professionals. It differentiated between barriers that are based on perceptions and actual barriers. Table 3.8 demonstrates how both perceptions and actual barriers were validated by pilot representatives in the semi-structured interviews by listing barrier codes, descriptions, and participant statements. Table 3.9 provides a summary of this study's outcomes where it can be seen that more than half of the most common barriers that recurred in focus group outcomes were based on perceptions and were not actual barriers.

TABLE 3.8 Codebook for the analysis of semi-structured interviews transcript

Barrier	Description (Listed in Table 3.1)	Example statement	Outcome
Lack of awareness	The event when people, be it end-users or professionals, do not realize the magnitude of climate change consequences and the urgency of action. It can be manifested as a lack of demand for sustainability measures.	"Even it would be in their favour it takes a lot of time and effort to […] convince the LAs for adapting highly efficient, low energy and low carbon options […]" (SIP02)	Actual
Cultural preferences	Unwillingness to stray away from traditional designs, technologies, or materials and accept or adopt new ones.	"Even the fact that the quality of recent build timber construction is up to a high-quality standard the old picture of a failed timber frame house is shaping the behavior and opinion." (SIP02)	Perception
Lack of knowledge	The non-consideration of sustainability measures that go beyond existing policies and regulations generally associated with a lack of interest in sustainability.	"In this Technical Guideline (TGD) is outlined a minimum standard that all buildings must comply with. Unfortunately, the LAs (local authorities) took and take this minimum requirement as a benchmark." (SIP01)	Actual
Business-as-usual mindset	Applicable when the decision making is based on established rules of thumb due to the reluctance to go beyond what is already known or required by current policy and regulations.	"[…] we need to take on extra time and effort to convince the responsible auteurs to take on better values and to invest in future proved buildings" (SIP01)	Actual
Uncertainty and risks of innovation	Reluctance to adopt new methods and designs and use new materials and technologies due to insufficient testing and lack of experience in implementation, maintenance, and management.	" […] individuals do not want to be held responsible if a new type of design fails, so they are very cautious […]. Even it would be in their favour […]" (SIP02)	Perception

TABLE 3.9 Summary table of outcomes

Barrier	Method		Outcome
	Fact Tracing	Follow-Up Interviews	
Higher costs	X		Perception
Lack of awareness	X	X	Actual
Lenient building regulations	X		Perception
Shortage of skills	X		Actual
Cultural preferences		X	Perception
Lack of knowledge		X	Actual
Business-as-usual mindset		X	Actual
Uncertainty and risks of innovation	X	X	Perception
Lack of adequate financial incentives	X		Perception
Payback period and return on investment	X		Perception

3.7 Discussion

3.7.1 A shift in the model composition: Housing professionals' perceptions as the obstacle

In an investigation of barriers, one can distinguish three main features composing the overall barrier model: the obstacle, the subject, and the action. The obstacle is defined as the obstructive entity, the subject consists of the entity that is affected by the obstruction, and the action comprises the phenomenon that is being prevented [12]. In this study, implementing and upscaling nearly zero-energy housing would qualify as *the action*. This action would have an impact on the environment altogether which includes virtually everyone rendering all people the *subject* of obstruction. The consultation of housing professionals in the process of identifying barriers, or *obstacles*, insinuates they are an objective and external entity to the model composition, unaffected by or unaffecting the overall investigation. While this research approach does generate valuable insight on the transition process, shifting the model composition and looking at housing professionals as a subjective element with subjective perceptions having the potential to become obstacles themselves reveals an entirely different list of impediments. This study allowed the distinction of these perceptions and demonstrated several times over how a shift in approach could potentially lead to a change in outcome.

In this study, the barrier of higher costs that describes concerns around the extra costs specific to nearly zero-energy housing due to all the added energy efficiency measures and that underlines a trade-off between energy performance and affordability is a manifestation of participants' perceptions because it was formulated with reference to the costs of traditional dwelling designs as a benchmark. Instead, if the costs of new-build housing designs complying with the soon-to-be mandatory building regulations were considered as the benchmark, higher costs may not have been identified as a barrier. Additionally, the affordability of new-build nearly zero-energy housing is currently being addressed in policy documents and the development of NZEB regulations [4]. This echoes findings from previous studies recognizing this same barrier as based on an impression rather than an investigation of actual costs [26,30,35,37]. The barrier of uncertainty and risks of innovation that describes in this particular study participants' concerns around airtightness and mechanical ventilation systems was revealed to be a manifestation of perceptions. Current research has surpassed uncertainties about technologies within nearly zero-energy housing, and the literature is now focusing on energy-plus housing [61]. The barrier of lenient building regulations that portrays nearly zero-energy housing as exceeding current mandatory requirements was also revealed to be a perception seeing as policy documents state that NZEB regulations are to be enacted starting the second half of 2019 [52]. Additionally, focus group statements describing lenient building regulations or governmental entities giving precedence to housing provision rather than a zero-energy performance can be said to portray a dependence of housing professionals on higher authorities. Recalling the follower-type depiction of professionals, this becomes a manifestation of professionals' perception of themselves believing that change is more likely to be achieved following a top-down approach. This was identified as a cognitive barrier itself in previous research [36]. Overall, given that these barriers, or perceptions, persist despite research and policy documents stating otherwise is an indication of the strength of the overarching preference for the business-as-usual approach, another finding that echoes previous study outcomes [26,37]. In fact, this recalls the theoretical barriers of bounded rationality and inertia that describe professionals falling back on previously established knowledge, resisting change to avoid uncertainty, potentially resulting in the overlooking of adequate energy efficiency measures [12].

3.7.2 The overarching barrier of information dissemination and assimilation

This study's data collection was conducted throughout the year 2019. On a general level of analysis, it can be said that housing professionals were consulted about the implementation and uptake of nearly zero-energy housing in the same time frame as corresponding policy and regulations were being developed [60]. Relevant dates around the implementation of NZEB regulations and construction were already released. Even when final documents were still in progress, drafts and draft assessments were being published. In other words, NZEB information was available regardless of whether or not it was still under review, and it was only a matter of months before the NZEB regulations were enacted. This parallelism underlines a potential gap between (inter)national policy makers and local practice. It suggests a lack of awareness and knowledge of the soon-to-be mandatory, more stringent building regulations. The fast development of technology potentially leading to the unawareness of professionals has already been flagged by previous research as impeding the "future success of delivering a more sustainable built environment" ([26], p.144). Indeed, an earlier study on the feasibility of zero-carbon homes marked a 6-year gap between industry's expectations and actual policy goals when asking professionals about their perceptions on a realistic timeline for the transition

[17]. Another study attributed the increasing gap between industry, technology, and policy to professionals' perceptions of their own overestimated level of knowledge on current designs and technologies [36]. In hindsight, this begs the question: Is the gap between policy developments and local practice caused by a lack of awareness of housing professionals and a persistence of the business-as-usual approach? Or does the overarching barrier behind this gap lie within information dissemination? Or perhaps a combination of both? What is certain is that a successful transition toward a nearly zero-energy built environment requires policy and industry to coincide. While a top-down approach has been recognized as most effective for the implementation of new regulations, the current gap suggests that it might not be enough and highlights a potential flaw in how information is being transferred.

3.7.3 The role of information dissemination in a transition process

The importance of information dissemination and the critical role it plays in a transition process has been raised in many previous studies. Corresponding measures and recommendations have already been identified and previously formulated [12, 22, 23, 62, 63]. However, the majority of these recommendations were initially directed at end-users, and very few in comparison had housing professionals as their target audience. Meanwhile, the transfer of information, new policies, and regulations to relevant housing professionals can be as challenging as the transfer of information to end-users [7]. Intensive knowledge transfer between housing professionals is known to be essential to achieve actual rather than incremental change [64], even more so when recalling the fragmented decision-making process present in complex sustainability transitions such as the shift toward a zero-energy built environment [25]. Thus, a lot can be learned if these same findings were directed toward housing professionals. For instance, when it comes to learning new information, it is argued that people are selective about which information to accept and assimilate. They are passive rather than active information seekers [12]. Keeping in mind the fast-developing technologies/policies and the overwhelming amount of information available, looking at this study's outcomes through this lens could explain why focus group participants were potentially not up to date with the latest policy developments around NZEBs. Another example concerns the rational-actor assumption that accounts people as actors who respond rationally to the information that is made available to them. Previous research on end-user behavior revealed that reasoning is ineffective [62]. Within the context of this study, this could justify why the lack of awareness of housing professionals is still a barrier even though the NZEB concept was introduced more than a decade ago and the urgency to transition toward a zero-energy built environment is continuously increasing. Last but not least, research on end-users' decision-making process suggested that a timely and measured integration of information provision throughout the process is most effective for the actual implementation of desired outcomes [22]. Within the context of this study, the absence of key actors to effectively transfer the most recent policy developments could explain the desynchronization between policy developments and the knowledge and awareness within local practice.

3.8 Conclusion and Policy Implications

3.8.1 Policy implications and recommendations

All in all, there is a need for innovation in information dissemination within the provision end of the market be it on a general level between policy and local practice or on a more detailed level between housing professionals themselves. Maintaining the shift in model composition and referring back to the insights gained from previous research directed at end-users leads to the formulation of several suggestions specific to housing professionals and the provision of NZEBs. First, the provision of NZEB information should be more consistently and systematically linked to concrete situations and/or opportunities in a particular context. Just like information provision should be integrated into end-users' decision-making process [22], policy and regulatory information provision should be integrated into the process of new housing provision through the inclusion and training of key intermediaries. These trained experts should be incorporated at key decision-making moments that local authorities, social housing associations, private developers, or other housing professionals encounter throughout the process of housing provision.

Second, recalling the formulation of information that is vivid, clear, concise, and customized to the specific context in question [12, 22, 23, 62, 63], the distributed NZEB information should be personalized and tailored to the situational context of its targeted audience for a more impactful dissemination. Within the communication channels amongst housing professionals, this would entail varying necessary NZEB information to fit the professional field it is addressing. Just like the successful diffusion of labels for highly efficient housing required a formulation that is contextually compatible with the professionals implementing them [43], policy regulations and expert knowledge need to be actively translated to tailor the expertise and interests of the targeted audience of housing professionals: architects, engineers, contractors, developers, and local authorities, among others. Thus, the training of intermediaries would not only cover NZEB-related information and regulation but also communication skills to develop the ability to address different housing professionals according to their different interests and goals. Additionally, developing an understanding of housing professionals' different expertise and interests is of particular importance in the attempt to overcome the challenging, complex, and fragmented decision-making process that occurs in practice when implementing NZEBs.

Third, referring back to the introduction of sustainability champions that would increase the likelihood of creating an environmentally aware community [22, 62, 65], the number of NZEB practices should significantly increase through industry advocates or pilot projects within local authorities. If the rational-actor reasoning is applied to housing professionals, it can be expected that the availability of information on NZEB design, benefits, regulations, and the overall urgency of action would provoke concern and result in the smooth adoption of the relevant changes. However, focus group outcomes revealed the prevalence of the business-as-usual approach despite very soon to be mandatory regulations, an occurrence confirmed by previous research stating that raising awareness is not enough to change long-established perceptions and habits [62]. Thus, implementing the reverse hypothesis that starts with the implementation of environmental practices underlines the need for a bottom-up approach to work in tandem with the top-down regulations. In other words, imposing new regulations alone on housing professionals is not enough, and there is a need to simultaneously shift the business-as-usual approach through industry advocates and pilot projects to achieve a successful transition of the industry as a whole. This reversed approach would particularly help increase the likelihood of raising openness within housing professionals to more effectively integrate NZEB information.

3.8.2 Concluding remarks

The main aim of this paper was to demonstrate the importance and potential impact of the perceptions of professionals involved in the provision of NZEBs when identifying barriers to their implementation and uptake. In doing so, this study's engagement in the discussion of energy or sustainability transition is twofold. On a general level, not only did this study recognize the importance of the human factor in the process of change, but it also incorporated it in its investigation. Through its shift in model composition, individuals were involved as actors and not just recipients within the process of change. On a more specific level, this study contributed to narrowing the research gap around experts' behavior within the context of NZEBs by setting the perceptions of professionals as the focal point of its investigation of barriers to the implementation and uptake of nearly zero-energy housing.

Falling back on this paper's main outcomes, more than half of the identified barriers were revealed to be perceived and not actual barriers. That is to say, the explicit distinction of the factor of perception throughout the study's iterative research process did indeed succeed in articulating housing professionals' perceptions. First, purposely choosing not to adopt the explicit concurrence approach in the identification of barriers allowed the prevention of bias when gauging professionals' current knowledge and perceptions around existing barriers to the implementation and uptake of nearly zero-energy housing. Second, following up the qualitative data analysis with fact tracing allowed the establishment of an updated understanding of the state of the art with regard to the most recent policy developments addressing the transition toward NZEBs. This initiated the distinction between perceived and actual barriers. Namely, the barriers of higher costs, lenient building regulations, cultural preferences, uncertainty and risks of innovation, lack of adequate financial incentives, and the payback period and return on investment barriers were identified as perceptions and not actual barriers. Third, seeking out input from professionals involved in an ongoing project led to the validation of outcomes such as the negative perception of innovative sustainability measures or designs translated into the uncertainty and risks of innovation barrier. It also allowed the validation of overarching barriers such as the lack of awareness, the lack of knowledge, and the strength of the business-as-usual approach. Last but not least, distinguishing the factor of perception within the identification of barriers shed light on a potential significant gap between policy developments and local practice indicating an overarching potential barrier to information dissemination and assimilation. Thus, this paper called for innovation in information dissemination be it between policy and industry or between housing professionals themselves which in turn was the focus of the suggestions and recommendations formulated.

Finally, though insightful, this paper's outcomes are specific to the study context in question. Considering the scarcity of research on the human factor in the supply end of the NZEB market, precedence was given to identifying professionals' perceptions and to demonstrating their potential impact on the identification of barriers to nearly zero-energy housing. Rather than increasing sample size for more generalizable outcomes, the paper takes a closer look into the detailed qualitative data collected from a small sample. This is what allowed the distinction of perception, an implicit characteristic that is initially difficult to identify and articulate. Thus, having established this initial demonstration, future research can build upon this study to investigate professionals' perceptions across larger samples and within different contexts.

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Institutional Review Board Statement: Ethical review and approval were waived for this study due to the following reasons:

- The study did not include participants who were unable to provide informed consent.
- No videos, pictures or other identifiable data are stored.
- The study did not include participants that are in dependent positions to the investigator.
- It was not necessary for participants to participate in the study without their knowledge or consent at the time.
- The study does not actively deceived participants.
- The study does not collect personal sensitive data such as financial data, location data, data relating to children or vulnerable groups.
- No substances are used in the study, no blood or tissue samples are taken, no pain is inflicted as a result of the study and the study does not risk causing psychological stress or anxiety.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

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Render of the dwellings built in Huldenberg, in Belgium as part of the Housing 4.0 Energy (H4.0E) project funded by Interreg North-West Europe. Copyright: Province of Flemish Brabant.

PART 4

STAGE II Social dimension – Market Demand

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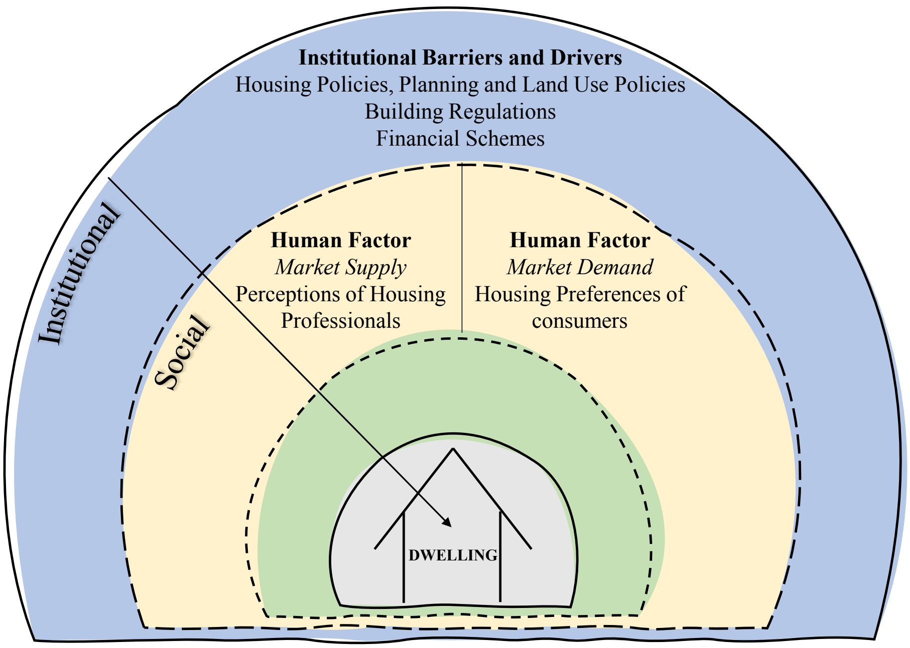
Institutional Barriers and Drivers
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4 The Demand for Small, Low-Carbon, Zero-Energy, Timber Dwellings

A Study of Consumers’ Stated Housing Preferences

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** This chapter is under review at the time of writing this manuscript.*

In Chapter 3 the social dimension relevant to small, low-carbon, (near) zero-energy dwellings was investigated from the supply end of the market. The distinction between actual and perceived barriers revealed a shift in the model composition where professionals’ perceptions are the overarching obstacle. This confirmed the significant impact of the human factor in the process of change. Having covered the social dimension from the supply end of the market, this chapter investigates the social dimension relevant to small, low-carbon, (near) zero-energy dwellings from the demand end of the market. Recalling that smaller, low-carbon, (near) zero-energy dwellings are being proposed as a solution that would not only answer to sustainability concerns but also address latest housing market developments, this chapter investigates the extent to which such dwellings fulfil consumers’ current housing preferences. Through the distribution of housing preferences questionnaire in Zoutleeuw, Huldenberg and Bertem in Belgium and Almere in the Netherlands, it tests the main assumption stating that current housing preferences are also shifting towards smaller dwellings due to an increase in the number of smaller households of one to two persons, elderly households and lower income households.

The introduction section 4.1. lays the foundation leading up to the proposed solution of smaller, low-carbon, (near) zero-energy dwellings. The following section 4.2. elaborates on literature pertaining to the evaluation of housing preferences. The method and materials section 4.3. provides a brief introduction to the H4.0E project within which this research is conducted (4.3.1.). It also lays out the reasoning behind choosing for the multi-attribute utility method (4.3.2.) which was foundational to tailoring the housing preferences questionnaire (4.3.3.). The results are described in detail in section 4.4 ranging from sample characteristics (4.4.1.), to respondents' current housing situation (4.4.2.), factors affecting housing preferences (4.4.3.) and MAUT outcomes (4.4.4.). Results are then discussed in section 4.5. and concluding remarks are made in section 4.6.

ABSTRACT In line with the decarbonization plan by 2050, small, low-carbon, zero-energy timber dwellings are being proposed as a solution to the growing housing shortage in Europe. Based on the increase of smaller, elderly and low-income households, it is assumed that demand is also leaning towards smaller dwellings. This contribution tests this assumption from the consumer's perspective. The Multi-Attribute Utility Theory served as the framework for the housing preferences questionnaire that was distributed in Almere (NL), Huldenberg, Zoutleeuw, and Bertem (BE). Overall, there is no demand for the smallest timber dwellings of 50 m^2 or less. However, the analysis of trade-offs emphasized the importance of distinguishing between smallest versus smaller dwellings. Significant differences in preferences were traced between one and two-person households suggesting that smaller dwellings are likely to satisfy single-households. The elderly manifested a preference for ageing in place significantly influenced by their status as owner occupiers and lower income households are more likely to make concessions around dwelling size.

KEYWORDS small housing; timber housing; housing preferences; multi-attribute utility theory

4.1 Introduction

The built environment is widely acknowledged as a significant contributor to climate change, accounting for over 30% of global greenhouse gas emissions. The building sector has been identified as a crucial element in achieving the goal of net-zero CO_2 emissions by 2050, as recognized by the International Energy Agency and the Intergovernmental Panel on Climate Change (IPCC) (IEA, 2022; IPCC, 2022). However, recent studies assessing progress towards decarbonization by 2050 have indicated that the built environment is falling behind, with a widening gap between the sector's actual performance and the decarbonization pathway outlined by experts (United Nations Environment Programme, 2022). Moreover, the United Nations Habitat estimates that, in order to meet the growing demand for housing, approximately 96,000 new housing units will be required every day by 2030 notwithstanding the fact that housing already constitutes the largest segment within the building stock (Golubchikov & Deda, 2012; UN-Habitat, 2022). Given the slower-than-anticipated response of the built environment to decarbonization efforts coupled with the growing housing shortage, the focus of building-related mitigation strategies has shifted towards prioritizing sufficiency policies. These policies primarily aim to minimize the demand for energy, materials, and other resources while still fulfilling people's wellbeing (IPCC, 2022). In the context of new-build housing, sufficiency policies entail going beyond the now mandatory requirement of zero-operational energy and emphasize the reduction of embodied energy. This translates into downsizing new-build dwellings and designing smaller dwellings that have both a zero-energy consumption and a lower embodied carbon through the use of more sustainable material such as timber (Cabeza, 2022). Consequently, from a sustainability perspective, the proposed solution is the pursuit of smaller, low-carbon, zero-energy dwellings.

From the housing market perspective, substantial structural shifts in economic conditions, demographic characteristics, and social attitudes had a significant impact on household composition and life trajectories beyond the 21st century. For instance, the 2008 economic crisis altered income distributions across advanced economies in Europe and reinforced social exclusion through increasing income inequalities (Beer, Faulkner, Paris, & Clower, 2011; OECD, 2023). Higher life expectancies and declining fertility rates rendered elderly people one of the fastest growing segments of the population (Beer et al., 2011). A combination of higher separation rates, different household formation patterns and diverse household compositions led to the increase of smaller households composed of one to two persons which now account for nearly two-thirds of all European households (eurostat, 2022).

These particular developments are believed to have changed the nature of housing demand whereby smaller households would prefer smaller dwellings either as a trade-off for lower housing costs or for lower maintenance and more accessibility. In other words, based on these developments, it is suggested that housing demand may also shift towards smaller dwellings while market supply has been continuously overlooking this shift (Mulliner & Algrnas, 2018; Pittini et al., 2017). Thus, from the housing market perspective, smaller dwellings are also presented as a solution to the increasing housing shortage.

Building upon this proposed solution of smaller, low-carbon, zero-energy new-build dwellings from both the sustainability and the housing market perspectives, this study aims to investigate whether or not there is a demand for such dwellings from the consumer's perspective. To that aim, this study addresses the following main research question: *To what extent do smaller, low-carbon and zero-energy dwellings fulfil current housing preferences?* This paper is part of a broader study that explores the potential of a shift to smaller, low-carbon and zero-energy dwellings. It draws upon the findings of the *Housing 4.0 Energy: Affordable & Sustainable Housing through Digitization* (H4.0E) project funded by Interreg North-West Europe which involved the construction of small, low-carbon, zero-energy timber dwellings in Almere, the Netherlands and Flanders, Belgium as well as the exploration of their upscaling potential in Europe (NWEurope, 2021).

The following section elaborates on literature pertaining to housing preferences with a focus on distinguishing the different types of housing preferences and identifying the different factors affecting them. Then, the H4.0E project is introduced and the Multi-attribute Utility Theory method, which served as the framework for developing the customized questionnaire employed in this study, is presented. This is followed by the outline of outcomes and the discussion. Finally, the last section concludes this paper with final remarks on the implications and contributions of this study's findings.

4.2 Housing Preferences Research

4.2.1 Categories of housing preferences

Housing research distinguishes two main categories of housing preferences; revealed preferences and stated preferences (Boumeester, 2011). By definition, revealed preferences are based on a household's current housing situation and actual housing choices whereas stated preferences reflect the household's hypothetical likings (Hasu, 2018). When evaluating a household's revealed preferences, the assumption is that their housing decisions and consumption are a result of the fulfilment of unconstrained preferences. Yet, due to market constraints, especially in supply-led housing markets where the influence of consumers is limited, actual choices do not necessarily reflect preferences. A household's housing consumption or actual choice becomes more a product of trade-offs and adjustments that reflect the housing market conditions rather than absolute personal preferences (Boumeester, 2011; Hasu, 2018). Ideally, households would be able to adhere to their stated housing preferences; however, in reality, trade-offs are often necessary due to constraints imposed by the housing market (Boumeester, 2011). Mostly, households with more affluence and time have the privilege to hold on to their stated preferences whereas more vulnerable households experience more pressure and end up compromising their stated preferences and accepting the housing options that are available to them (Hasu, 2018).

By distinguishing these different categories of housing preferences, the disparity between the concepts of choice and preference becomes more explicit. Stated housing preferences reflect the degree of attractiveness assigned to a house while revealed preferences reflect actual housing consumption. In a supply-led market, it is argued that a household's stated preferences form a more accurate representation of their true housing aspirations (Boumeester, 2011). It is also argued that finding the proper balance between a household's stated preferences and its housing consumption, or revealed preferences, is key as a significant gap between both could lead to high dissatisfaction levels (Beer et al., 2011). Even more so considering that willingness to move is contingent upon current satisfaction levels. Thus, the investigation of both stated and revealed housing preferences is necessary as it allows the comparison between housing aspirations and choices as well as gauging current satisfaction levels and willingness to move. However, demand and the popularity of new dwellings is better assessed through a focus on stated preferences considering they are a better representation of housing aspirations especially in a supply-led housing market (Boumeester, 2011).

4.2.2 Important factors affecting housing preferences

Factors affecting housing preferences not only vary from one household to another but are also variable through time depending on the household's life trajectory, also known as life cycle (Beer et al., 2011; Hasu, 2018). A household's life cycle includes personal changes such as a work promotion or sudden unemployment, the birth of a child or an empty-nest, unions or separations, the illness, disability or death of a partner. Such changes are acknowledged to have an impact on housing preferences as they lead to the readjustment of priorities when it comes to the different housing attributes. These changes manifest themselves through different household characteristics be it socio-demographic such as household size, income and age or contextual such as country or location. While the potential impact of household size and income can be considered straightforward whereby a larger household requires a larger dwelling and a lower income limits the household's freedom of choice (Hasu, 2018) the same does not apply to the impact of age or to that of location.

On the one hand, literature around the potential impact of age raises contradictory expectations from the housing preferences of elderly households. Some argue that age affects the importance assigned to functional housing attributes and that elderly households prefer to downsize for more accessibility within and around the dwelling and lower maintenance requirements (Andersson, Abramsson, & Malmberg, 2019; de Jong, van Hattum, Rouwendal, & Brouwer, 2018; Hasu, 2018). Others emphasize the 'ageing in place' trend that describes elderly households' unwillingness to move. This entails a stronger preference for the current dwelling as a result of the mismatch between the price of the family home and that of a smaller dwelling, the instability and uncertainty within the rental market and/or the cultural norm of passing on family wealth to offspring (Beer et al., 2011; de Jong et al., 2018).

On the other hand, literature around the potential impact of the location varies per context and is linked to different contextual subfactors such as the type of residential area, the local housing market structure and government and/or financial policies established around housing provision (Andersson et al., 2019; Beer et al., 2011; Elsinga & Hoekstra, 2005; Karsten, 2007; Opit, Witten, & Kearns, 2020). For instance, a previous study identified a link between type of residential area and housing identity as strong variations were observed in indicators of self-image among households located in different residential areas despite their similar demographic characteristics. Specifically, the housing decisions of city-oriented urban families in the Netherlands were found to be guided by the self-image of career driven working parents as opposed to the social construct of a good suburban family with conventional gender roles. This was manifested through the priority and the high importance assigned to attributes like the proximity of the dwelling to the centre, to work and to children facilities (Karsten, 2007). Another study identified a link between type of residential area and choice of tenure. In Sweden, rental tenure was chosen in rural areas over tenant cooperative apartments which was more common in urban areas (Andersson et al., 2019). A link was also identified between choice of tenure and the local housing market structure and government and financial policies established around the provision of housing (Beer et al., 2011; Boumeester, 2011; Hasu, 2018). The literature has repeatedly emphasized that people's decision to enter homeownership is highly dependent on housing subsidies, loans and interest rates, lending regulations in addition to the local market conditions and its shortages (Beer et al., 2011). However, the study outcomes vary per study location. For instance, in Australia, research findings around the housing preferences of elderly women highlight security of tenure as one of their main concerns (Opit et al., 2020). Conversely, in Sweden, housing stability did not necessarily go hand in hand with homeownership since tenants' rights are stronger (Andersson et al., 2019). An outcome that was already suggested by Elsinga and Hoekstra in 2005 where their study revealed that, in Austria, tenants were as satisfied as homeowners due to the dominance of the private rental sector and the absence of policies encouraging homeownership (Elsinga & Hoekstra, 2005).

Thus, while household characteristics such as size, age, income and location are all recognized to have a significant impact on housing preferences, the impact of some is not as straightforward as others. Contradictory findings arise around the impact of age and the literature misaligns when it comes to the impact of location where outcomes vary per context. Overall, this highlights the complex nature of housing preferences and the need for a nuanced understanding of the factors shaping them.

4.2.3 Study contribution

Small, low-carbon, zero-energy, timber dwellings are being proposed as a solution that simultaneously answers sustainability concerns and housing market challenges. Within the housing market context, it is assumed that there is indeed a growing preference for smaller dwellings based on latest economic, demographic, and societal developments that increased the number of smaller households composed of one to two persons, elderly households, and lower income households. In parallel, housing preferences literature argues that adopting a bottom-up approach that starts at the level of studying consumer preferences is necessary for the provision of new dwellings. Information about people's current stated housing preferences provides insight into how they would like to live and how diverse these living aspirations and expectations could be. This stage of housing research is key as

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it establishes the foundation for accurately mapping out the current demand for housing eventually leading to higher satisfaction levels and a more resilient living environment (Boumeester, 2011; Jansen, Coolen, & Goetgeluk, 2011; Mulliner & Algrnas, 2018; Opit et al., 2020). Given this backdrop, this study aims to examine the extent to which small, low-carbon, zero-energy, timber dwellings could be a solution and test the assumption that there is a growing preference for them from the consumer's perspective. Following the stance of shaping supply, this study adopts a bottom-up approach in its investigation. Building on the literature reviewed, its main objectives are to determine consumers' both stated and revealed housing preferences, to gauge potential trade-offs between different housing attributes and to account for the potential factors affecting housing preferences through the following characteristics: household size, age, income and study location.

4.3 Materials and Methods

4.3.1 The H4.0E project and the H4.0E pilot dwellings

The main aim of the H4.0E project was to respond to the growing housing shortage by providing more sustainable solutions in line with prioritizing sufficiency policies and downsizing. Accordingly, this was reflected in the H4.0E dwelling designs built in Almere and in Huldenberg. All dwellings are single-family houses characterized namely with a relatively small size and a full timber structure. In Almere, the dwelling location is considered to be suburban (Tzaninis & Boterman, 2018) and most dwellings are either detached or semi-detached with an average net floor area (NFA) of 65 m^2. The smallest dwelling in Almere has a NFA of 45 m^2. In Huldenberg, the dwelling location is considered to be rural and most dwellings are also detached or semi-detached with an average NFA of 53 m^2. The smallest dwelling in Huldenberg has a NFA of 43 m^2 (NWEurope, 2021). Table 4.1 lists the main characteristics of H4.0E pilot dwellings in Almere and Huldenberg.

TABLE 4.1 H4.0E pilot dwelling profiles

Dwelling Characteristic	Almere – NL	Huldenberg – BE
Dwelling Type	Detached/Semi-detached	Detached/Semi-detached
Residential Area	Suburban	Rural
Dwelling Size (NFA)	65 m^2 (minimum of 45 m^2)	53 m^2 (minimum of 43 m^2)
Number of Bedrooms	1 to 2 bedrooms	1 bedroom
Building Material	Timber	Timber

4.3.2 The multi-attribute utility theory method

Housing literature provides various methods to investigate housing preferences and all have been successfully implemented throughout the literature. As such, method selection was based on the extent to which its outcomes match the study's goals (Jansen et al., 2011). One way of differentiating between methods is to make distinctions around data origin (stated versus revealed preferences), freedom of attribute choice, and theoretical approach (compositional versus de-compositional approach). Since stated housing preferences can be evaluated using all methods, data origin was not the determining factor when selecting the research method. Considering one of the main aims of this study is to evaluate the demand for small, low-carbon, zero-energy, timber dwellings within the H4.0E project, freedom of attribute choice is restricted to the housing attributes of such designs in particular. Moreover, this study was conducted at the early design stage of the project and stated housing preferences were investigated based on abstract dwelling profiles. Given the circumstances at hand, adopting a compositional theoretical approach satisfied the study's objectives at the time. As a result, the Multi-Attribute Utility Theory (MAUT) method was applied in the investigation of current stated housing preferences (Jansen, 2011).

In its compositional approach, the MAUT method implements the Simple Multi-Attribute Rating Technique whereby, through the distribution of a questionnaire, respondents are first asked to rate, on a scale from 0 to 10, individual housing attributes by importance and then individual housing attribute levels by preference. Importance and preference scores are then used to compute individual utility scores, or part-values, for each housing attribute level. Individual utility scores form the main output of the MAUT method. They add up to obtain overall scores (total values) reflecting the desirability of various housing compositions and profiles. In other words, based on individual utility scores or part-values, complete dwelling profiles can be scored and compared, thus providing an indication of their overall level of attractiveness to the respondents (Boumeester, 2011; Edwards, Newman, Snapper, & Seaver, 1982; Jansen et al., 2011; Von Winterfeldt & Edwards, 1993).

4.3.3 Housing preferences questionnaire

Within this framework and based on the descriptions of the H4.0E dwellings built in Almere and Huldenberg (Table 4.1), the housing attributes that are most informative to this study consist of dwelling type, residential area, dwelling size, number of bedrooms and building material. Forming a total of 5, the selected housing attributes do not exceed the recommended maximum of 8, thus preventing overloading the respondents during the data collection via questionnaire. The same applies to the attribute levels included. While the aim is to collect as much information as possible, the challenge is to get as many complete responses as possible. For this reason, the level of detail when determining attribute levels was kept general and the range was restricted between 3 and 4 as recommended rendering the questionnaire easy and straightforward (Boumeester, 2011; Jansen et al., 2011). Table 4.2 provides the detailed list of housing attributes and attribute levels investigated in this study.

TABLE 4.2 Housing attributes and attribute levels

Housing attribute	Attribute level	Housing attribute	Attribute level
Dwelling Type	Detached Semi-detached Terraced Apartment	Number of Bedrooms	One bedroom Two bedrooms Three bedrooms Four bedrooms
Residential Area	Urban Suburban Rural	Building Material	Concrete Timber Bricks
Dwelling Size	Less than 50 m^2 Between 51 and 80 m^2 Between 81 and 100 m^2 More than 100 m^2		

Similar to most housing preference research, to gauge the potential gap between current and desirable housing conditions, hence willingness to move, a section of the questionnaire was reserved to gathering information on the respondents' current housing situation as well as their current overall satisfaction and comfort levels. Moreover, the questionnaire also gathered information on household characteristics including household size, age, and level of income (Boumeester, 2011)[1]. The data was analysed using the Statistical Package for the Social Sciences (SPSS) software.

4.3.4 Sample selection and response rate

The questionnaires were distributed within the framework of the H4.0E project. The distribution process differed per pilot location. In the Netherlands, the survey was sent out through the municipality of Almere in autumn 2019. An invitation letter was sent to 3000 individuals from the municipality's population register asking them to participate in the survey. The size of the sample was based on an expected response rate of 10%. The letter contained a unique code that would allow respondents to access and complete the questionnaire online. Two weeks after the initial invitation letter, a reminder letter was sent to 1250 randomly chosen persons who had not yet completed the questionnaire. In total 297 responses were collected, thus fulfilling the targeted response rate of 10%, out of which 234 were complete questionnaires.

In Belgium, the distribution of the questionnaire was launched in April 2021[2]. The survey was conducted in collaboration with 3 municipalities in Flanders: Zoutleeuw, Huldenberg and Bertem. Paper invitations were sent to a total of 7600 residents. To increase responses, announcements were recurrently included in the municipalities' newsletters and websites. Residents had the option of completing the questionnaire online or on paper and the survey was kept online for a period of 5 months. A similar number of responses was received from all 3 municipalities and they amounted to a total of 563 responses resulting in a response rate of 8% in Flanders. Overall, this amounts to a total sample of 797 responses.

1 Refer to Appendix section A4 for excerpts from the housing preferences questionnaire. The full questionnaires are available upon request.

2 The pandemic caused significant delays in the distribution of the questionnaire in Flanders which explains the time difference between the two pilot locations.

4.4 Results

4.4.1 Sample characteristics

Table 4.3 provides a detailed composition of the main variables characterizing the sample. As targeted, 79% of the sample is composed of households of one to two persons. The larger part of the respondents fall within the senior age group of 60 year old or more and have a middle to high income with only 16% having a low income and the remaining 10% opting not to disclose their income information.

TABLE 4.3 Sample characteristics

Variable	Sample Size (n)	Value	Statistics n (%)
Study Location	797	Almere	234 (29%)
		Flanders	563 (71%)
Household Size	791	1 to 2 persons	622 (79%)
		3 persons	110 (14%)
		>3 persons	59 (7%)
Age	671	Young (≤ 30)	92 (14%)
		Middle (31 to 59)	219 (32%)
		Senior (≥ 60)	360 (54%)
Household Net Monthly Income3	793	Low income	125 (16%)
		Middle income	340 (43%)
		High income	249 (31%)
		Other	79 (10%)

3 Income ranges differ per geographic context. In the Netherlands, a low household net monthly income is equal to or below €2150, a middle income ranges between €2150 and €3550, and a high income is above €3550. In Flanders, a low income is equal to or below €1500, a middle income ranges between €1500 and €3000, and a higher income is above €3000.

4.4.2 Current housing situation and willingness to move

Table 4.4 describes the respondents' current housing situation by listing their revealed housing preferences. What is important to highlight is that an overwhelming majority of the respondents are owner-occupiers and almost half of them live in a detached-dwelling. The larger part of the respondents live in a dwelling that is larger than 100 m^2, the largest dwelling size included in this study, and the majority also have three or four bedrooms in their dwellings. Lastly, 80% of the respondents live in a dwelling that is made of bricks compared to only 9% who live in a concrete dwelling and a minority of 2% living in a timber dwelling. When it comes to the respondents' willingness to move, Table 4.5 shows that the greater part of the respondents were not in favour of leaving their current dwelling with 61% stating that they are not willing to move. A large portion of the respondents have been living in their current dwelling for more than 20 years. Overall, the majority stated to be satisfied and comfortable in their current dwelling with a minority of 6% reporting dissatisfaction and/or discomfort.

In investigating the potential impact of current housing characteristics on the respondents willingness to move, satisfaction and comfort levels, a series of Chi-square tests were conducted to gauge the potential association between the dependent and independent variables. There is strong evidence of an association between the respondents' willingness to move and the time spent in their current dwelling. This suggests that the respondents are less likely to relocate as the duration of their stay in their dwelling increases. Similarly, there is a significant association between willingness to move and the respondents' satisfaction and comfort ratings. This validates satisfaction and comfort as key catalysers or, in this case, inhibitors to willingness to move. Additionally, it is worth noting that the association between willingness to move and tenure type was revealed to be significant with a medium effect size. Given that a majority of the respondents are homeowners, this finding suggests that owning a home is highly valued and is a key factor influencing their decision to move. When it comes to the impact of current housing characteristics on satisfaction and comfort ratings, another point to consider is that all associations were revealed to be statistically significant except for building material. In other words, the type of building material used in a dwelling does not affect the satisfaction and comfort of respondents unlike the other housing characteristics tenure type, dwelling size, dwelling type, and number of bedrooms[4].

4 Refer to Appendix section A1, Table APP 1.1 for Chi-square results

TABLE 4.4 Current housing situation through revealed housing preferences

Variable	n	Value	Statistics n (%)
Tenure Type	797	Owner Occupation	589 (74%)
		Private Renting	82 (10%)
		Social Renting	46 (6%)
		Other	80 (10%)
Dwelling Type	797	Detached	383 (48%)
		Semi-detached	126 (16%)
		Terraced	189 (24%)
		Apartment/Studio	93 (11%)
		Other	6 (1%)
Dwelling Size	797	Less than 50 m^2	15 (2%)
		50 to 80 m^2	80 (10%)
		80 to 100 m^2	102 (13%)
		More than 100 m^2	511 (64%)
		I don't know	89 (11%)
Number of Bedrooms	793	One	38 (5%)
		Two	144 (18%)
		Three	325 (41%)
		Four	286 (36%)
Building Material	797	Concrete	70 (9%)
		Timber	12 (2%)
		Bricks	640 (80%)
		Combination or other	75 (9%)

TABLE 4.5 Willingness to move and current satisfaction and comfort levels

Variable	Sample Size	Value	Statistics
Willingness to move	794	Yes	306 (39%)
		No	488 (61%)
Time in current dwelling	778	0 to 5 years	195 (25%)
		5 to 10 years	64 (8%)
		10 to 15 years	65 (8%)
		15 to 20 years	81 (10%)
		More than 20 years	373 (48%)
Satisfaction Rating	792	Very dissatisfied	10 (1%)
		Dissatisfied	38 (5%)
		Neutral	115 (15%)
		Satisfied	334 (42%)
		Very satisfied	295 (37%)
Comfort Rating	793	Very uncomfortable	10 (1%)
		Uncomfortable	39 (5%)
		Neutral	115 (15%)
		Comfortable	372 (47%)
		Very comfortable	257 (32%)

4.4.3 Factors affecting housing preferences

In answering this study's objectives, the independent variables include four main household characteristics: study location, household size, age group, and household net monthly income. In parallel, the dependent variables are preference ratings assigned to the 18 housing attribute levels investigated in this study (refer to Table 4.2). Table 4.6 lists the mean housing preference ratings per study location. Considering the types of variables involved are either nominal or ordinal, a series of Mann-Whitney tests and Kruskal-Wallis tests followed by post-hoc Mann-Whitney tests were conducted[5].

When investigating the study location as a factor, results showed statistically significant differences in mean preference ratings with p-value less than 0.05 between the two contexts for most of the housing characteristics. Respondents in Almere generally assigned less extreme mean preference ratings compared to respondents in Flanders. As such, the differences in means do not necessarily indicate a difference in preferences and in most cases the overall ranking of housing attribute levels remained the same in both study locations. For instance, there is evidence of a statistically significant difference in the mean preference rating of a detached dwelling between Almere and Flanders. Yet, in both locations, a detached dwelling is the most preferred dwelling type. Thus, in the frame of this study, these results are solely indicative of differences in numerical scores assigned by the respondents and do not provide any information about their ranking. The only exceptions are the scores assigned to a dwellings size of 50 m^2 or less and bricks as the main building material where there was no evidence of a difference in means. Since both attribute levels represent the least preferred dwelling size and the most preferred building material in both study locations, the absence of a statistically significant difference in means confirms the universality of these perceptions. Put simply, a dwelling size below 50 m^2 is unequivocally regarded as the least favoured size across the board and is valued the same in both study locations. Likewise, bricks are indisputably recognized as the most preferred construction material and are valued the same in both study locations (Appendix section A2, Table APP 1.3.).

5 Refer to Appendix section A2, Table APP 1.2. for the statistical analysis process and Tables APP 1.3., APP 1.4., and APP 1.5. for the results

TABLE 4.6 Attribute levels mean preference ratings

Housing Attribute	Attribute Level	NL			BE		
		n	Mean	SD	n	Mean	SD
Dwelling Type (DT)	Detached	234	60.04	38.250	552	82.46	26.346
	Semi-detached	234	56.62	32.824	540	53.37	32.119
	Terraced	234	56.07	30.824	531	29.87	28.986
	Apartment	234	52.48	36.626	540	34.46	33.318
Residential Area (RA)	Urban	234	58.55	32.021	549	26.47	29.278
	Suburban	234	63.12	31.406	545	42.35	33.011
	Rural	234	54.17	34.882	560	88.32	17.098
Dwelling Size (DS)	Less than 50 m^2	234	14.00	24.482	511	10.90	18.765
	Between 51 and 80 m^2	234	38.93	34.606	512	26.95	28.868
	Between 81 and 100 m^2	234	65.04	32.667	515	47.73	34.653
	More than 100 m^2	234	62.69	38.513	523	79.45	28.269
Number of Bedrooms (NB)	One	226	16.54	25.949	524	15.76	25.422
	Two	226	55.73	35.542	530	52.53	37.432
	Three	226	63.21	34.943	539	65.34	33.843
	Four	226	42.91	38.347	524	41.79	39.226
Building Material (BM)	Concrete	234	60.94	32.638	525	49.95	31.807
	Timber	234	36.97	31.551	526	45.06	33.647
	Bricks	234	81.32	21.298	542	80.65	21.223

When investigating household size, age and income as factors, results showed statistically significant differences in means with p-value less than 0.05 for at least 11 housing characteristics per factor (Appendix section A2, Table APP 1.4.). Follow-up post-hoc tests allowed gauging statistically significant variations in mean preferences between the different household sizes, age and income groups with p-value less than 0.01. The most important pairwise comparisons to highlight are between a household size of one versus two persons, the younger versus the senior age groups, and the low versus the high income groups (Appendix section A2, Table APP 1.5.).

Starting with household size, more differences emerged between a one and two-person household rather than a two and three-person household. Particularly, one-person households assigned higher preference ratings to a smaller dwelling size of 50 to 80 m^2 and having one or two bedrooms compared to two-persons households who assigned higher preference scores to larger detached dwellings of more than 100 m^2 with three bedrooms. The only recorded difference between two and three-persons households was the higher preference rating given by three persons households to having 4 bedrooms in a dwelling. In terms of age groups, no differences were recorded between the young and middle age groups. Most differences were recorded between the middle and senior age groups where respondents within the middle age group assigned higher preference ratings to a detached, semi-detached and terrace dwelling, a suburban area, having three and four bedrooms and concrete as the main building material. Whereas respondents within the senior age group assigned higher preference ratings to having two bedrooms and bricks as the main building material. When it comes to income groups, most differences were recorded between the low and high income groups as well as the middle and high income groups. Respondents within the higher income group assigned higher preference scores to living in a rural area, in larger dwellings of more than 100 m^2 with four bedrooms. Whereas respondents within the lower and middle income groups assigned higher preference scores to all smaller dwelling sizes and having one or two bedrooms. Respondents with a lower income also assigned higher preference scores to living in an urban area compared to respondents with a higher income.

4.4.4 MAUT outcomes

All housing attributes investigated in this study were considered important to the respondents since the lowest average importance score almost reaches 70 (Table 4.7). This verifies the relevance of the housing attributes selected. Additionally, there is no evidence to support a difference between the average importance ratings of dwelling type, residential area, number of bedrooms and building materials. This indicates that, not only were the housing attributes included in this study considered important to the respondents, but also that they were considered as important in both contexts. The only exception is the dwelling size which is perceived as more important in Almere. The data was conclusive with residential area, dwelling type and dwelling size being the three most important attributes.

TABLE 4.7 Housing attributes average importance scores

Housing Attribute	Study Location					
	Almere			Flanders		
	n	Mean	SD	n	Mean	SD
Dwelling Type	234	78.96	17.631	559	76.23	19.332
Residential Area	234	86.57	12.750	563	86.77	13.118
Dwelling Size	234	78.09	14.952	559	75.24	17.848
Number of Bedrooms	234	71.58	20.647	559	69.75	21.881
Building Material	234	72.19	21.991	559	71.34	23.421

Table 4.8 lists the average utility points in every pilot location derived from the implementation of the MAUT method[6]. Through these individual utility scores respondents' trade-offs can be assessed. For instance, in Almere, a detached dwelling would add 12.2 utility points compared to an apartment dwelling that would add 10.7 utility points resulting in a difference of 1.5 points only. In Flanders, the same housing attributes would add 16.8 and 6.7 utility points respectively resulting in a 10 point difference. Thus, while a detached dwelling is the most preferred type in both study locations, it can be said that its trade-off could lead to the rejection of the dwelling in Flanders while this is not the case in Almere. The same applies to housing attribute levels under residential area where living in a rural area is highly valued in

6 Refer to Appendix section A3 for the detailed process of the implementation of the MAUT method.

Flanders, scoring 20.5 utility points and increasing the attractiveness of a dwelling profile by up to 14.2 points compared to an urban area. Whereas in Almere, although a suburban area is the most preferred type, it would only add 1.9 utility points to the attractiveness of a dwelling profile compared to a rural area, which is here the least preferred type of residential area.

TABLE 4.8 Housing attribute levels' average utility points

Housing Attribute	Attribute Level	Almere		Flanders	
		Utility Point	SD	Utility Point	SD
Dwelling Type	Detached	12.2	8.182	16.8	6.725
	Semi-detached	11.5	6.970	10.5	6.826
	Terraced	11.5	7.017	5.8	5.782
	Apartment	10.7	7.753	6.7	7.002
Residential Area	Urban	13.3	7.595	6.3	7.249
	Suburban	14.2	7.174	9.9	8.130
	Rural	12.3	8.194	20.5	5.182
Dwelling Size	Less than 50 m^2	3.00	4.919	2.1	3.720
	51 to 80 m^2	7.8	7.011	5.2	5.645
	81 to 100 m^2	13.1	6.769	9.3	6.986
	More than 100 m^2	12.9	8.257	16.0	6.360
Number of Bedrooms	One	2.8	4.544	2.6	4.418
	Two	10.1	6.969	9.3	7.181
	Three	11.8	7.163	12.2	6.998
	Four	8.1	7.641	8.1	8.151
Building Material	Concrete	11.2	6.878	9.2	6.877
	Timber	6.7	6.355	8.1	6.929
	Bricks	15.1	5.768	15.2	6.238

Following this reasoning, the outcomes indicate that the potential for trade-offs is higher in Almere than in Flanders where respondents were revealed to be more categorical about their housing preferences. Additionally, it is worth noting that a smaller dwelling size of less than 50 m^2 would decrease the attractiveness level of a dwelling by 10.1 utility points in Almere and 13.9 points in Flanders. That is to say that this dwelling size is highly likely to result in the rejection of a dwelling profile in both study locations.

More importantly, the negative impact a smaller house size could have on the level of attractiveness of a dwelling is increased by the fact that it is coupled with a smaller number of bedrooms. Consequently, a smaller dwelling size of 50 m^2 or less results in the decrease of the level of attractiveness of a dwelling profile by 19.1[7] points in Almere and 16.8 points in Flanders. As such, the results demonstrate the importance of taking into account the potential of a consequential chain of negative effects the trade-off of one housing attribute level could have on another. Last but not least, while bricks, the most preferred type of building material, was shown to be the same in both study locations, the trade-off potential appears to be higher in Flanders where a concrete alternative would only add 1.1 utility points to the attractiveness of a dwelling in comparison to timber. Whereas in Almere, results indicate that respondents were more categorical seeing as the concrete alternative adds 4.5 utility points compared to timber.

Based on these average utility scores, the dwelling profiles with the most preferred and least preferred characteristics are composed and scored in Table 4.9. These descriptions represent the two extreme dwelling profiles per location. Overall, respondents in both study locations have similar housing preferences. The most prominent differences to highlight are the type of residential area which reflects their current housing situation: a suburban area in Almere and a rural area in Flanders. The most preferred dwelling size is smaller in Almere and is 80 to 100 m^2 when in Flanders respondents prefer dwellings that are larger than 100 m^2. In terms of least preferred dwelling characteristics, main differences concern the dwelling type, which is an apartment in Almere versus a terrace dwelling in Flanders, and the type of residential area which is a rural area in Almere and an urban area in Flanders. Overall, any dwelling composition will score between 35.4 (sd=16.695) and 66.3 (sd=18.247) in Almere and 26.2 (sd=17.104) and 81.3 (sd=14.630) in Flanders. Based on these extremes, an averagely attractive dwelling profile would have a score of 50.9 (sd=14.044) in Almere and 53.8 (sd=9.942) in Flanders.

7 19.1 utility points are a result of adding the 10.1 points from the trade-off of dwelling size which is the difference between a dwelling size of 80 to 100 m^2 and a size of 50 m^2 or less to the 9 points from the trade-off of the number of bedrooms which is the difference between having 3 bedrooms and having only 1 bedroom. The same applies to the outcome obtained for Flanders.

TABLE 4.9 Extreme dwelling profiles in Almere and in Flanders*

Most preferred profile – Almere			Least preferred profile – Almere			Average level of attractiveness
Attribute level	Utility	Total	Attribute Level	Utility	Total	
Detached dwelling	12.2	**66.3****	Apartment dwelling	10.7	**35.4**	**50.9**
Suburban area	14.2		Rural area	12.3		
81 to 100 m²	13.1		Less than 50 m²	3.0		
Three bedrooms	11.8		One bedroom	2.8		
Bricks	15.1		Timber	6.7		
Most preferred profile – Flanders			**Least preferred profile – Flanders**			**Average level of attractiveness**
Attribute level	**Utility**	**Total**	**Attribute level**	**Utility**	**Total**	
Detached dwelling	16.8	**81.3**	Terraced dwelling	5.8	**26.2**	**53.8**
Rural area	20.5		Urban area	6.3		
More than 100 m²	16.0		Less than 50 m²	2.1		
Three bedrooms	12.2		One bedroom	2.6		
Bricks	15.2		Timber	8.1		

* *A sensitivity analysis was conducted where scores were recomputed following the equal weights method. The sensitivity analysis outcomes confirmed the extreme dwelling profiles obtained through the weighted additive method and overall rankings of individual housing attribute levels remained the same. Refer to Appendix section A3 Table APP 1.7. for the detailed outcomes of the sensitivity analysis.*

** *Overall scores were computed through the SPSS software. The differences in scores computed in the software and scores obtained from the addition of separate utility score averages are due to incremental rounding differences resulting from the latter.*

Table 4.10 provides the overall scores of the H4.0E dwelling profiles based on current market housing preferences in Almere and in Flanders. The small H4.0E dwelling profiles in both Almere and Flanders scored below the average level of attractiveness set in Table 4.10 with totals of 38.9 (sd=17.476) and 50.8 (sd=13.695) respectively. Similarly, the medium H4.0E dwelling profiles in both contexts scored just around the average level of attractiveness with totals of 50.9 (sd=19.969) and 53.8 (sd=14.783) respectively. While the data was inconclusive about the medium dwelling profiles having an average level of attractiveness, it was conclusive about the small H4.0E dwelling profiles having a below average level of attractiveness.

TABLE 4.10 H4.0E dwelling profiles scores in Almere and Flanders

H4.0E profile – Almere Small House			H4.0E profile – Huldenberg Small House		
Attribute level	Utility	Total	Attribute Level	Utility	Total
Detached dwelling	12.22	**38.9**[8]	Detached dwelling	16.75	**50.8**
Suburban area	14.19		Rural area	20.53	
45 m^2	2.97		43 m^2	2.11	
One bedroom	2.76		One bedroom	2.64	
Timber	6.72		Timber	8.11	
H4.0E profile – Almere Medium House			**H4.0E profile – Huldenberg Medium House**		
Attribute level	**Utility**	**Total**	**Attribute level**	**Utility**	**Total**
Detached dwelling	12.22	**51**	Detached dwelling	16.75	**53.9**
Suburban area	14.19		Rural area	20.53	
65 m^2	7.75		53 m^2	5.16	
Two bedrooms	10.09		One bedroom	2.64	
Timber	6.72		Timber	8.11	

In examining how housing preferences could differ from one study location to another, the different H4.0E dwelling profiles were scored in each other's contexts (Table 4.11). Overall, the small H4.0E dwelling profiles achieved similar scores indicating that smaller dwelling sizes considerably decrease the level of attractiveness of a house regardless of study location. The dwelling profile that did achieve a higher score when its context was changed is the H4.0E Almere medium dwelling. This profile was revealed to be more attractive in Flanders with the main difference in housing characteristics being linked to dwelling size through a higher number of bedrooms. This reiterates the importance of dwelling size and is a direct manifestation of the consequential chain effect mentioned above.

TABLE 4.11 H4.0E dwelling profiles scores with interchanged study locations

Dwelling Profile	Almere (average score: 50.9, sd=14.044)	Flanders (average score: 53.8, sd=9.942)
H4.0E Almere Small	38.9, sd= 17.476	50.8, sd= 13.695
H4.0E Almere Medium	50.9, sd= 19.969	60.4, sd= 15.079
H4.0E Huldenberg Small	38.9, sd= 17.476	50.8, sd= 13.695
H4.0E Huldenberg Medium	43.6, sd= 19.242	53.8, sd= 14.784

8 Overall scores were computed through the SPSS software. The differences in scores computed in the software and scores obtained from the addition of separate utility score averages are due to incremental rounding differences resulting from the latter

4.5 Discussion

4.5.1 The distinction between the smallest and smaller dwelling sizes

In light of the latest demographic, societal and economic developments, the nature of housing demand is said to have changed and it was assumed that there is a growing preference for smaller dwellings. This assumption was mainly based on the increase of smaller households composed of one to two persons, the increase of the elderly population, and the increase of low income groups. Taking into account these housing market shifts in combination with decarbonization goals set for 2050, small, low-carbon, zero-energy timber dwellings were derived as a solution to both sustainability challenges and the growing housing shortage. Within this context, the aim of this study was to explore the extent to which there is a demand for such dwellings from the consumer's perspective. That being said, this study's outcomes demonstrated that, based on the respondents' stated housing preferences, there was no demand for small, timber dwellings of 50 m^2 or less. These two housing attribute levels in particular are common characteristics of the least attractive dwelling profiles in both Almere and Flanders. Conformingly, the smallest H4.0E dwelling profiles of 45 and 43 m^2 conclusively scored below the average level of attractiveness in both study locations despite the fact that they comply with the most preferred dwelling type (detached dwelling) and dwelling location (suburban/rural). Nevertheless, considering that the somewhat larger dwellings, referred to as H4.0E medium dwelling profiles, achieved scores that were close to the average levels of attractiveness in both contexts, this study's outcomes do not exclude the possibility of timber dwellings of 50 to 80 m^2 satisfying consumer preferences. Recalling that individual utility scores trace how certain housing attribute levels can positively and significantly compensate for others, MAUT results demonstrated how housing characteristics such as a detached dwelling with a layout that ensures at least 2 bedrooms located in a suburban residential area in Almere and a rural area in Flanders could compensate for a smaller dwelling size of 50 to 80 m^2 and timber as a building material and increase the overall attractiveness of the dwelling. In other words, while the smallest dwelling sizes do negatively affect the level of attractiveness of a dwelling profile, the H4.0E medium dwellings were found to be conclusively more attractive and relatively satisfactory of current housing preferences. In this way, it becomes crucial to distinguish between smallest and smaller dwellings. Although there is no demand for the smallest dwelling sizes, smaller dwellings could potentially satisfy current housing preferences.

4.5.2 Housing attributes affecting residents' satisfaction, comfort and willingness to move

In analysing the deeper implications of this study's outcomes, the bottom-up investigation of different aspects of consumers' housing preferences shed light on additional valuable insight that can inform the housing provision process in the wider perspective. Starting with the comparison of respondents' revealed and stated preferences, the results did not show a significant mismatch as insinuated in previous literature (Boumeester, 2011). A majority of the respondents expressed high satisfaction and comfort levels with their current dwellings and reported a reluctance to move. The larger part of the respondents were owner-occupiers living in a detached dwelling that is larger than 100 m^2 with at least three bedrooms. Statistically, the associations between these characteristics of their current housing situation and their satisfaction and comfort ratings were all revealed to be significant. Following the reasoning behind distinguishing the concepts of choice versus preference, this entails that for most of the respondents, their current dwellings do represent their actual housing aspirations. The only exception was building material. Although the majority of the respondents lived in a conventional brick dwelling, this housing attribute was not revealed to have a significant impact on their satisfaction and comfort levels. In the provision of small, low-carbon, zero-energy timber dwellings, this emphasizes the importance of dwelling type, dwelling size and number of bedrooms as main housing attributes that significantly contribute to residents' satisfaction and comfort, while underlining building material as a non-contributor. Put differently, residents are more likely to reject a dwelling based on its type, size and number of bedrooms and they are less likely to reject it based on the building material used. Additionally, with tenure type having the most impact on willingness to move, this indicates that owner occupation remains the ultimate goal in the respondents' housing pathways (Beer et al., 2011). This outcome applies to both locations involved in this study insinuating that despite living in different residential areas; suburban in Almere and rural in Flanders, respondents value the same tenure type: owner-occupation. This contests previous findings that underline the variation of choice of tenure per different residential area (Andersson et al., 2019). From a broader perspective, this could also be a reflection of local policies in the Netherlands and Belgium that are more encouraging of homeownership rather than other tenure types as was the case in Sweden and in Austria (Andersson et al., 2019; Elsinga & Hoekstra, 2005).

4.5.3 Perceived value of housing attribute levels across household characteristics

In investigating the potential impact of household characteristics on stated housing preferences, this study's outcomes uncovered several main findings. First, in terms of household size, results revealed significant variations in preference values already between one and two-person households; two subgroups that are often combined in housing market research and by housing suppliers. Comparatively, the differences in average ratings between one and two-person households exceeded the ones between two and three-person households suggesting a higher degree of similarity in housing preferences between two and three-person households. This finding could be reflective of variations in housing careers whereby households of two persons are already steps ahead in planning for their next life stage bringing them closer to the life cycle of three-person households (Beer et al., 2011; Hasu, 2018). More importantly, in the broader context of housing provision, this finding implies that the housing solution proposed for smaller households of one to two persons is demonstrated to be satisfactory to single-person households only. Second, regarding age, variations of outcomes were not indicative of differences in preferences as the overall ranking of dwelling characteristics remained the same across groups. Instead, variations were due to generally lower scores given by senior respondents compared to the ones reported by younger respondents with the only exception being bricks, a building material that was conclusively more valued by the senior subgroup. Put differently, despite significant variations in mean preference values, most and least preferred housing characteristics remained the same across different age groups with the single actual difference pertaining to bricks. Within the broader context of housing market supply, this questions the assumption that there is a demand from the elderly population group for smaller, more accessible dwellings that tailor to their evolving needs. Also, with the majority of the senior respondents not willing to move, this corroborates the tendency of 'ageing in place' (de Jong et al., 2018). Last but not least, concerning income, respondents with low to middle incomes demonstrated to assign more similar values to housing preferences with most differences recorded with the high income group. Expectedly, the higher income group valued a detached dwelling, the largest dwelling size, and the highest number of bedrooms significantly more than both lower income groups. Additionally, the ranking of their mean preference ratings highlights a noticeably greater range of values and divergence of scores especially within dwelling type and dwelling size. Thus, the results showed that respondents from the higher income group are more categorical and definite about their housing preferences which in turn implicitly suggests less trade-off potential. In that way, results affirm that households with more affluence have the privilege to hold on to their absolute stated preferences rather than make trade-offs (Hasu, 2018).

4.5.4 Perceived value of housing attribute levels across study locations

In gauging trade-offs, results uncovered both similarities and differences worth highlighting between the two study locations. A dwelling size of 50 m^2 or less was the least preferred in both Almere and in Flanders and there was no evidence to support a difference in utility means between the two contexts. This outcome serves as evidence of a similarity indicating that the respondents had a similar perception of the added value of this housing characteristic. This also entails that the aversion towards smaller dwellings of 50 m^2 or less remained unaffected by the study location and that the low level of attractiveness of that dwelling size was universal. Likewise, bricks was the most preferred building material in both study locations and there was no evidence to support a difference in utility means between the two contexts. Following that same reasoning, it can be said that the high preference for a dwelling made of bricks was also universal and unaffected by study location. A potential explanation to this outcome is the fact that both countries share a long-standing tradition of brick construction. An additional similarity is timber voted as the least preferred building material in both study locations. However, here it is worth noting that, the perceived added value of timber is lower in Almere and the preference of concrete over it is more prominent compared to Flanders. Contextual factors influencing these ratings could be linked to the perception of less durability of timber and concerns regarding the extent to which it can be fire resistant.

In terms of differences, the most prominent one pertains to the most preferred dwelling size. With numerical attributes such as dwelling size, it can be expected that utility values increase with size. However, the results showed that dwellings between 80 and 100 m^2 are the most valued in Almere while dwellings that are larger than 100 m^2 are perceived as the most attractive in Flanders. This could indicate that respondents in Almere take into account other factors that could indirectly be linked to larger dwellings in their evaluation. Examples are higher housing costs whether they are rental costs or purchase costs, higher energy costs linked to more heating and more maintenance requirements and maintenance costs. More importantly, it is noteworthy to emphasize that none of the other sample characteristics investigated in this study, including household size, age and income, changed the ranking of the most preferred dwelling size. Considering the common sample characteristics in both contexts, including a majority of small households, this renders the type of residential area the only factor that has an impact on dwelling size preferences. From the broader perspective of housing provision, this refutes the assumptions that being part of a smaller household, a senior household and/or a low-income household increases the preference for a smaller dwelling size. It rather validates the trend where households residing in more urbanized settings display a greater inclination towards embracing smaller living arrangements.

4.5.5 Study limitations

The pandemic had a decisive influence on the study design and implementation. Significant delays caused a misalignment between the housing preferences questionnaire and the design and construction of H4.0E dwellings. As a result, local housing preferences were gauged based on abstract dwelling profiles and simplified housing characteristics. The availability of actual dwelling images during data collection would have allowed the presentation of more complex dwelling scenarios to consumers thus mimicking a decision making process that is closer to real world decision making. Additionally, in its selection of housing attributes and attribute levels this study excludes housing cost from its analysis. Having low housing costs is very likely to achieve a high utility value that compensates for all other less preferred housing characteristics considering it is unavoidably consumers' most preferred option. Put differently, including housing cost would have shadowed trade-off outcomes considering that, whenever possible, consumers tend to opt for the most economical option, and given the choice, they are unlikely to select a higher-priced alternative. Since the aim of this investigation was to explore the extent to which small, low-carbon, zero-energy timber dwellings satisfy current housing preferences, the priority was to focus on gauging housing preferences outside of housing costs. Instead, precedence was given to allowing the distinction of housing preferences between smaller dwelling sizes and specific building materials. Thus, while housing costs are acknowledged as an intrinsic aspect of the housing decision process, including them would have hindered the fulfilment of this study's aim. Lastly, this study was focused on specific locations relevant to the H4.0E project; namely Almere in the Netherlands, and Bertem, Huldenberg, and Zoutleeuw in Flanders, Belgium. Additionally, since one of the main assumptions tested is the preference of smaller dwellings due to the growing number of smaller households of one to two persons, the sampling method was centred on prioritizing this sample characteristic. This combination of the unique conditions of the selected locations together with the specific characteristics of the target group may limit the applicability of the findings beyond these contexts. Thus, while this study's sample is considered sufficient to draw meaningful patterns in the data and provide a good representation of the population under investigation, the outcomes cannot be generalized to entire populations such as the Netherlands and Belgium or broader. Larger sample sizes may be necessary to increase generalizability of the findings.

4.6 Concluding Remarks

The aim of this study was to investigate the extent to which there is a demand for small, low-carbon, zero-energy timber dwellings through an explorative analysis of stated housing preferences with a special focus on smaller households composed of one to two persons. Accordingly, a housing preferences questionnaire tailored based on the MAUT method was distributed in Almere in the Netherlands and Huldenberg, Zoutleeuw and Bertem in Belgium.

On a general level of analysis, study outcomes revealed that there is no demand for small timber dwellings of 50 m^2 or less. The smallest H4.0E dwelling profiles did not score highly on the attractiveness scale set by MAUT outcomes and timber was revealed as the least preferred building material. However, computing utility scores allowed tracing how housing characteristics interact with one another and how some could compensate for others. Trade-off results demonstrated that the combination of a specific dwelling type, residential area and number of bedrooms can compensate for a smaller dwelling size and a timber structure. More importantly, the fact that H4.0E medium dwelling profiles scored around the average level of attractiveness highlighted the importance of distinguishing between smaller and the smallest dwelling sizes and findings validate the possibility of smaller timber dwellings of 50 to 80 m^2 satisfying consumer preferences.

On a more detailed level of analysis, building on housing preferences literature, this study accounted for household size, age, income, and study location as potential factors in its investigation of stated housing preferences. First, results traced significant differences in preferences between one and two-person households implying that the housing solution proposed for smaller households of one to two persons might be preferred by single-person households only. Put differently, this study's outcomes challenge the assumption that small households of one to two persons have similar housing preferences. Instead, one and two-person households should be considered two separate groups possibly at different life cycle stages for potentially more accurate predictions of housing needs throughout the housing provision process.

Second, results contradict the assumption that elderly households prefer smaller dwellings that are more convenient to their evolving needs. Conversely, outcomes confirm the 'ageing in place' trend supported by a general unwillingness to move that is significantly influenced by their status of owner-occupiers. Ageing in place could stem from the cultural norm of passing on family wealth to offspring. However, it could also be due to a mismatch between the price of the family home and that of a smaller dwelling and/or the instability and uncertainty within the rental market. Thus, changing the cultural norm through establishing financial planning incentives, alternative methods of wealth transfer and ensuring housing stability and affordability by improving tenant regulations could motivate the elderly to adjust their housing situation to fit their needs.

Third, outcomes also challenge the assumption that lower income households prefer smaller dwellings considering the most preferred dwelling size did not vary per income group. However, results do demonstrate that lower income households attribute higher values to smaller dwelling sizes. In other words, this study's findings suggest that, in a supply-led market, lower income households are more likely to make concessions and opt for smaller dwelling sizes whereas households with more affluence have the privilege to hold on to their absolute preferences.

Fourth, the comparison of stated housing preferences per study location identified current residential area as the only factor affecting dwelling size preferences whereby residents in a suburban area valued a smaller dwelling of 80 to 100 m^2 more than a larger dwelling whereas residents in a rural area valued the largest dwelling size exceeding 100 m^2 the most. This finding is a manifestation of the widely known trend that people living in more urbanized areas are accustomed to denser and smaller living due to the limited space characteristics of such settings. It can even be said that the choice of living in a more urbanized residential area is in itself a trade-off with living in a larger dwelling. Overall, this finding underlines study location as the factor that is more likely to influence housing preferences around dwelling size rather than household size, age or income as was assumed. Recalling that this study compares a suburban to a rural context, future research can aim to incorporate more diverse sampling locations, encompassing a broader range of urban, suburban, and rural areas to better gauge the impact of location on dwelling size preferences. Finally, having established the lack of preference for smaller dwellings sizes of 50 m^2 or less, future research can include housing cost as a trade-off to study its potential impact on dwelling size preferences and gauge the extent to which it influences people's acceptance of smaller dwelling sizes.

Data availability statement: The data presented in this study are available upon request from the corresponding author.

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Appendix 1

A1. Statistical analysis of sample characteristics

TABLE APP 1.1 Chi^2 results for associations between willingness to move, satisfaction, and comfort ratings and current housing situation

Dependent variable	Independent variable	p-value	Chi^2	Df	Cramer's V	Effect size*
Willingness to move	Tenure type	<0.001	106.95	3	0.367	Medium
	Satisfaction rating	<0.001	61.331	2	0.278	Small
	Comfort rating	<0.001	50.675	2	0.253	Small
	Time in current dwelling	<0.001	28.077	4	0.190	Small
Satisfaction rating	Tenure type	<0.001	92.368	6	0.241	Small
	Dwelling type	0.001	26.290	8	0.129	Small
	Dwelling size	<0.001	50.040	8	0.178	Small
	Number of bedrooms	<0.001	53.184	6	0.184	Small
	Building material	0.790	3.148	6	-	N/A**
	Time in current dwelling	<0.001	31.991	8	0.144	Small
Comfort rating	Tenure type	<0.001	80.707	6	0.226	Small
	Dwelling type	0.009	20.398	8	0.113	Small
	Dwelling size	<0.001	87.309	8	0.235	Small
	Number of bedrooms	<0.001	72.938	6	0.215	Small
	Building material	0.390	6.307	6	-	N/A
	Time in current dwelling	<0.001	35.919	8	0.152	Small

* *When looking at the strength of relationships, otherwise known as the size of the effect, an effect of ±0.1 was considered to be small, and effect of ±0.3 was considered as medium, and an effect of ±0.5 was considered to be large (Field, 2009).*
** *N/A: Not applicable. There is no evidence of an association between satisfaction and comfort levels and building material.*

A2. Factors affecting housing preference ratings

TABLE APP 1.2 Statistical analysis process

Independent Variable - IV	IV Type	Dependent Variable - DV	DV Type	Stage 1 – p<0.05	Stage 2 – p<0.01
Study Location	Nominal – 2 groups	Housing Preference Ratings	Ordinal	Mann-Whitney	N/A
Age Group	Ordinal			Kruskal-Wallis	Post-hoc Mann-Whitney
Household Size	Ordinal			Kruskal-Wallis	
Income Group	Nominal - >2 groups			Kruskal-Wallis	

TABLE APP 1.3 Mann- Whitney test results with statistical significance

IV	Pairwise comparison	DV	Test statistics	Sample size	P-value
Study Location	Almere, Flanders	Detached	41491.5	234, 552	<0.01
		Terrace	33415	234, 531	<0.01
		Apartment	45406,5	234, 540	<0.01
		Urban	30498,5	234, 549	<0.01
		Suburban	40413,5	234, 545	<0.01
		Rural	25406.5	234, 560	<0.01
		51 to 80 m^2	48904	234, 512	<0.01
		81 to 100 m^2	42308.5	234, 515	<0.01
		≥100 m^2	46673.5	234, 523	<0.01
		Concrete	48531	234, 525	<0.01
		Timber	53114.5	234, 526	<0.01

TABLE APP 1.4 Kruskal-Wallis test results with statistical significance

IV	DV	Test statistic	Degree of freedom	p-value
Household size	Detached	18.777	4	<0.01
	Semi-detached	15.457	4	<0.01
	Terrace	11.057	4	0.026
	Apartment	9.733	4	0.045
	51 to 80 m^2	15.434	4	<0.01
	≥100 m^2	29.994	4	<0.01
	One bedroom	17.033	4	<0.01
	Two bedrooms	39.478	4	<0.01
	Three bedrooms	19.884	4	<0.01
	Four bedrooms	59.364	4	<0.01
	Bricks	10.410	4	0.034
Age	Detached	17.194	2	<0.01
	Semi-detached	59.691	2	<0.01
	Terrace	12.678	2	<0.01
	Urban	7.189	2	0.027
	Suburban	13.366	2	<0.01
	≤50 m^2	11.247	2	<0.01
	51 to 80 m^2	15.760	2	<0.01
	≥100 m^2	6.006	2	0.05
	Two bedrooms	17.517	2	<0.01
	Three bedrooms	8.880	2	0.012
	Four bedrooms	92.380	2	<0.01
	Concrete	25.208	2	<0.01
	Timber	7.537	2	0.023
	Bricks	23.919	2	<0.01

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TABLE APP 1.4 Kruskal-Wallis test results with statistical significance

IV	DV	Test statistic	Degree of freedom	p-value
Income	Detached	53.101	3	<0.01
	Terrace	23.441	3	<0.01
	Apartment	19.553	3	<0.01
	Urban	18.581	3	<0.01
	Suburban	10.027	3	0.018
	Rural	61.173	3	<0.01
	≤50 m^2	14.823	3	<0.01
	51 to 80 m^2	40.511	3	<0.01
	81 to 100 m^2	27.156	3	<0.01
	≥100 m^2	68.724	3	<0.01
	One bedroom	9.551	3	0.023
	Two bedrooms	9.936	3	0.019
	Three bedrooms	9.663	3	0.022
	Four bedrooms	22.506	3	<0.01
	Timber	9.196	3	<0.027

TABLE APP 1.5 Post-Hoc Mann-Whitney test results with statistical significance

IV	Pairwise comparison	DV	Test statistics	Sample size	P-value
Household size	One, Two persons	Detached	30344.5	159, 453	<0.01
		Terrace	28813	152, 441	<0.01
		51 to 80 m^2	25510	150, 427	<0.01
		≥100 m^2	23896.5	149, 437	<0.01
		One bedroom	27113	150, 435	<0.01
		Two bedrooms	27583	150, 443	<0.01
		Three bedrooms	27715.5	156, 446	<0.01
	One, Three persons	Detached	6278.5	159, 110	<0.01
		Apartment	6607	154, 110	<0.01
		≥100 m^2	5497.5	149, 108	<0.01
		One bedroom	6224	150, 109	<0.01
		Two bedrooms	5859.5	150, 109	<0.01
		Four bedrooms	5336.5	150, 108	<0.01
	Two, Three persons	Four bedrooms	18386.5	438, 108	<0.01
Age	Young, Senior	Detached	12180.5	91, 354	<0.01
		Semi-detached	9447	91, 345	<0.01
		≤50 m^2	12211.5	90, 332	<0.01
		51 to 80 m^2	11261	89, 336	<0.01
		Four bedrooms	7286	91, 336	<0.01
		Concrete	11614.5	90, 342	<0.01
		Bricks	11762.5	89, 353	<0.01
	Middle, Senior	Detached	33723	219, 354	<0.01
		Semi-detached	25663.5	219, 345	<0.01
		Terrace	30741.5	217, 339	<0.01
		Suburban	31281	218, 348	<0.01
		Two bedrooms	29701	218, 342	<0.01
		Three bedrooms	32638.5	218, 345	<0.01
		Four bedrooms	22642	216, 336	<0.01
		Concrete	28882.5	216, 342	<0.01
		Bricks	30689	216, 353	<0.01

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TABLE APP 1.5 Post-Hoc Mann-Whitney test results with statistical significance

IV	Pairwise comparison	DV	Test statistics	Sample size	P-value
Income	Low, High	Detached	10107.5	124, 247	<0.01
		Terrace	10790	119, 244	<0.01
		Apartment	11534	121, 245	<0.01
		Urban	12782.5	123, 248	<0.01
		Rural	9046	124, 248	<0.01
		≤50 m^2	11336.5	115, 238	<0.01
		51 to 80 m^2	8865	117, 236	<0.01
		81 to 100 m^2	10433	117, 236	<0.01
		≥100 m^2	7720	115, 240	<0.01
		One bedroom	12274.5	121, 238	<0.01
		Two bedrooms	12353.5	120, 244	<0.01
		Four bedrooms	10663.5	120, 241	<0.01
	Middle, High	Detached	29279	332, 247	<0.01
		Terrace	33136	323, 244	<0.01
		Apartment	33297	328, 245	<0.01
		Rural	30029.5	339, 248	<0.01
		≤50 m^2	32733	319, 238	<0.01
		51 to 80 m^2	29295	321, 236	<0.01
		81 to 100 m^2	28902	323, 236	<0.01
		≥100 m^2	27306	331, 240	<0.01
		Two bedrooms	34350.5	325, 244	<0.01
		Four bedrooms	32607.5	324, 241	<0.01

A3. MAUT method implementation process

The implementation of the MAUT method includes the following main steps:

- The identification of housing attributes and attribute levels summarized in Table 4.2.
- The allocation of preference scores by the respondents to individual housing attribute levels as presented in Table 4.6.
- The allocation of importance scores by the respondents to the individual housing attributes investigated as presented in Table 4.7.
- The calculation of weights based on ratio estimation according to the following equation:

$$w_i = \frac{w_i'}{\sum_{i=1}^{n} w_i'}$$

where w_i is the normalized weight, a ratio of the importance score assigned by a respondent to a certain housing attribute, w_i', and the sum of all importance scores assigned by the same respondent to all housing attributes $\sum_{i=1}^{n} w_i'$.

Results are presented in Table APP. 1.6.

- The implementation of the compensatory weighted linear additive preference function according to the following equation:

$$v(x) = \sum_{i=1} w_i v_i \, (x_i)$$

where *v(x)* is the overall utility score of dwelling profile *x*, w_i is the normalized weight explained above and $v_i\,(x_i)$ is the preference score assigned by a respondent to the housing attribute *i.*

Results are presented in Table 4.8.

The implementation of a sensitivity analysis using the equal weights method where it is assumed that all attributes are assigned the same importance. In other words, utility scores are computed again, this time with equal weights factors. In this study, the weight for one out of five main housing attributes is 0.2. The results are presented in Table APP 1.7 and can be compared with the initial scores presented in Table 4.8.

TABLE APP 1.6 Housing attributes average importance scores and weights

	NL						BE					
	Importance scores			Weights			Importance scores			Weights		
	n	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD
DT	234	78.96	17.631	234	0.204	0.0390	559	76.23	19.332	549	0.201	0.0443
RA	234	86.57	12.750	234	0.226	0.0346	563	86.77	13.118	549	0.233	0.0432
DS	234	78.09	14.952	234	0.202	0.0274	559	75.24	17.848	549	0.198	0.0339
NB	234	71.58	20.647	234	0.184	0.0433	559	69.75	21.881	550	0.182	0.0452
BM	234	72.19	21.991	234	0.184	0.0465	559	71.34	23.421	550	0.186	0.0551

TABLE APP 1.7 Sensitivity analysis outcomes as per the equal weights method

Housing Attribute	Attribute Level	NL		BE	
		Utility Point	SD	Utility Point	SD
Dwelling Type	Detached	12.01	7.650	16.49	5.269
	Semi-detached	11.32	6.565	10.67	6.424
	Terraced	11.21	6.165	5.97	5.797
	Apartment	10.50	7.325	6.89	6.664
Residential Area	Urban	11.71	6.404	5.29	5.856
	Suburban	12.62	6.281	8.47	6.602
	Rural	10.84	6.976	17.66	3.420
Dwelling Size	Less than 50 m^2	3.00	4.896	2.18	3.753
	Between 51 and 80 m^2	7.79	6.921	5.39	5.773
	Between 81 and 100 m^2	13.01	6.534	9.55	6.931
	More than 100 m^2	12.54	7.703	15.89	5.654
Number of Bedrooms	One	3.31	5.190	3.15	5.084
	Two	11.15	7.108	10.51	7.486
	Three	12.64	6.989	13.07	6.769
	Four	8.58	7.669	8.36	7.845
Building Material	Concrete	12.19	6.528	9.99	6.361
	Timber	7.39	6.310	9.01	6.729
	Bricks	16.27	4.260	16.13	4.245

A4. Housing preferences questionnaire

Part 1: General Information				
How old are you?				
Click or tap here to enter text.				
What is your gender?				
☐ Man	☐ Woman	☐ Other		
How would you describe your living situation?				
☐ Alone	☐ with partner	☐ with family	☐ with friends	
If you are living with family or other, please describe your situation below.				
Click or tap here to enter text.				
What is the size of your household?				
☐ I live alone	☐ 2 person	☐ 3 persons	☐ More than 3 persons	
What is your net monthly income (€) excluding travel and vacation allowance or other?				
*income brackets vary per study location				
What is your main source of income?				
☐ Employment	☐ Self-employment	☐ Pension	☐ Social welfare	
If other, please specify.				
Click or tap here to enter text.				

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Part 2: Current Housing Situation									
What is your current living arrangement?									
□ Owner		□ Private rent		□ Social rent		□ Other			
If other, please specify.									
Click or tap here to enter text.									
How big is your current house (m2)?									
□ ≤ 50 m^2		□ > 100 m^2		□ I don't know					
What is the type of your dwelling?									
□ Detached		□ Semi-detached		□ Terrace		□ Apartment			
How many bedrooms do you have in your current dwelling?									
□ One	□ Two	□ Three	□ Four						
What is the main building material of the external walls of your dwelling?									
□ Concrete	□ Bricks	□ Timber	□ Other						
If other, please explain.									
Click or tap here to enter text.									
How many years have you been living in your current dwelling?									
Click or tap here to enter text.									
On a scale from 1 (very dissatisfied) to 5 (very satisfied), how satisfied are you with your current dwelling?									
Very dissatisfied		□ 1	□ 2	□ 3	□ 4	□ 5	Very satisfied		
On a scale from 1 (very uncomfortable) to 5 (very comfortable), how comfortable are you with your current dwelling?									
Very uncomfortable		□ 1	□ 2	□ 3	□ 4	□ 5	Very comfortable		
Are you willing to move?									
□ Yes	□ No								
Why (not)? Please explain below.									
Click or tap here to enter text.									
Did you take any action on the matter?									
□ Yes		□ No		□ No, I am not willing to move.					
If not, why? If yes, what? Please explain below.									
Click or tap here to enter text.									

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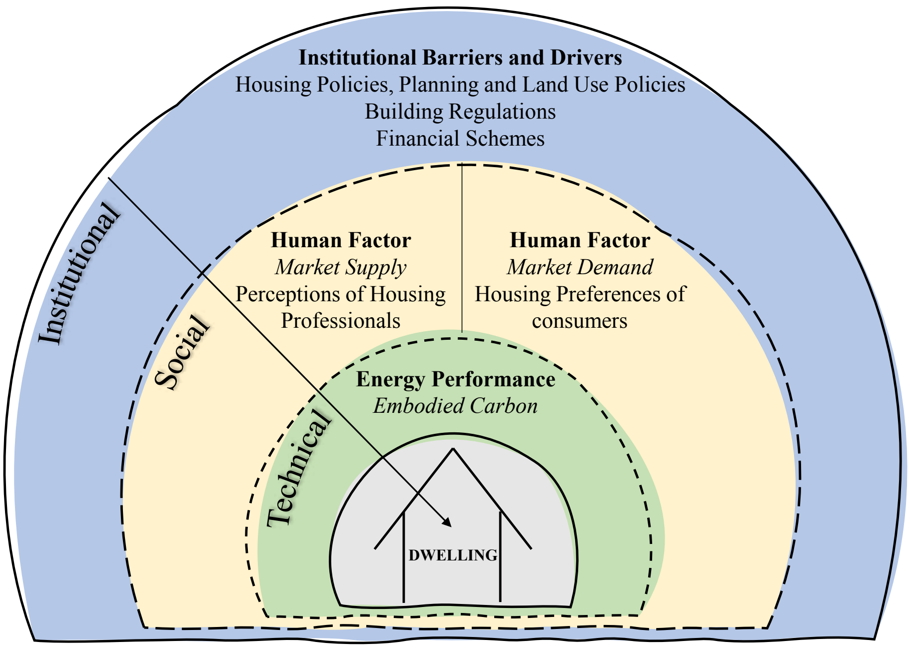
Part 3: Housing preferences									
On a scale from 1 (not important at all) to 10 (extremely important), how important are the following housing attributes to you?									
Dwelling type									
◻ 1	◻ 2	◻ 3	◻ 4	◻ 5	◻ 6	◻ 7	◻ 8	◻ 9	◻ 10
◻ 1	◻ 2	◻ 3	◻ 4	◻ 5	◻ 6	◻ 7	◻ 8	◻ 9	◻ 10
Dwelling size									
◻ 1	◻ 2	◻ 3	◻ 4	◻ 5	◻ 6	◻ 7	◻ 8	◻ 9	◻ 10
Number of bedrooms									
◻ 1	◻ 2	◻ 3	◻ 4	◻ 5	◻ 6	◻ 7	◻ 8	◻ 9	◻ 10
Building material									
◻ 1	◻ 2	◻ 3	◻ 4	◻ 5	◻ 6	◻ 7	◻ 8	◻ 9	◻ 10
Are there any other housing attributes that are extremely important to you?									
◻ Yes	◻ No								
If yes, please specify.									
Click or tap here to enter text.									
On a scale from 0 (least preferred) to 10 (most preferred), how would you value the following housing characteristics?									

The construction of a Wikihouse in Almere in the Netherlands as part of the Housing 4.0 Energy (H4.0E) project funded by Interreg North-West Europe. Copyright: Wikihouse.

PART 5

STAGE III Technical Dimension


Institutional Barriers and Drivers
Housing Policies, Planning and Land Use Policies
Building Regulations
Financial Schemes
Institutional
Social
Human Factor
Market Supply
Perceptions of Housing Professionals
Human Factor
Market Demand
Housing Preferences of consumers
Technical
Energy Performance
Embodied Carbon
DWELLING

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5 The Assessment of Downsizing and the Use of Timber as Embodied Carbon Reduction Strategies for New-Build Housing

Submitted as: Souaid, C., ten Caat, N., Meijer, A., & Visscher, H. (2023). The Assessment of Downsizing and the Use of Timber as Embodied Carbon Reduction Strategies for New-Build Housing. *Building and Environment* **2023**.

** This chapter is under review at the time of writing this manuscript.*

In Chapter 4 the social context relevant to small, low-carbon, (near) zero-energy dwellings was investigated from the demand end of the market. The outcomes of the housing preferences questionnaire highlighted the importance of distinguishing between the smallest and smaller low-carbon, zero-energy dwellings. They revealed that while there was no demand for dwellings of 50 m^2 or less, slightly larger dwellings of 50 to 80 m^2 do have the potential to fulfil the current housing preferences of households in Flander and in Almere. In that way, outcomes refute the assumption that the housing preferences of smaller, elderly and lower-income households are leaning towards smaller dwellings. Additionally, results underlined the fact that respondents are less likely to reject a dwelling profile based on the main building material used even though timber was their least preferred one. Overall, more effort is needed in promoting said dwellings for a more effective shift and an accelerated uptake.

Having covered the social dimension from the demand end of the market, this chapter finally reaches the technical dimension surrounding small, low-carbon, (near) zero-energy dwellings, as per this research's conceptual framework. The normalization of a zero operational energy through mandatory building regulations increased the importance of embodied energy rendering them the most influential share of a dwelling's life cycle emissions. Thus, this chapter tackles the technical dimension through focusing on the dwellings' embodied carbon footprint. Recalling the shift of environmental policies that now call for the prioritization of the avoidance of the demand for energy and materials, this chapter not only investigates the use of low-carbon materials such as timber, but also the impact of downsizing as embodied carbon reduction strategies.

The first part of this chapter, section 5.1., introduces and outlines the context in which this research is situated. It simultaneously describes how embodied carbon has regained relevance in the past years with the normalization of a zero operational energy (5.1.1.) and the rise of downsizing as an embodied carbon reduction strategy (5.1.2.). It also elaborates on the literature around the relationship between house size and embodied carbon (5.1.3.) as well as the literature focused on conducting life cycle assessments of dwellings (5.1.4.). Section 5.2. describes the study contribution and provides the main research question addressed. The methods are described in section 5.3., starting with the case study description (5.3.1), the study scope (5.3.2), the tool used (5.3.3.) and the assumptions made (5.3.4.). Results are presented and analysed in section 5.4 and discussed in section 5.5. leading up to the study conclusion in section 5.6.

ABSTRACT

This paper investigates downsizing and the use of timber as embodied carbon (EC) reduction strategies for new-build housing. Using TOTEM, a partial life cycle assessment is conducted focusing on the material impact of three housing scenarios: Small House, Medium House, and Large House. Two construction variations are modelled for each scenario comparing a modular timber design to a traditional concrete alternative. Designs are based on actual dwellings built in Almere, the Netherlands as part of the Housing 4.0 Energy project funded by Interreg North-West Europe. Results show a total embodied carbon ranging from 42,608 to 70,384 $kgCO_2eq$ for the timber designs and 54,681 to 91,270 $kgCO_2eq$ for its concrete counterparts. Downsizing alone led to a 40% material impact reduction. The simultaneous implementation of downsizing and the use of timber as the main building material achieved 53% carbon savings.

The relationship between house size and embodied carbon was revealed to be sub-linear. Through a hierarchical study approach, this paper demonstrates how practitioners can use outcomes at the level of the building element and component to inform their primary and secondary design choices early on for an overall improved carbon footprint and a simultaneous prevention of unnecessary embodied carbon emissions. Lastly, situating this paper's results in previous literature shed light on the lack of comparability of LCA studies obstructing a proper understanding of outcomes, thus highlighting the need for harmonized LCA methodological and documentation guidelines be it in industry or in the scientific community.

KEYWORDS Embodied carbon, life cycle assessment, tiny housing, timber construction, downsizing

5.1 Introduction and Background

In 2022, the building sector was responsible for more than 30% of the global final energy consumption making it one of the most significant contributors to climate change [1]. Being a significant contributor is also an indication of where change is most needed. The Intergovernmental Panel on Climate Change (IPCC) repeatedly reported the potential that lies within the built environment when it comes to opportunities to reduce greenhouse gas (GHG) emissions and achieve the decarbonisation goal set out for 2050 [2]. Yet, the latest Global Status report for buildings and construction highlighted a widening gap between the observed performance of the building stock and the desired pathway towards a zero-carbon target in 2050 [3]. Within the residential sector, the IPCC highlighted that global direct and indirect emissions increased by about 50% since 1990 [2]. Simultaneously, in Europe, the total number of households is increasing seeing as the majority of households are now smaller and composed of one to two persons. That is to say that, while the liveable space per person remained the same, if not increased in some countries, it is also complemented with the need for more dwellings due to the increase of smaller households [4]. In fact, numerous European countries are facing a growing housing shortage [5]. Thus, on the one hand, the urgency of climate change calls for more rapid change within the built environment to get back on track towards a net zero emissions scenario in 2050 [1]. On the other hand, future housing needs predictions render this coming decade crucial for new-build housing.

5.1.1 The increasing relevance of embodied carbon

Within the context of new-build, the political focus has been on designing to decrease energy demand throughout a building's operation phase [6]. Conformingly, research has focused on investigating the reduction of a building's operational energy [7] and regulations now often enforce a zero-operational energy performance. However, a building's environmental impact is not restricted to its use stage but also includes GHG emissions released from the production, construction, and end-of-life stages, known as embodied carbon. As such, characterizing a building as zero-energy based on its operational energy alone becomes inaccurate from a life cycle perspective. Even more so since it is argued that there is a trade-off between operational and embodied energy [7] and that emissions saved throughout the use stage are partly, if not totally, off-set by emissions released in the initial stages due to the need for extra building materials and/or technical systems [8]. Indeed, theoretically, with a zero operational energy performance, embodied energy makes up 100% of a building's carbon footprint [9]. It becomes the sole source of GHG emissions, hence, the most significant and influential one [8]. In practice, this translates into the increase of the share of embodied energy with the decrease of operational energy [10, 11], reaching 90% in extreme cases [8]. This was designated as the 'carbon spike' effect indicating the high carbon investment at the initial stages of a life cycle, a relatively shorter amount of time, risking the building's overall consumption budget [7, 12]. This increasing contribution of embodied energy is reinforced further when taking into account the future possibilities of the decarbonisation of the energy grids [8, 13, 14]. All in all, the normalization of a zero operational energy performance through building regulations significantly increased the relevance of embodied energy [14]. This has forced a shift of the political focus. What had been previously under-addressed amongst mitigation strategies has now regained traction and the reduction of embodied carbon has reached the top priority level of several international environmental programs [3, 15, 16].

5.1.2 Downsizing as an embodied carbon reduction strategy

At the outset, through life cycle assessment (LCA), literature explored numerous embodied carbon reduction strategies [3, 10]. A well-known example is the use of low-carbon building materials [17] such as timber, a material choice that is being extensively investigated [7, 18-22]. However, the permanence that is peculiar to embodied energy combined with the urgency of climate action calls for a more radical approach. Unlike operational energy, once measures are implemented in a building, their embodied emissions cannot be reduced. The implementation of

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any further measures automatically causes an increase in the building's embodied energy regardless of its potential benefits [6]. As such, avoidance, the fundamental embodied carbon reduction strategy, regained precedence [23]. In their sixth assessment report, the IPCC re-introduced the *Sufficiency, Efficiency, and Renewables* hierarchical framework where sufficiency encourages first and foremost the avoidance of 'demand for energy and materials over the life cycle of buildings and goods' (p.7 lines 43-44) [24]. When sufficiency is met with an alarming growing need for new-build housing, it translates into building less and becomes 'adjusting the size of buildings to the evolving needs of households by downsizing dwellings' (p.4 lines 29-30) [24]. In that way, it becomes crucial not only to use low-carbon materials to reduce embodied carbon and prevent outweighing operational emissions reductions but to simultaneously decrease quantities and design to limit embodied carbon emissions at an early stage prior to any application.

5.1.3 The relationship between house size and embodied carbon

Literature promoting sufficiency strategies agrees that an increase in house size unmistakably results in an increase of its embodied carbon [10, 25, 26]. Even beyond the carbon spike, previous research demonstrated that maintenance, repair and/or replacement requirements are higher for larger dwellings [27]. That being said, research investigating the impact of downsizing on a dwelling's embodied carbon is generally limited and existing studies do not align when it comes to the nature of the relationship between house size and embodied carbon, the definition of a small house, and the reporting of outcomes. Findings concerning the relationship between house size and embodied carbon are contradictory and the correlation between them was demonstrated to be either super-linear [27, 28], or sublinear [29][9]. Dwelling size was either determined based on number of extra rooms in relation to the household size [27] or based on square meter of floor area [11, 28, 29]. Additionally, most studies are geographically located in contexts where the average house size investigated is considerably large reaching up to 328 m^2 in the U.S. and 246 m^2 in Australia [27-29]. This leads to outcomes that are not directly relatable to contexts like Europe where the average house size is known to be smaller and concepts such as the 'Tiny House' are being explored [30]. When

9 A linear correlation entails a 1:1 ratio. A house with double the size entails double the embodied carbon. A super-linear correlation exceeds a 1:1 ratio. A size with double the size entails three times the embodied carbon. A sublinear correlation is less than a 1:1 ratio. A house with double the size entails less than double the embodied carbon.

reporting outcomes, larger dwellings appear to be more energy efficient per square meter and smaller dwellings with the lowest total emissions have the highest emissions per square meter [11, 29]. These different misalignments amongst previous studies lead to their lack of comparability which only reinforces the existing gap on the investigation of embodied carbon reductions from downsizing. Overall, not only is there a need to investigate the impact of house size on embodied carbon and to clarify the nature of this correlation, but there is also a need to bring smaller dwellings into the discussion and to investigate the potential impact - and benefits - of downsizing at the lower end of the range of housing sizes.

5.1.4 The lack of comparability of LCA studies and outcomes

On a higher level of inquiry, the lack of comparability of outcomes is not specific to studies exploring downsizing but rather a well-known aspect of LCA studies and was identified as one of the most significant barriers hindering the field's growth [6, 14, 31, 32]. For instance, reported carbon reduction outcomes from the use of timber vary from 10% [13], to surpassing 50 % [20, 33]. Discrepancies between outcomes are a result of significant variations of study characteristics, scope definitions, LCA databases, the biogenic carbon accounting approach, and the lack of transparency around study assumptions and modelling choices [8, 34]. Differences in building types, size, geographic locations, structures, construction materials, and building services render any attempt at a comparison of different results invalid [8, 31]. Different scope definitions attributed to the system boundaries leading to the exclusion/inclusion of life cycle stages increase the complexity of such comparisons [35]. Limited system boundaries often lead to the underestimation of a building's total embodied energy [13], otherwise known as truncation errors. Additionally, each implementation of LCA entails a level of uncertainty around embodied carbon estimations due to various assumptions made. Known examples concern the assumptions made around carbon storage accounting and end-of-life scenarios from the use of timber [14]. Lastly, a lack of transparency obstructs the proper understanding of study outcomes and/or their verification and replication [6]. Consequently, due to the lack of comparability of existing LCA studies, there is no general consensus on the extent of the effectiveness of embodied carbon reduction strategies. Transparency is key and clear reporting of the decision making process is necessary to better grasp the impact of such decisions on overall results.

5.2 Study Contribution and Main Research Question

In sum, the urgency of climate change combined with housing needs predictions calls for the prioritization of avoidance and sufficiency through downsizing in the implementation of embodied carbon strategies. However, research investigating downsizing is limited and the nature of the correlation between house size and embodied carbon remains unanswered. There is also a need to bring smaller dwellings into the discussion and to investigate the potential impact of downsizing at the lower end of the range of housing sizes. Additionally, while past literature agrees on the effectiveness of downsizing as an embodied carbon reduction strategy, the lack of comparability of LCA outcomes entails a lack of consensus on the extent of said effectiveness. This calls for the need for full transparency and clear reporting for a better understanding of study outcomes.

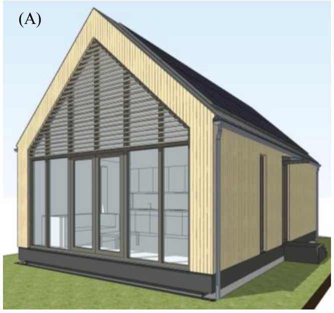
Given this backdrop, this study answers the following main research question: *What is the impact of downsizing and the use of timber on the embodied carbon of a new-build dwelling?* In response, this paper's contribution is threefold. First, through a shift of approach that prioritizes avoidance and sufficiency, its objective is to make the case for the simultaneous implementation of both downsizing and the use of timber as embodied carbon reduction strategies by exemplifying the savings of each strategy individually and highlighting the additional savings of implementing them together. Second, in its investigation of the relation between house size and embodied carbon, this paper sets out to investigate a selection of housing sizes at the lower end of the range to reach outcomes that would better reflect the European context. Third, in response to the need for more transparent LCA studies, this paper tackles its research question through a highly detailed case study with clearly defined system boundaries, and a clear documentation of the decision making process underlying its outcomes.

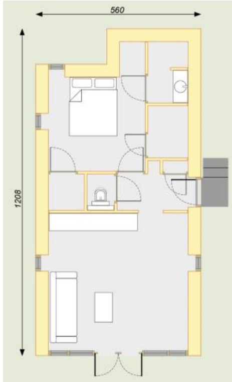
Section 5.3 begins with a comprehensive description of the case study, followed by a clear definition of the scope, an outline of the tool used and a list of study assumptions. Section 5.4 presents the embodied carbon analysis results. Findings are then discussed in section 5.5 including study limitations and final conclusions are drawn in section 5.6.

5.3 Methods

5.3.1 Case study description

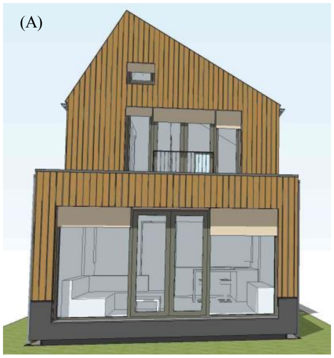
In this paper, a small house is defined to have a net floor area (NFA) of up to and including 50 m^2. A medium sized house has a NFA between 50 and 100 m^2 exclusively, and a large house has a NFA of 100 m^2 and above. This study investigates existing dwellings built as part of the project entitled Housing 4.0 Energy: Affordable & Sustainable Housing through Digitization (H4.0E) funded by Interreg North-West Europe [36]. Particularly, three detached dwellings built in Almere, in the Netherlands, are investigated with a NFA of 45, 76 and 104 m^2. The H4.0E dwellings follow ‘Wikihouse’, a design concept created to encourage self-building by providing digitally produced timber frame kits to be assembled on site [37]. With the exception of the dwellings’ foundations, structural building elements such as beams and columns are made by assembling Multiplex wood panels. Every dwelling size is referred to as a scenario: the “Small House” (45 m^2), the “Medium House” (76 m^2), and the “Large House” scenario (104 m^2). Figure 5.1 provides a description of each with a render showing the exterior of the dwelling, a simplified floor plan and a list of the main dwelling characteristics. All three scenarios have the same location and structural design. Main differences are related to house size, hence material quantities. Data was collected from architectural drawings, bill of quantities and additional information provided by architects and engineers involved in the H4.0E project for an improved robustness of results [29].

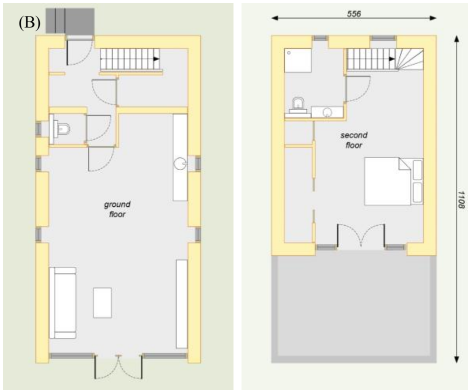




(C) Dwelling type: Detached
Net floor area: 45 m²
Gross floor area: 59 m²
Number of floors: 1
Glazing: 23%

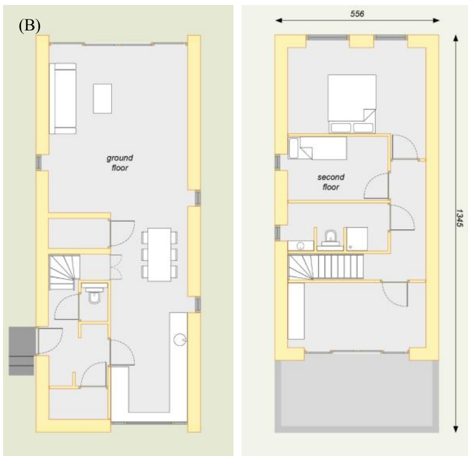
Scenario 2: Medium House





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

Scenario 3: Large House



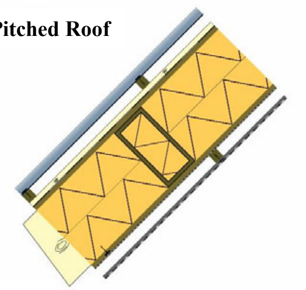
(C) Dwelling type: Detached
Net floor area: 104 m²
Gross floor area: 137 m²
Number of floors: 2
Glazing: 20%

FIG. 5.1 Characteristics of study scenarios (A) Dwelling exterior (B) Floor plans (C) Main dwelling characteristics

To investigate the impact of timber as the main building material, there is a need for a benchmark, otherwise known as a “business as usual” reference dwelling. For this purpose, a theoretical baseline was created with concrete, both prestressed and cast in-situ, and limestone blocks and bricks as the main building materials. Concrete was chosen as the alternative construction variation considering it remains the standard go-to building material in the sector [7]. The detailed baseline designs were tailored to the Dutch context based on the input of practitioners within the H4.0E project. Thus, two construction variations were assessed: the timber-based (H4.0E) construction and the concrete-based baseline as the traditional alternative, resulting in six different models. In each scenario, the timber design and the baseline alternative had the same floor space and the engineering integrity of the house was preserved in each variation. Figures 5.2 and 5.3 provide section drawings showing the detailed composition of the dwellings’ main building elements as well as their thermal performance under each construction variation. The initial thermal performance of the H4.0E building envelope surpasses Dutch standards and was maintained the same when designing the building envelope of the baseline alternatives[10].

10 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 5.3.

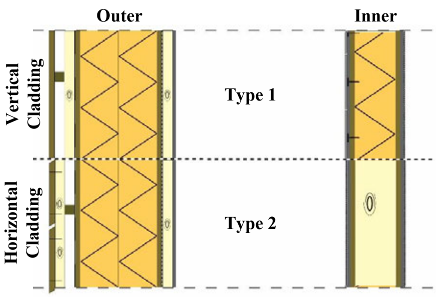
Timber Pitched Roof



Timber Pitched Roof – U-value = 0.11 W/m^2K

(1) Galvanised Steel | Corrugated Sheet – screwed (0.6 mm)
(2) Softwood | Battens – nailed, untreated (50 mm)
(3) Softwood | Battens – nailed, untreated, c.t.c. 450 mm (47x22 mm)
(4) EPDM | Proofing Membrane – partially glued (1.2 mm)
(5) Plywood | Board – nailed (18 mm)
(6) Glass Wool | Blanket – between beams (300 mm)
(7) Plywood | Board – nailed (18 mm)
(8) PP-LDPE | Proofing Sheet – stapled (0.22 mm)
(9) Softwood | Battens – nailed, untreated (63 mm)
(10) Gypsum Fibre | Board – screwed, with joint filler (18 mm)
(11) Traditional Plaster | Thick Coating – by machine (7 mm)

Timber Walls



Timber Outer Walls (Types 1&2) – U-value = 0.11 W/m^2K

(1) Larch | Planks – nailed, untreated (22 mm)
(2) Softwood | Battens – screwed, untreated, c.t.c. 600 mm (38x38 mm)
(3) PE | Proofing Membrane – stapled (0.2 mm)
(4) Plywood | Board – nailed (18 mm)
(5) Glass Wool | Blanket – between beams (300 mm)
(6) Plywood | Board – nailed (18 mm)
(7) PP-PE | Proofing Membrane – taped (0.22 mm)
(8) Softwood | Battens – screwed, untreated c.t.c. 600 mm (63 mm)
(9) Gypsum Fibre | Board – screwed, with joint filler (12.5 mm)
(10) Acrylic Paint | Film Coating (-)

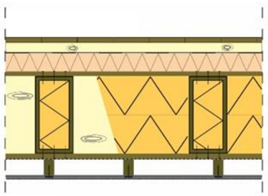
Timber Inner Wall | Type 1 – U-value = 0.2 W/m^2K

(1) Glazed Ceramic | Rigid Tiles – glued on board (200x200x9mm)
(2) Gypsum Fibre | Board – screwed with joint filler (12.5 mm)
(3) Plywood | Board – screwed on softwood (18 mm)
(4) Glass Wool | Blanket – between beams (150 mm)
(5) Plywood | Board – screwed (18 mm)
(6) Gypsum Fibre | Board – screwed with joint filler (12.5 mm)
(7) Acrylic Paint | Film Coating (-)

Timber Inner Wall | Type 2 – U-value = 1.53 W/m^2K

(1) Acrylic Paint | Thin film (-)
(2) Plywood | Board – screwed (18 mm)
(3) Cavity (support beam drawn) (64 mm)
(4) Plywood | Board – screwed (18 mm)
(5) Acrylic Paint | Film Coating (-)

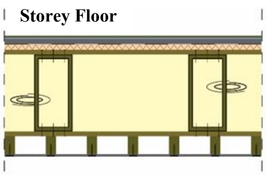
Timber Roof Terrace



Timber Roof Terrace – U-value = 0.09 W/m^2K

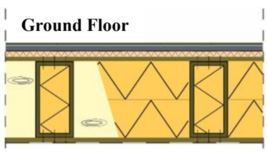
(1) Hardwood | Planks – screwed, treated (140x20 mm)
(2) Softwood | Supporting Battens (40 mm)
(3) EPDM | Proofing Membrane – partially glued (1.2 mm)
(4) Stone Wool | Board – loose laid (fixed on inclination) (40/100 mm)
(5) Plywood | Board – nailed (18 mm)
(6) Glass Wool | Blanket – between beams (300 mm)
(7) Plywood | Board – nailed (18 mm)
(8) PP-LDPE | Proofing Sheet – stapled (0.22 mm)
(9) Softwood | Battens – nailed, untreated (63 mm)
(10) Gypsum Fibre | Board – screwed, with joint filler (18 mm)
(11) Traditional Plaster | Thick Coating – by machine (7 mm)

Timber Floors



Timber Storey Floor – U-value = 0.65 W/m^2K

(1) Laminate | Parquet – with XPS underlayment (7+6 mm)
(2) Gypsum Fibre | Board – with slots for floor heating* (18 mm)
(3) PE | Proofing Membrane (0.2 mm)
(4) EPS | Board – upon floor slab (20 mm)
(5) Plywood | Board – nailed (18 mm)
(6) Cavity (cross beams drawn) (300 mm)
(7) Plywood | Board – nailed (18 mm)
(8) Softwood | Joists & Beams – nailed, treated, uncontaminated (70 mm)
(9) Gypsum Fibre | Board – screwed with joint filler (10 mm)
**heating system and slots are not drawn*



Timber Ground Floor – U-value = 0.11 W/m^2K

(1) Laminate | Parquet – with XPS underlayment (7+6 mm)
(2) Gypsum Fibre | Board – with slots for floor heating* (18 mm)
(3) PE | Proofing Membrane (0.2 mm)
(4) EPS | Board – upon floor slab (20 mm)
(5) Plywood | Board – nailed (18 mm)
(6) Glass Wool | Blanket – between beams (300 mm)
(7) Plywood | Board – nailed (18 mm)
(8) PE | Cavity Membrane (water barrier) – taped (0.6 mm)
**heating system and slots are not drawn*

FIG. 5.2 Detailed composition of main building elements under the timber design

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) Stone Wool | Blanket – between beams	*(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/m², 180 mm, d=3.5 mm)	(n.a.)
(5) PVC | Insulation Clips – for cavity wall	(n.a.)
(6) Stone Wool | 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	(200x200x9mm)

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) Stone Wool | Board – upon floor slab	*(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

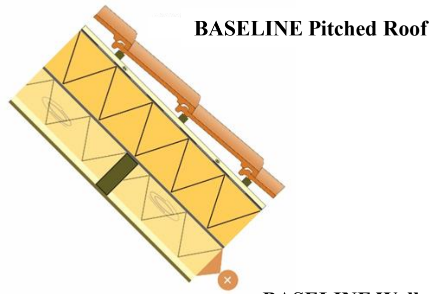
(1) Concrete | Screed	(50 mm)
(2) Steel | Mesh Reinforcement – 50x50	(n.a.)
(3) Concrete | Hollow Slab Floor – prestressed	(150 mm)
(4) Traditional Plaster | Thick Coating – by machine	(7 mm)
(5) Acrylic Paint | Film Coating	(-)

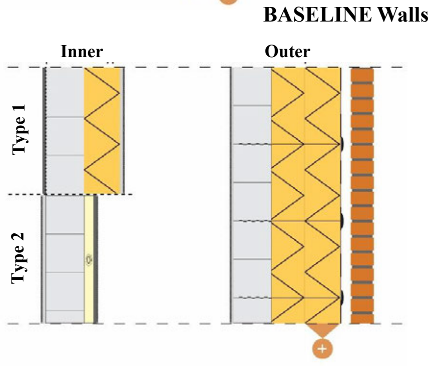
BASELINE Storey Floor – U-value = 0.52 W/m²K

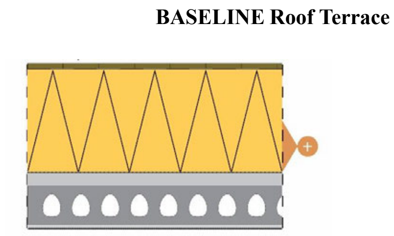
(1) Laminate | Parquet – with XPS underlayment	(7+6 mm)
(2) PE | Proofing Membrane	(0.2 mm)
(3) Concrete | Screed	(50 mm)
(4) Steel | Mesh Reinforcement – 50x50	(n.a.)
(5) Stone Wool | Board – upon floor slab	(50 mm)
(6) Concrete | Hollow Slab Floor - prestressed	(150 mm)

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 – upon floor slab	(50 mm)
(6) Concrete | Hollow Slab Floor - prestressed	(150 mm)
(7) Stone Wool | Board – below floor slab	*(275 mm)*
(8) PE | Cavity Membrane (water barrier) – taped	(0.6 mm)







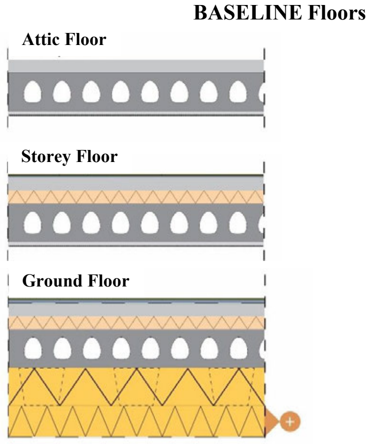


FIG. 5.3 Detailed composition of main building elements under the baseline design

5.3.2 Study scope

The physical system boundary is associated with the different materials, components and elements that make up a dwelling. The temporal system boundary is linked to the service life of the dwelling and includes the different modules of a LCA as defined in the standards [13].

Physical system boundary

The physical system boundary of a dwelling is composed of its structural elements and building services including renewable energy technologies. Structural elements can be responsible for up to 50% of the initial embodied carbon and 20% of the whole life cycle carbon [14]. Accordingly, this study incorporates all building materials, components and elements related to the construction of the dwellings. Due to uncertainties around the estimation of embodied carbon values and assumptions around the maintenance, replacement, and end-of-life of building services and renewable technologies, these were excluded from this study. Including sanitary elements and furniture is not common practice in LCA studies. Thus, in an effort to avoid uncertainties and to increase the comparability of outcomes with existing studies, these were also excluded from this study (Table 5.1). Additionally, it is worth noting that larger dwelling sizes require additional fittings and furniture. Including such elements would accentuate the embodied carbon savings of smaller dwellings and excluding them indicates that this study's outcomes are conservative.

TABLE 5.1 Building elements included and excluded from the study's physical system boundary

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

Temporal system boundary

A dwelling's temporal system boundary ranges between 30 and 100 years, with the most common service life duration varying between 50 and 60 years. Although the average lifespan of a dwelling is more than 60 years, it is known that severe renovations will be required after this period. Accordingly, the temporal system boundary of choice in this study, also known as the estimated service life (ESL), is assumed to be 60 years [38]. In terms of LCA modules, the different temporal system boundaries are: cradle to gate, cradle to site, cradle to end of use, cradle to grave and cradle to cradle [9] as illustrated in Figure 5.4 according to the life cycle modules of the European standard EN15978:2011. Figure 5.4 also provides a clear definition of the temporal system boundary adopted in this study with modules A1 to A5, B2, B4, and C1 to C4 (highlighted in green) included in this investigation. The H4.0E dwellings were designed to have a zero operational energy[11] and the selected dwellings have the same building services and renewable technologies installed. Theoretical baselines were designed by maintaining the same thermal performance (Figures 5.2 and 5.3). Accordingly, to focus on material impact, operational energy use related modules B1, B6 and B7 are considered beyond the scope of this study. Since repair activities (B3) are user-specific and no default scenarios are available [38], determining user-specific repair scenarios is also considered beyond the scope of this study. Considering, the focus of this investigation is new-build and with a service life of 60 years, refurbishment activities (B5) fall outside of the scope. Lastly, following the European standard cut-off, module D is considered beyond the scope of this study.

11 As part of the H4.0E project, the operational energy of the dwellings was monitored for a period of one year. Results revealed that three out of the five H4.0E dwellings monitored in Almere were energy positive thus producing more energy than they consume for a period of one year. This supports the assumption made in this study claiming that the operational energy of the dwellings is zero. However, for privacy reasons, the detailed data and analysis were not disclosed in this paper.

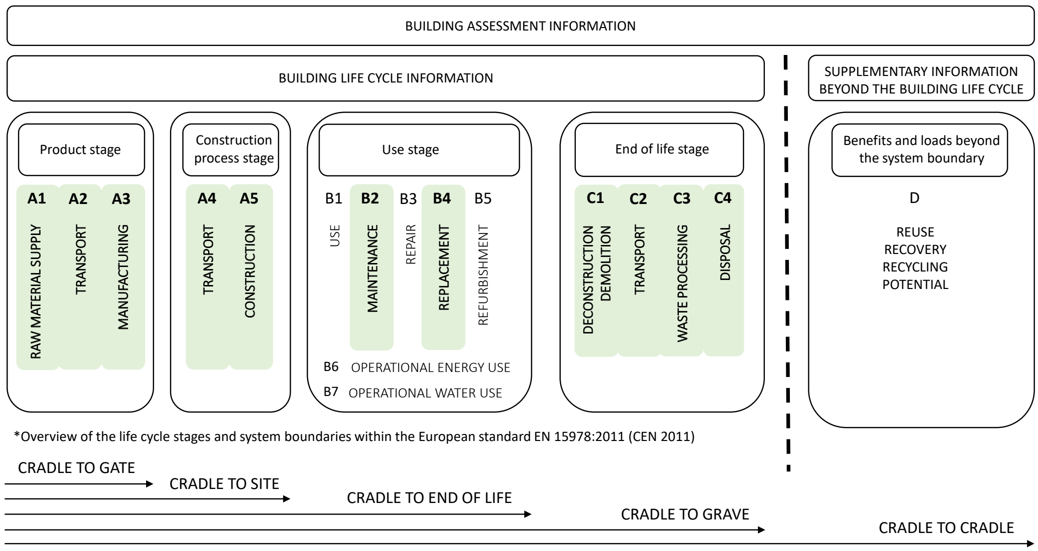


FIG. 5.4 EN 15978 Life cycle stages modules within different temporal system boundaries

5.3.3 TOTEM: Tool to Optimize the Total Environmental Impact of Materials

This study uses the Belgian based Tool to Optimize the Total Environmental Impact of Materials (TOTEM) for the embodied carbon analysis [38]. TOTEM adopts a hierarchical structure that divides a building into four levels: building, element, component, and material, thus allowing the analysis to go across different levels of detail, from the aggregated to the specific (Figure 5.5). Accordingly, TOTEM provides access to aggregated databases. This reduces the need for assumptions regarding material types and/or quantities within building elements and components which might have otherwise been overlooked.

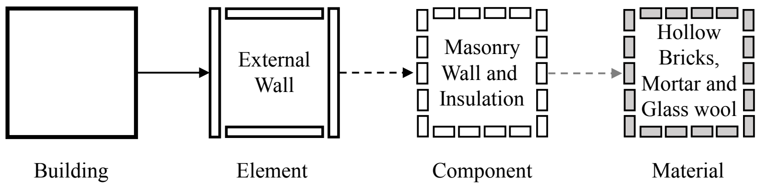


FIG. 5.5 Visualization of TOTEM hierarchy with an example

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). There are three main functional units for data entry: square meters (m^2) for plane surfaces (roof, walls, floors, windows), linear meter (m) for structural elements (beams) and individual piece (doors) [38]. The key metric focused on in this paper is the global warming potential (GWP) and the embodied carbon dioxide equivalent (CO_{2eq}) is used to capture it [13]. Most building materials included in the TOTEM library are based on the Swiss Ecoinvent database [39]. Preference is given to the data and processes that are representative of Western Europe. When such context specific data is not available, global data records are included after being modified to better represent the Belgian and/or Western-European context [38][12].

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

5.3.4 Study assumptions

Central to achieving transparency is a clear communication of study assumptions. The main assumptions abided by through the use of TOTEM are listed herein [38].

- The static -1/+1 approach for biogenic carbon is adopted where a negative value of carbon emissions is assigned in the product stage of the biomaterial and is cancelled out by the equivalent positive value in its end-of-life (EOL) stage, mostly through incineration, making the carbon balance neutral from the whole life cycle perspective.
- The impact from the incineration of construction and demolition waste is allocated in its entirety to the material being incinerated.
- Maintenance and replacement scenarios are based on the type and function of every building element. Elements that serve the safety or comfort of the residents undergo maintenance/replacement interventions regardless of the expected service life of the dwelling. Elements that serve aesthetic reasons only undergo interventions when the remaining service life of the dwelling is equal to or exceeds half of the original frequency time of the intervention[13].
- The carbonation of concrete was not integrated in the embodied carbon calculations because of its expected negligible impact within the lifespan considered [14].
- The impact of the recycling process falls outside the system boundaries of the waste product.
- EOL scenarios are constructed per building material/component (Figure 5.6).

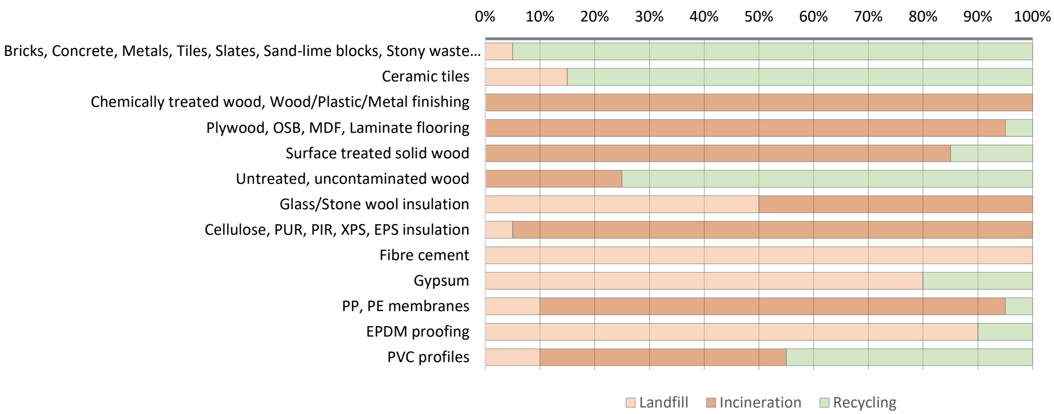


FIG. 5.6 End-of-life scenarios (adapted from [38])

13 Refer to Study Inventory in the supplementary materials for more information on the estimated service lives per individual building complement within all building elements included in the study

5.4 Results and Analysis

The presentation of results follows TOTEM's hierarchical structure: the building level (section 5.4.1), the building element level (section 5.4.2), and the building component level (section 5.4.3).

5.4.1 Building level

Total embodied carbon outcomes

Table 5.2 provides the total life cycle embodied carbon in kilograms of CO_2 equivalent (kgCO_2eq) for every scenario over an ESL of 60 years. For the timber scenario, results reveal a total embodied carbon of 42,608 kgCO_2eq for the 'Small House', 52,883 kgCO_2eq for the 'Medium House', and 70,384 kgCO_2eq for the 'Large House' confirming the fact that a larger dwelling inevitably has a higher embodied carbon due to a bigger floor area and the need for more construction materials [8, 10, 25]. The scaling of outcomes through the use of a spatial functional unit leads to a change in order where the 'Small House' timber scenario has the highest embodied carbon of 722 kgCO_2eq per square meter (kgCO_2eq/m^2), the 'Medium House' 512 kgCO_2eq/m^2, and the 'Large House' 514 kgCO_2eq/m^2. This is a direct manifestation of how the scaling of outcomes plays in favour of larger dwellings by masking the differences between the total impact of the dwellings [11]. In that way, this study echoes previous research findings stating that solely measuring embodied carbon per spatial functional unit is not enough as it inadequately captures the actual environmental impact of the dwelling and additional metrics are necessary for a more accurate representation [29]. Additionally, when comparing construction alternatives, Table 5.2 also shows that all three timber models (Models 1, 3, and 5) achieve an embodied carbon that is lower than their baseline counterparts (Models 2, 4, and 6). This echoes the unanimity of previous studies around the better performance of timber as a construction material [7, 18-22].

TABLE 5.2 Total life cycle material impact of H4.0E dwellings and their baseline alternatives

Scenario	Small House		Medium House		Large House	
Life cycle embodied carbon	Timber (Model 1)	Baseline (Model 2)	Timber (Model 3)	Baseline (Model 4)	Timber (Model 5)	Baseline (Model 6)
Total Outcome ($kgCO_2eq$)	42,608	54,681	52,883	69,725	70,384	91,270
Normalized Outcome ($kgCO_2eq/m^2$)	722	927	512	675	514	666

Total embodied carbon reductions per strategy

Figure 5.7 provides embodied carbon savings through reduction percentages from the implementation of downsizing and the use of timber. Findings show that all reduction percentages exceed the TOTEM significance threshold of 20% thus ruling out potential changes in outcomes due to uncertainties around the assumptions made [38]. First, 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 embodied carbon reductions varying between 22 and 24%. Second, the comparison of outcomes between baseline designs alone traces reductions resulting strictly from a change in house size. As such, downsizing resulted in embodied carbon reductions varying between 22 and 40%. Third, the comparison between the large baseline house, Model 6[14], and the timber dwelling designs, Models 1 and 3, traces the simultaneous reductions from both downsizing and the use of timber. Overall, only the implementation of both strategies together achieves the highest embodied carbon reduction with 42% for the Medium House and 53% for the Small House scenario. These reduction percentages also indicate that, when it comes to the nature of the relationship between house size and embodied carbon emissions, a one to two ratio only occurs when timber and downsizing strategies are implemented simultaneously. In other words, the embodied energy consumed by a single large concrete house is twice as much as the embodied energy consumed by a single small timber house as per the 53% reduction percentage obtained. Nevertheless, the relationship was revealed to be sub-linear [29] and not super-linear [28] considering a medium sized timber dwelling already consumes 42% less embodied carbon than its larger concrete counterpart.

14 Model 6 was considered the reference case scenario since it better represents the ‘business as usual’ dwelling with a NFA of 100 m^2 and concrete as its main building material.

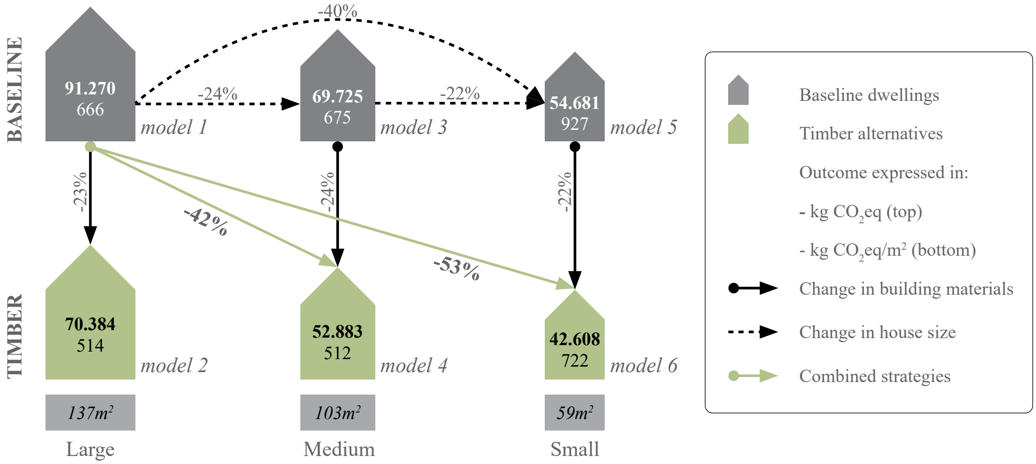


FIG. 5.7 The process behind calculating reduction percentages per strategy and their outcomes

Total embodied carbon reductions per temporal system boundary

Based on the temporal system boundaries described in section 3.2, Figure 5.8 shows embodied carbon reductions achieved from cradle to gate, cradle to site, cradle to end-of-life and cradle to grave. When comparing timber to baseline designs, a recurrent pattern reveals itself whereby achieved embodied carbon reductions start off considerably high from cradle to site, varying between 80 to 90%, to slowly be reduced to 22 to 24% from cradle to grave. Put differently, in the temporal analysis of GHG emissions, the production of building materials used to represent a dominating share of life cycle emissions. With the use of timber as the main building material, this initial carbon spike is tempered and the production of a timber dwelling is up to 90% less carbon intensive than the production of a concrete dwelling. Instead, another carbon spike occurs throughout the end-of-life of a dwelling where a significant amount of reductions are offset. This can be attributed to the choice of the static carbon storage accounting model (-1/+1) where a zero biogenic carbon balance is assumed over the life cycle of the material. This translates into timber structures having a greater amount of carbon emissions in their end-of-life stage due to the assumption of incineration as the end-of-life scenario [22]. In that way, this gradual presentation of outcomes confirms the importance of exploring different biogenic accounting methods and end-of-life scenarios for timber to better represent its benefits as a fractional reduction in these stages would have a large reduction effect on the total embodied carbon of timber dwellings.

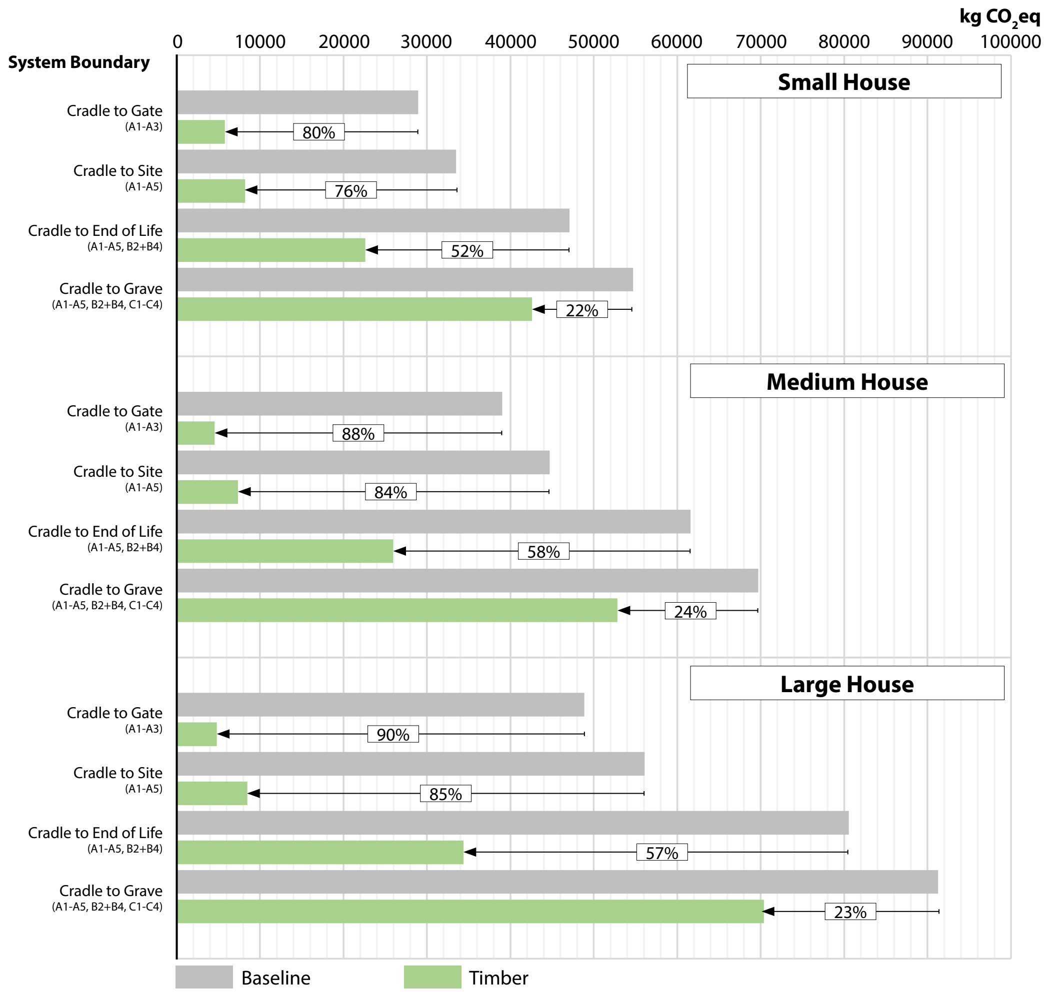


FIG. 5.8 Total embodied carbon reductions per temporal system boundary

5.4.2 Building element level

Figure 5.9 shows the impact of every building element on the embodied carbon outcomes in all six models. The figure reveals that the pitched roof, ground floor and external walls are important contributors in the timber-based designs 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. Variations in the order of importance of building elements per dwelling can be attributed to the differences in quantities and architectural designs such as the surface area of the pitched roof or the glazing (refer to Figure 5.1). Overall, it can be said that the building envelope controls the weight on embodied carbon outcomes. These outcomes highlight the importance of primary design choices related to the composition of the building frame and manifest their significant impact on a dwelling's total embodied carbon footprint.

Figure 5.9 also shows embodied carbon outcomes per life cycle module colour coded according to the different building elements included in the design. The disposal end-of-life module C4 was revealed to be responsible for the highest share of embodied carbon in all three timber-based dwellings varying between 34 and 36% of their total embodied carbon footprint. Whereas the production modules A1 to A3 are more dominating in the concrete-based baselines with a share of 53 to 56% of the dwellings' total embodied carbon footprint. Looking into the composition of these outcomes per building element, it becomes clear that disposal module C4 consists of the building elements made of timber whereas production modules A1 to A3 consist of the building elements made of concrete. This reiterates that adopting the static model of biogenic carbon accounting results in much higher end-of-life emissions for timber structures in comparison to the concrete alternative where most of the material is assumed to be recycled [22] (refer to Figure 5.7). More importantly, for both designs, replacement module B4 was revealed as a significant contributor to the dwellings' embodied carbon footprint with a share of 20% to 32%. This has been flagged by previous studies stressing on the importance of accounting for the maintenance and/or replacement of building elements throughout the building's service life [27]. The results confirm the fact that larger dwellings do require more upkeep seeing as the share of embodied carbon emissions coming from Module B4 increases with the size of the dwelling in both construction alternatives [27]. Additionally, it is worth noting that doors, windows and skylights, secondary elements that are not always included in LCA studies, were revealed to be amongst the important contributors in addition to main building elements such as ground floor, external walls, and pitched roof. This is a direct manifestation of how the exclusion of such elements can lead to the underestimation of a dwelling's total embodied carbon footprint and be considered selective scoping.

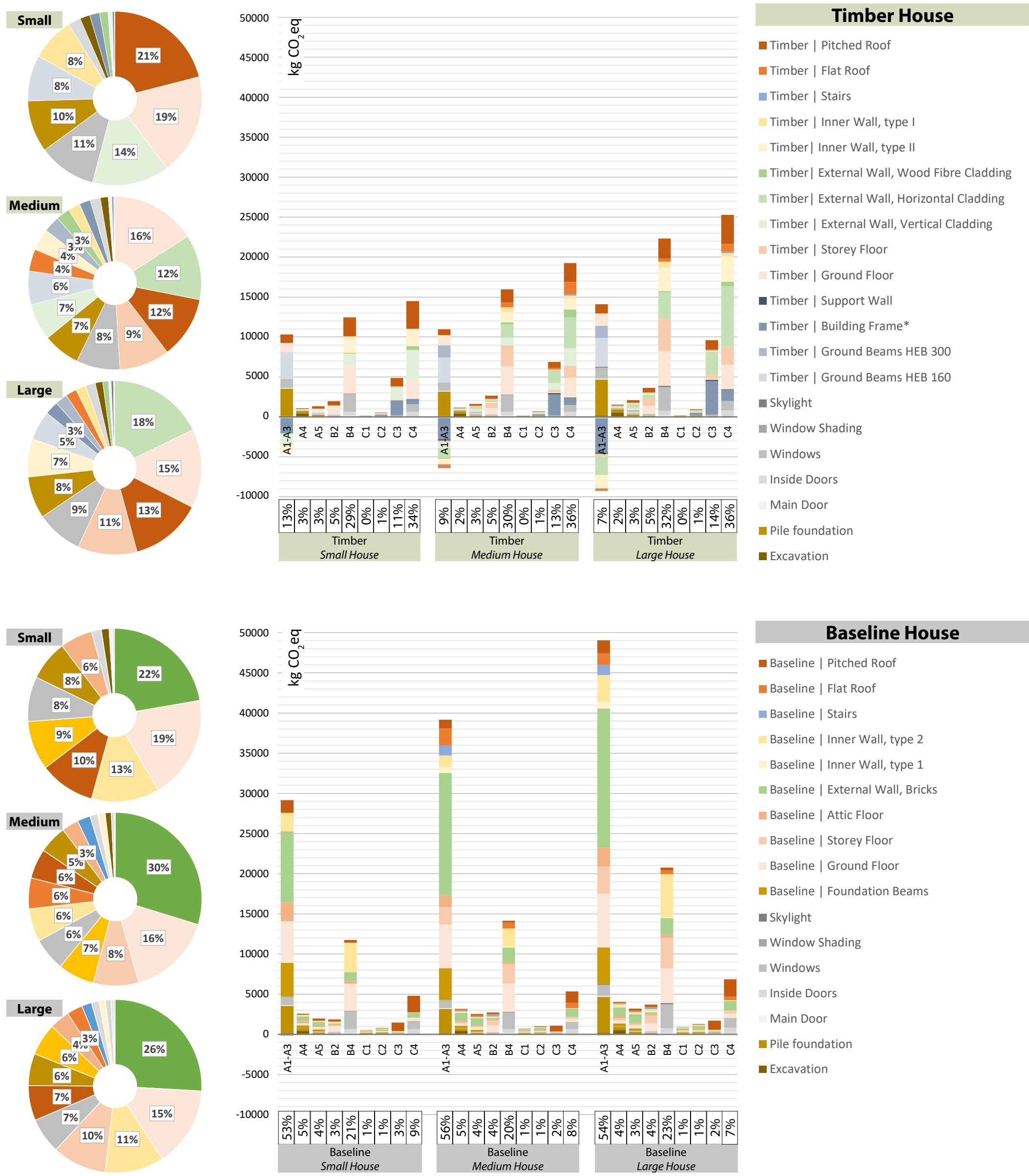


FIG. 5.9 Embodied carbon outcomes per building element and per life cycle module

5.4.3 Building component level

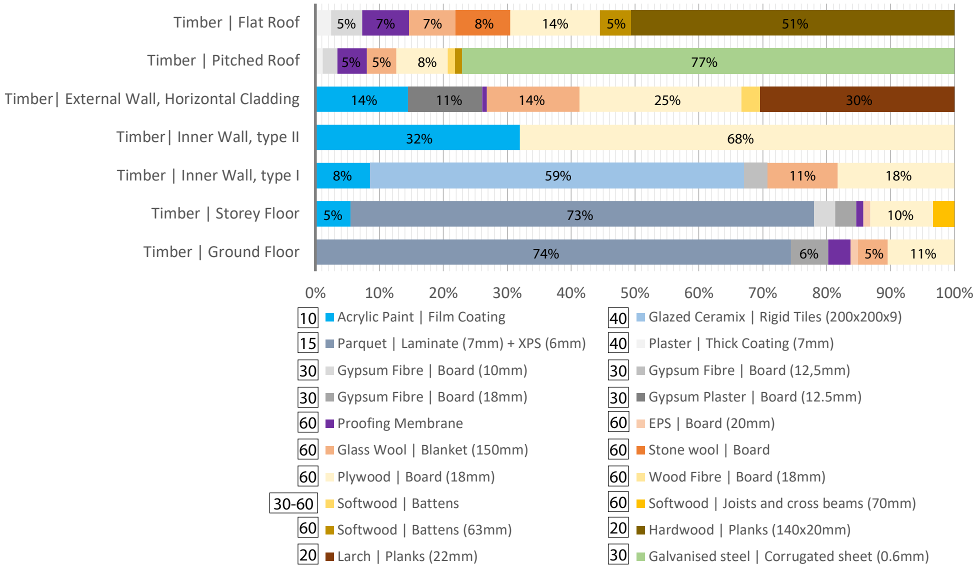
Figure 10[15] displays embodied carbon contributions per building components within the main elements of both construction variations. The ESL of every building component is also indicated. The presentation of results at the building component level allows the identification of highly carbon intensive secondary design choices outside of the primary design choices. Starting with the dominant building elements identified in section 5.4.2., the outcomes reveal that finishing components are major contributors in both construction variations. In the dwelling floors, the use of parquet laminate, a common choice of flooring in the Netherlands, accounted for the majority of the embodied carbon reaching 74% of the total impact of the floors in the timber dwelling and ranging from 59% to 67% in the baseline design. In the pitched roof, galvanized steel was chosen as the finishing of the timber dwellings in the H4.0E project and amounted to 77% of the building element's total embodied carbon. In the walls, although not dominant, acrylic paint is responsible for a considerable share of the walls' total embodied carbon. This finishing type becomes even more significant when considering its cumulative share in all building elements.

Following the same reasoning, insulation becomes another design choice with potentially significant embodied carbon consequences. Albeit not dominant, insulation (EPS board and glass wool blanket insulation) is a recurrent component in several building elements of the dwelling. Figure 5.11 traces the carbon intensity of different insulation types versus their thermal performance (R-value). Generally, soft insulations have a lower material impact than rigid insulations. Yet, within the different types of soft insulations, cellulose insulation has the lowest material impact while maintaining a similar thermal performance as its counterparts. This indicates that a different choice of insulation could reduce the material impact of the dwelling while maintaining a similar thermal performance.

Lastly, it is worth noting that finishing components tend to have shorter service lives than the structural and insulating components. Galvanized steel roofing has a service life of 30 years, parquet laminate flooring 15 years, and acrylic paint coating 10 years. Considering this study includes maintenance and replacement modules in its analysis and taking into account the ESL of 60 years for the entire dwelling, this leads to having several rounds of maintenance/replacement. In this light, the importance of the choice of finishing materials is highlighted when it has often been overlooked in the past since accounting for finishing is not common

15 For the purpose of conciseness, results reported in this section are restricted to the Medium House scenario.

practice in LCA. Overall, these outcomes underline the importance of secondary design choices and manifest their potentially significant aggregated impact on a dwelling's total embodied carbon footprint.



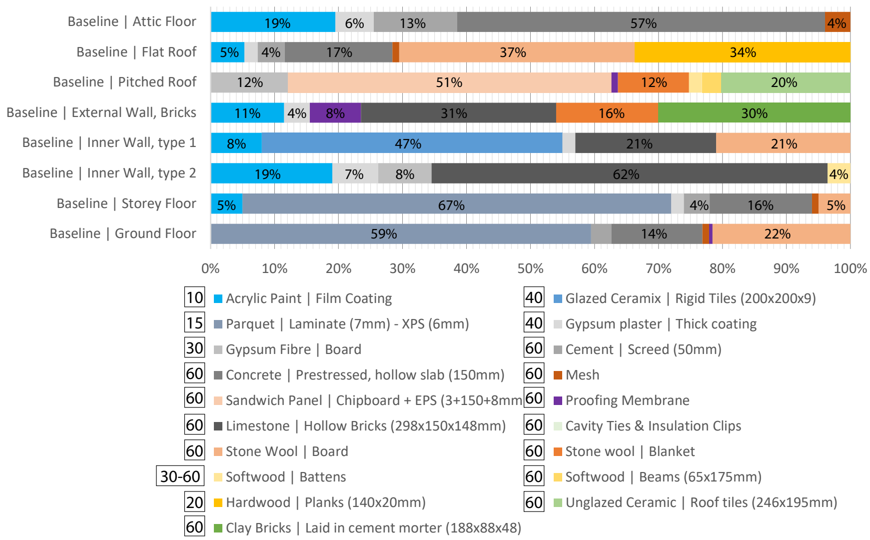


FIG. 5.10 Material impact per building component in the main building elements of the Medium House scenario in the timber and baseline construction variations. Numbers in squares are the estimated service life of the elements within each component.

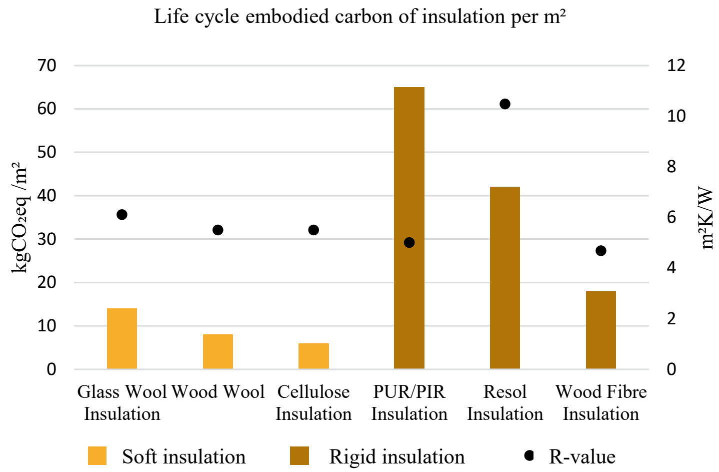


FIG. 5.11 Material impact versus thermal performance of different insulation types for the same thickness of 220 mm

5.5 Discussion

This section elaborates on changing secondary design choices for further embodied carbon reductions by presenting an optimal dwelling design based on the results obtained above. It then situates this study's outcomes within LCA literature.

5.5.1 Optimal design

The hierarchical structure of outcomes allowed the identification of most carbon intensive building elements and components. Changes with the highest potential of decreasing the embodied carbon of the dwellings were identified. Accordingly, a better performing scenario was modelled to numerically gauge the corresponding reductions. Modifications consist of substituting finishing materials with natural based alternatives. This includes changing the galvanized steel roofing to local slating, the parquet laminate flooring to hardwood flooring and eliminating all acrylic paint coatings. The glass wool insulation layers were also substituted with cellulose insulation and, when applicable, rigid insulation such as EPS was replaced with wood based rigid insulation. Table 5.3 presents the outcomes of the optimized design modelled based on the medium house scenario. In comparison to the timber design, these changes resulted in an overall 29% additional reduction in embodied carbon emissions, surpassing the 20% significance threshold. This outcome confirms the importance of accounting for secondary design choices in a LCA and doing so at an early design stage to prevent countering savings.

While this optimized design achieves higher embodied carbon savings, this study recognizes that its implementation in practice is not as straightforward. For instance, in the case of the H4.0E project, residents opted for glass wool instead of cellulose insulation to decrease their costs. That is to say that material choice is dependent on user preferences which are in-turn determined by external factors including the affordability, availability and established norms around natural based materials. Here, the promotion of sustainable alternatives becomes critical to encourage broader use.

TABLE 5.3 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
Normalized Outcome (kgCO_2eq/m^2)		675	512	361
Total Outcome (kgCO_2eq)		69,725	52,883	37,291
Reduction Percentage		0%	24%	29%

5.5.2 Comparability of outcomes

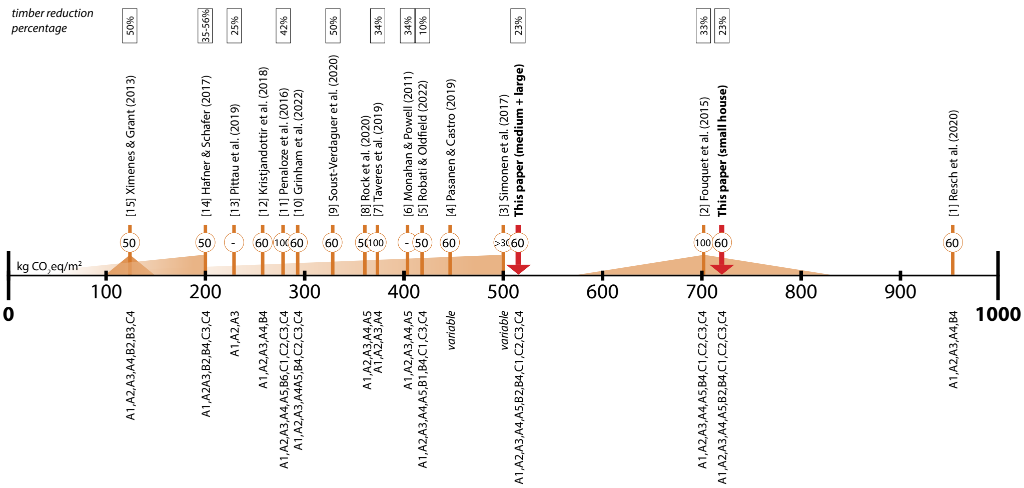


FIG. 5.12 A visual representation of situating this study's outcomes in previous literature

Figure 5.12 consists of a visual representation of where this study's outcomes stand in comparison to previous LCA studies. This representation is based on Table 5.4[16] where previous studies are enumerated by listing their embodied carbon outcomes in a decreasing order and distinguishing location, building type, floor area, ESL, embodied carbon reduction percentage from the use of timber (TR), life cycle modules, biogenic carbon, and used database(s)[17]. The embodied carbon studies referred to vary between benchmark and case studies with a particular focus on timber construction and residential buildings or dwellings. As can be seen, this paper's outcomes fit within the wide array of outcomes presented in Figure 5.12 and Table 5.4. Under timber reduction percentages, ranging from 10 to 56%, they fall in the lower range of the band with the embodied carbon savings from the use of timber limited to an average of 23%. Under embodied carbon outcomes, ranging from 100 to 968 kgCO2eq/m^2, they fall in the upper range of

16 To increase comparability, the list was restricted to studies that included outcomes expressed in kilograms of CO_2 equivalent per square meter of floor area.

17 Reference studies tap into a wide range of databases including private LCA datasets, publicly available datasets, previous research outcomes, published embodied carbon 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.

the band with a minimum of 512 kgCO2eq/m^2 and a maximum of 722 kgCO2eq/m^2. When looking into reasons underlining these variations in outcomes, several differences in study characteristics obstructing the comparability of LCA studies come to light.

TABLE 5.4 An overview of literature specific to embodied carbon studies and timber construction

Study	Reference	Descrip-tion	Location	Building Type	Floor Area[1] (m^2)	ESL (years)	Outcome ($kgCO_2eq/m^2$)	TR[2] (%)	Life Cycle Modules[3]	Biogenic Carbon[4]	Database
1	[32]	Case study	Norway	Building	102 (HFA)	60	968[a]	-	A1-4, B4	No	Self-ac-quired
2	[18]	Case study	France	Dwelling	122 (NFA)	100	574-820	33%	A1-5, B4, C1-4	Yes	Ecoin-vent 3.01
3	[43]	Benchmark study	V[5]	V	V	≥30	<500	-	V	V	Mixed[6]
4	[44]	Benchmark study	V	Building	V	60	444	-	V	No	OneClick-LCA
5	[14]	Case study	Australia	Building	43,229 (GFA)	50	417	10%	A1-5, B1, B4, C1, C3, C4	Yes	Mixed
6	[41]	Case study	U.K.	Dwelling	45 (GFA)	-	405	34%	A1-5	No	Mixed
7	[21]	Case Study	V	Dwelling	56 (GFA)	100	380	34%	A1-4	No	ICE v. 2.0
8	[8]	Global trend study	V	V	V	50	377	-	A1-A5	No	Mixed
9	[19]	Case study	Uruguay	Dwelling	63 (GFA)	60	328.5[a]	50%	A1-5, B2-B4, B6, C1, C2, C4	No	Mixed
10	[13]	Case study	U.S.	Building	356 (HFA)	60	297	-	A1-5, B4, C2-4	No	Mixed
11	[40]	Case study	Sweden	Building block	-	100	281	42%	A1-5, B6, C1-4	Yes	Ecoin-vent 2.2
12	[11]	Case study	Norway	Dwelling	102-202 (HFA)	60	263	-	A1-4, B4[b]	No	Ecoin-vent 3.0
13	[42]	Case study	Italy	Building	820 (GFA)	-	224	25%	A1-3	No	Ecoin-vent 3.0
14	[20]	Case study	Germany/ Austria	Dwelling	176	50	<200[a]	35-56%	A1-3, B2, B4, C3-C4	Yes	Oekobau. dat 2015
15	[33]	Case study	Australia	Dwelling	221-296	50	100-145[a]	50%	A1-4, B2-3, C4[b]	No	Mixed

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.
1 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)
2 Abbreviation TR for reduction percentage from the use of timber.
3 Life cycle modules are specified as per the EN 15978 standard.
4 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.
5 Benchmark studies cover variable locations, building types, floor areas, and ESLs, which is denoted by the letter 'V' in the table.
6 When reference studies tap into several databases, the occurrence is designated as 'Mixed'.

Difference in temporal boundaries

A different temporal system boundary is manifested through the accounting of different life cycle modules (studies 3, 4, 6-8, 10, 12, 13). Differences in the life cycle modules included/excluded can lead to the underestimation of a building's embodied carbon [13] and truncation errors explain some of the large differences in outcomes. For instance, study 11 excluded maintenance and replacement modules B2 and B4 in their investigation of an increased use of bio-based materials [40]. In our study, these modules alone constituted up to 37% of the timber dwellings' embodied carbon footprint. Studies 6 and 7 around modular and prefabricated timber housing only include modules A1 to A5 limiting the scope to the construction site stage [21, 41]. Applying such system boundaries to this paper's outcomes leads to a much higher average reduction of 51% from the use of timber and much lower total embodied carbon values with an average 61 $kgCO_2eq/m^2$ from cradle to gate, 93 $kgCO_2eq/m^2$ from cradle to site, and 299 $kgCO_2eq/m^2$ from cradle to end of use. These differences in outcomes are even more accentuated considering this study adopts the static -1/+1 approach whereas studies 6 and 7 adopt the static 0/0 approach for biogenic carbon. Another manifestation of a different temporal system boundary is through a different ESL assumed as is the case in studies 2, 3, 5, 7, 8, 11, 14, and 15. Overall, it can be argued that a shorter ESL of 30 or 50 years is not indicative enough as it does not factor in the full embodied carbon related to the maintenance and replacement of building components. Similarly, a longer ESL of a 100 years factors in advantages that go beyond the service life of a building and attenuates the initial, replacement and end-of-life carbon spikes that occur in the first 60 years.

Difference in physical system boundaries

Recalling that a dwelling's physical system boundary consists of the different building elements and components making up its structure, previous studies adopted different lines of reasoning when determining the elements to be included/excluded in their analysis. For instance, study 13 excluded internal partitions and doors because they were considered to vary per resident based on different spatial distribution needs [42]. Study 14 classified flooring, external cladding, roofing, shading, windows, and doors as finishing elements and omitted them from the reported LCA outcomes [20]. In study 15, there is no mention of components such as insulation, proofing membranes or coatings in the composition of building elements [33]. Evidently, a less detailed element composition and material inventory leads to lower embodied carbon emissions and study 12 explicitly states this as one of its own limitations [11]. Additionally, through the prioritization of comparative outcomes, recurrent elements/components were excluded based on the argument that they would not influence differential percentages. Study 11 excluded doors, windows, roof asphalt and wall painting [40]. Study 15 excluded glass from the embodied carbon calculations of windows when tracing reductions per building element between different construction alternatives since it has the same impact in both alternatives [33]. Following the same reasoning, study 13 excluded foundations, ground floor and finishes from their analysis [42] and study 14 excluded the basement to overcome its potentially large influence on the results [20]. While this approach sheds light on the intended purpose of the study, it does not give a representative outcome of the total emissions of a dwelling as a whole. Despite also having a comparative purpose, embodied carbon models in this paper were based on actual dwelling designs and building elements were composed to the slightest detail based on architectural drawings, bill of quantities and input from professionals involved in the project. User choices around spatial distribution and varying finishing materials were included in the analysis based on active consultations with relevant stakeholders. Overall, this partly explains why this study's total embodied carbon outcomes were revealed to be higher than the outcomes of the studies listed herein.

Other differences in study characteristics

The different approach in modelling biogenic carbon explains differences in outcomes with studies 2 and 11 [18, 40]. These studies adopt the dynamic model which is known to better represent the actual benefits of using timber versus concrete. Considering this paper adopts the static (-1+1) model, this explains the lower reduction percentages reported in comparison to studies 2 and 11. The importance of decision making around the end-of-life of timber appears with study 15 where long term carbon storage in landfilling resulted in a 40 to 60% difference in GHG emissions outcomes [33] as opposed to not accounting for carbon storage. This is in agreement with other studies that identified landfilling as the least carbon intensive end-of-life scenario compared to incineration or recycling [14, 18, 33]. Considering this study assumes 85 to 100% incineration of its wood (Figure 5.6) this is another explanation to the difference in outcomes. In confirmation, Study 5 actually demonstrates through an uncertainty analysis the extent to which embodied carbon savings are dependent on the assumptions made and the input data used which in turn explains the low reduction percentage reported [14]. Lastly, different building characteristics explain the differences with results from study 9. Despite similarities in house type and size, the dwelling considerably differs in its design where foundations, external cladding, and flooring are all made of wood [19]. These elements/components are amongst the most carbon intensive elements in H4.0E dwellings (Figures 5.9 and 5.10). Moreover, study 9 is based in Uruguay, a geographic context that is significantly different from North-West Europe.

Overall, it is recognized that the results looked at for comparison are not harmonised in terms of study characteristics which entails systematic uncertainties. Nevertheless, these general trends provide a precedent against which findings of this paper can be compared. In terms of embodied carbon savings from the use of timber, this study echoes previous research findings. It supports the unanimity around the better performance of timber in terms of embodied carbon reductions compared to more traditional construction materials such as concrete. It confirms the significant impact of different assumptions on outcomes especially those related to biogenic carbon accounting and end-of-life decision making. The avoidance of truncation errors through a broadened temporal system boundary and the choice for a high level of detail and accuracy through an elaborate physical system boundary justifies why this paper's outcomes were higher than at least 10 reference studies in terms of total embodied carbon in $kgCO_{2eq}/m^2$. More importantly, in the attempt of situating its outcomes in past literature, this paper faced the lack of comparability of LCA studies thus reiterating it as a significant barrier as was flagged by previous studies [6, 14, 31, 32]. Finally, through tracing differences in study characteristics and scoping, this study stresses the importance of prioritizing transparency in LCA studies. It emphasizes the need in the global scientific community for clear, harmonized guidelines on how to both perform and document LCA outcomes [8, 9].

5.5.3 Study limitations

There are several limitations to this study that are worth mentioning. First, considering the aim of this study was to highlight the importance of material impact and investigate embodied carbon reduction strategies, a partial LCA was conducted and modules related to the operational energy use were considered outside of the temporal scope. This was based on the fact that current building regulations in many countries no longer tolerate a non-zero operational energy performance. Second, due to missing data, this study also excluded furniture, sanitary elements and building services from its physical system boundary. On the one hand, including furniture and sanitary elements is not common practice in LCA studies which explains data scarcity and the lack of reference and comparable studies. On the other hand, while including building services is becoming more common, calculating their embodied carbon has still not been standardized and modelling uncertainties remain. Additionally, in terms of the relation between house size and embodied carbon, these exclusions render this study's outcomes conservative. Taking into account these additional elements can further accentuate the relationship between house size and embodied carbon seeing as larger dwellings usually require more amenities and bigger building services systems [25]. Nevertheless, overall it is recognized that

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accounting for operational energy use would have provided a complete overview of the full life cycle performance of dwellings and gauging the additional embodied carbon emissions from sanitary elements, furniture and building services would have enabled a more comprehensive total embodied carbon footprint further accentuating the benefits of downsizing.

Third, through the use TOTEM, this study is subject to a low geographical representativeness. Although TOTEM, taps into the Swiss Ecoinvent database and mostly extracts data that is specific to Europe, some assumptions are made more specific to the Belgian context [38]. This goes hand in hand with the limited access and flexibility when using LCA tools to change embodied carbon data and numerical coefficients to values that are more representative of the current study context. This is recognized to potentially have induced systematic uncertainty in this study's calculations. Moreover, through the use of TOTEM, the static approach to accounting biogenic carbon is adopted. Flexibility in changing this approach and the choice of the end-of-life scenario of timber would have also enabled reaching more representative outcomes. Fourth, the modular construction characteristic of the Wikihouse designs is not reflected in generated outcomes. Seeing as the TOTEM database does take in environmental product declarations (EPD) from industry, this could have been possible with an EPD specific to the Wikihouse timber panels. Overall, this reiterates the long overdue need for the construction and product industry to get familiar with different LCA tools, develop their EPDs, and share their outcomes for more accurate carbon footprints [9].

Lastly, this study restricts its analysis to the global warming potential (GWP), the most common impact indicator, considering its importance for climate change policies [19]. Evidently, LCAs address many more impact categories. More specifically, what could have especially been relevant within the context of this study is when the different end-of-life scenarios specific to timber such as incineration or landfilling are taken into account. Here, other impact indicators become as important in gauging related consequences such as the emission of toxic substances or the contamination of groundwater resources [33]. Put differently, while beyond the scope of this study, it is recognized that expanding the LCA boundaries to account for other impact indicators would provide a more holistic view on the contribution of GHG emissions to climate change.

5.6 Conclusion

This research conducts a partial LCA of new-build timber dwellings to investigate the impact of both downsizing and building material choice as embodied carbon reduction strategies. Outcomes confirm that sufficiency through downsizing is the most effective reduction strategy, considering that the magnitude of reductions coming from downsizing exceed those coming from the use of timber as the main construction material. Additionally, the comparative analysis succeeds in demonstrating that the simultaneous implementation of both strategies leads to the most significant carbon savings of 53%. Furthermore, the relationship between house size and embodied carbon emissions was revealed to be sub-linear. Despite all outcomes confirming the advantages of smaller housing, whether or not such a design characteristic matches with current housing demand remains to be seen. Considering the aspect of permanence of embodied carbon and the potential of downsizing in saving energy, it becomes worthwhile for future research to investigate current housing preferences and establish public trends that are more in line with the environmental reality that is aiming for sufficiency.

The hierarchical structure adopted in this study allowed a gradual gain of insight that increased in depth with every level of information. Total embodied carbon results per building element over the life cycle of a dwelling allowed gauging the potential impact of primary design choices through the identification of most carbon intensive building elements: the ground floor, the external walls and the pitched roof. In turn, within each building element, embodied carbon results per building component allowed the identification of the most carbon intensive secondary design choices namely around the finishing materials such as the choice of roofing and flooring. A closer look into individual components enabled the identification of materials with short service lives requiring high maintenance and frequent replacement such as the parquet laminate flooring and the acrylic paint coating. Implementing design changes based on this gained insight through modelling a better performing scenario confirmed further improvement with 29% of additional embodied carbon savings. Accordingly, a hierarchical study approach allows designers and practitioners to use the building element and component level of information to make efficient design choices at an early stage thus improving the embodied carbon footprint of dwellings and preventing unnecessary emissions simultaneously.

On an overarching level of analysis, this research sheds light on different manifestations of scoping in LCA literature. Be it explicit, through the exclusion of life cycle modules, or implicit through the prioritization of comparative outcomes, this study confirms potential truncation errors with its higher embodied carbon outcomes. It is in agreement with the previously argued prediction that achieving a low to net zero balance over the full life cycle of a building becomes more difficult as more precise data becomes available. The lack of comparability highlighted the crucial role that can be attributed to transparency. More importantly, it stressed on the global need for harmonized and clear LCA methodological and documentation guidelines both in the practical and scientific community.

Authorship Contribution Statement

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

Declaration of Competing 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.

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Wikhouses built in Almere in the Netherlands as part of the Housing 4.0 Energy project funded by Interreg North-West Europe. Copyright: Wikihouse.

PART 6

Conclusion

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6 Conclusion: The Potential of Small, Low-Carbon, Zero-Energy Dwellings

A Multidimensional Approach

6.1 Introduction

This research was conducted as part of the H4.0E project funded by Interreg North-West Europe. The aim of the H4.0E project was to provide new housing solutions that would help reduce future GHG emissions within the housing sector and contribute to closing the gap between housing supply and demand. To that aim, 44 new dwellings were designed and built in Belgium, Ireland and the Netherlands.

The **aim** of this research is to **investigate the implementation of small, low-carbon, (near) zero-energy dwellings in practice and assessing their potential as a solution** that would address sustainability challenges while simultaneously answer to the growing housing shortage in Europe. Accordingly it addresses the following main research question:

- **To what extent are small, low-carbon, (near) zero-energy dwellings a housing solution in North-West Europe?**

  Recalling the urgency of climate action and the need to switch from incremental change to long-term sustainable solutions, the research scope is not restricted to the technical feasibility of the implementation of such dwelling designs and their corresponding performance. In addressing it main research question, this research adopts a multidimensional outlook in its investigation where, having the dwellings as the focal point, it covers the institutional and social dimensions surrounding the dwellings in addition to the technical one. The adoption of this multidimensional outlook entailed conducting four separate studies answering to four different research sub-questions as listed below.

- **Question 1:** **What are the institutional barriers to the implementation and uptake of NZEBs? What insights can be gained from the investigation and identification of these institutional barriers and how can they inform policy?**

  Study 1: Institutional barriers to the implementation and uptake of small, low-carbon, zero-energy dwellings

- **Question 2:** **To what extent do the perceptions of housing professionals affect the identification of barriers to the implementation of NZEBs?**

  Study 2: Perceived barriers to nearly zero-energy housing: Empirical evidence from Kilkenny, Ireland

- **Question 3**: **To what extent do smaller, low-carbon and zero-energy dwellings fulfil current housing preferences?**

  Study 3: The demand for small, low-carbon, zero-energy timber dwellings: A study of consumers' stated housing preferences

- **Question 4**: **What is the impact of downsizing and the use of timber on the embodied carbon of a new-build dwelling?**

  Study 4: The assessment of downsizing and the use of timber as embodied carbon reduction strategies for new-build housing

  The following section addresses the sub-questions that were formulated based on the conceptual framework articulated in this research and each sub-question is answered separately.

6.2 Addressing research sub-questions

6.2.1 The Institutional Dimension

In the study “Institutional barriers to nearly zero-energy housing: A context specific approach”, the goal was to address the institutional dimension and establish the policy environment surrounding the implementation and uptake of small, low-carbon, (near) zero-energy dwellings. Recognizing the potential impact of established policies on the implementation and uptake of such dwellings as well as the importance of maintaining a link between energy research and stakeholders and policy makers, this study conducted focus groups with housing professionals in Flanders, Ireland and the Netherlands where potential financial, legislative, technical, cultural and overarching barriers were explored. Accordingly, the following research sub-question was answered:

- **What are the institutional barriers to the implementation and uptake of NZEBs? What insights can be gained from the investigation and identification of these institutional barriers and how can they inform policy?** [pertains to chapter 2]

At first glance, study results revealed that the general most common barriers to sustainability measures, including NZEBs, identified in previous literature were mentioned again in at least one of the three different study contexts (Table 6.1). Examples are the perception of ‘higher costs’ associated with the implementation of sustainability measures compared to standard construction followed by the ‘uncertainty and risks of innovation’ which translates into the reluctance to use new materials, technologies, methods and/or designs due to insufficient testing and lack of experience in implementing, maintaining and managing them. However, a closer look into individual study locations generated new and more context specific outcomes which led to the formulation of more precise policy suggestions that take into account local peculiarities (Table 6.2). For instance, in Ireland, the barrier of ‘self-build mortgage schemes’ translates into funds not being released unless most of the works are completed and approved by an architect/engineer. Whereas in Almere, self-build mortgage schemes require a project completion guarantee from self-builders in case of injuries. Identifying this difference between contexts allowed highlighting the precedence of redirecting established financial schemes in Ireland towards encouraging new designs and the implementation of measures that exceed building regulations versus revisiting the completion guarantee in the Netherland requirement to promote self-building and particularly support lower-income households. This is an example of how nuances were identified and differences in precedence were made between the three pilot countries, thus allowing the formulation of more specific and context relevant policy suggestions.

In making the distinction between general barriers that were identified in past literature but persisted in 2019 and new, context specific barriers, this first study contributes to the discussion by highlighting the importance of conducting context-specific investigations rather than reaching generalizable outcomes. More importantly, through tracing the evolution of general barriers to NZEBs that were already identified in previous studies yet persisted in 2019, this study sheds light on known factors that are still perceived as obstructive to the implementation of small, low-carbon, (near) zero-energy dwellings in 2019. On a higher level of analysis, this persistence of barriers through time raises the question of how these constraints have been addressed and why they have been recurring over time despite the formulation of recommendations and measures to overcome them. The fact that barriers already addressed were still being identified despite previous recommendation and efforts to solve suggests an imbalance between policy formulation and its implementation in industry. Having reached this overarching conclusion, the first study in this thesis reinforced the importance of preserving the link with policy makers and stakeholders. Based on its findings, it called for a follow-up interaction with housing professionals where a context-specific approach is adopted to re-evaluate the barriers that persisted. This follow-up would add new insight into the reasons behind this persistence despite previously formulated recommendations and implemented efforts to overcome them, thus closing the gap between policy formulation and implementation.

TABLE 6.1 Barriers to small, low-carbon, zero-energy dwellings that persisted in 2019 (adapted from Souaid et al., 2021)

#	Institutional Barrier	Category	Rank[a]	BE	IR	NL
1	**Higher costs**	**Financial**	**1**	**X**	**X**	**X**
2	Lenient building regulations	Legislative	2	X	X	
3	Lack of awareness	Cultural	2	X	X	
4	Shortage of skills	Technical	2		X	
5	Unclear and conflicting policies	Legislative	3	X	X	
6	**Uncertainty and risks of innovation**	**Technical**	**3**	**X**	**X**	**X**
7	**Lack of adequate financial incentives**	**Financial**	**4**	**X**	**X**	**X**
8	**Lack of knowledge**	**Cultural**	**5**	**X**	**X**	**X**
9	**Cultural preferences**	**Cultural**	**5**	**X**	**X**	**X**
10	Payback period and return on investment	Financial	5		X	X
11	Lack of experience and expertise	Technical	5	X	X	
12	Lack of communication and coordination	Overarching	6	X	X	
13	Limited authority	Legislative	6	X	X	
14	**Inadequate policy**	**Legislative**	**7**	**X**	**X**	**X**
15	**Business as usual approach**	**Cultural**	**7**	**X**	**X**	**X**
16	Lack of priority and trade-offs	Financial	7	X	X	
17	**Access to land**	**Legislative**	**8**	**X**	**X**	**X**
18	Insufficient investment	Financial	8		X	
19	Lack of involvement	Overarching	9		X	
20	Split incentive	Financial	9	X		
21	Lengthy governmental approval process	Legislative	10		X	X
22	Climate and geography	Technical	10		X	X
23	Community opposition	Cultural	10		X	

a This ranking refers to the number of times a certain barrier appeared in previous studies with the most common barrier coming in first place and the least common barriers coming in the tenth place. When barriers have the same ranking, this indicates that they appeared in the same number of previous studies.

TABLE 6.2 Context specific barriers to the implementation of small, low-carbon, (near) zero-energy dwellings and policy suggestions per study location (adapted from Souaid et al., 2021)

Category	Belgium	Ireland	Netherlands
Financial barriers	Profit maximization	Inconsistent financial schemes benchmarks Cost of certification Loan to security scheme Self-build mortgage schemes	Self-build mortgage schemes Residual counting
Policy suggestions	Provide financial institutions with detailed information on innovations and design developments to add reassurance and promote sustainable construction over profit maximization	Establish common benchmarks for the financing of sustainability measures Redirect established financial schemes towards encouraging new designs and the implementation of measures that exceed building regulations Revisit the cost of certifications to balance out designer and consultant fees for more effective upscaling	Revisit the completion guarantee requirement to promote self-building and particularly support lower-income households Ensure the capitalization of savings from self-building considering land price determination based on residual counting could counter cost savings through self-building as they count as part of the building costs
Legislative barriers	Local authority design requirements Social housing design requirements Restrictions on small dwellings Restrictions on compact construction	Local authority design requirements Individual certification scheme	Local authority design requirements Long periods of testing and development
Policy suggestions	Revisit social housing design requirements that prioritize universality to facilitate tenant allocation and shift to giving precedence to efficient designs Shift the approach in the subdivision of land by giving precedence to area development rather than parcel-based allocation	Revisit the established individual certification scheme to accelerate the design approval process and facilitate the upscaling of small, low-carbon, (near) zero-energy dwellings	Increase land accessibility to low to middle-income home-owners wanting to self-build in land organization policy
Technical barriers	Lack of standards	Lack of standards Dwelling lifespans	
Policy suggestions	Develop mandatory standards addressing the embodied carbon of new-build dwellings	Provide clear and detailed information around the designs of small, low-carbon, (near) zero-energy dwellings including life cycle (cost) assessment to overcome concerns around shorter lifespans	Standardize small, low-carbon, (near) zero-energy dwelling designs such as the Wikihouse to prevent long periods of testing and development
Cultural barriers	Societal daily habits Lack of information Perception of small dwellings Reluctance to move	Thermal comfort perception Societal daily habits Perception of timber dwellings	Lack of information Perception of timber dwellings Perception of self-build

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TABLE 6.2 Context specific barriers to the implementation of small, low-carbon, (near) zero-energy dwellings and policy suggestions per study location (adapted from Souaid et al., 2021)

Category	Belgium	Ireland	Netherlands
Policy suggestions	Promote and highlight the benefits of small-scale living to contest people's negative association with container homes and reduce their reluctance to move Particularly highlight both energy and cost savings from small-scale living rather than focusing on highlighting the negative impact of traditional designs and constructions	Redirect the focus of publicity campaigns in Ireland to promote the robustness of timber frame dwellings Find alternative solutions to people's daily habits such as the use of radiators for drying clothes	Redirect the focus of publicity campaigns in the Netherlands to promote the durability and resistance of timber frame dwellings to water Promote and normalize self-building to increase market uptake

6.2.2 The Social Dimension – Market Supply

In the study "Perceived barriers to nearly zero-energy housing: Empirical evidence from Kilkenny, Ireland" the goal was to address the social dimension by accounting for the potential impact of the human factor on the supply side of housing provision. More specifically, the goal was to incorporate the human factor by including housing professionals as actors for change in the investigation and unravelling the potential impact of their perceptions in the identification of institutional barriers to the implementation and uptake of small, low-carbon, (near) zero-energy housing. Accordingly, the following research sub-question was answered:

- **To what extent do the perceptions of housing professionals affect the identification of barriers to the implementation of NZEBs?** [pertains to chapter 3]

The study starts by highlighting the fact that most investigations of barriers are conducted in consultation with professionals, making their input significantly deterministic of the results and conclusions reached. It proceeds by underlining the fact that, within previous research, professionals are namely consulted as external and objective entities to the investigation and argues that this could have led to the undermining of the potential impact of their perceptions in their identification of barriers to the implementation of sustainability measures. Following this reasoning, the study dedicates special attention to perceptions in the supply side of the housing market. It adopts a shifted model composition where housing professionals are considered a subjective element with subjective perceptions having the potential to become obstacles themselves. Seeing as the goal of this study is to capture the perceptions of professionals, which are namely implicit and potentially difficult to identify and articulate, and considering the complexity of the research process implemented, the study focused on a single context; Ireland. Results revealed that 6 out of the 10 most common barriers to the implementation and uptake of NZEBs that were identified in previous literature and reoccurred in the focus group outcomes in Ireland, were indeed perceived rather than actual barriers. Table 6.3 lists these 10 most common institutional barriers by first listing the total number of mentions in transcripts per institutional barrier, then by providing the method that determined the status of either perceived or actual barrier.

TABLE 6.3 Perceived versus actual institutional barriers to the implementation and uptake of NZEBs in Ireland (adapted from Souaid et al., 2022)

Institutional Barrier	Number of mentions	Method	Outcome	
			Perceived	Actual
Higher costs	31	Fact tracing	√	
Lack of awareness	10	Fact tracing and follow-up interviews		√
Lenient building regulations	5	Fact tracing	√	
Shortage of skills	17	Fact tracing		√
Cultural preference	17	Follow-up interviews	√	
Lack of knowledge	8	Follow-up interviews		√
Business-as-usual mindset	11	Follow-up interviews		√
Uncertainty and risks of innovation	13	Fact tracing and follow-up	√	
Lack of adequate financial incentives	13	Fact tracing	√	
Payback period and return on investment	18	Fact tracing	√	
		Total	6	4

In distinguishing between actual and perceived barriers, the second study in this thesis reiterates the potential gap between policy developments and local practice and answers to the need for understanding more closely why previously established barriers persist and why their corresponding remedial measures have persistently failed to redress the situation. The investigation of potential reasons underlying the perceptions of housing professionals led to an entirely different list of impediments. Namely, study outcomes revealed the preference of the business as usual approach, a lack of awareness, and information dissemination as the three overarching barriers that potentially justify the gap between policy formulation and implementation in practice thus hindering the process of shifting towards smaller, low-carbon, (near) zero-energy housing. Accordingly, the study called for innovation in information dissemination be it between policy and local practice or between housing professionals themselves to reduce the revealed dyssynchronisation between policy developments and the knowledge and awareness within local practice. Overall, the study suggests the integration of policy and regulatory information in the process of new housing provision through incorporating trained experts at key decision-making moments that local authorities, social housing associations, private developers and/or others encounter throughout the process. The study also suggests for information around policies and regulations to be actively translated to tailor the expertise and interests of the targeted audience of housing professionals. Additionally, the study called for the need for policy and industry to coincide by complementing top-down regulations with increased bottom-up initiatives through the increase of pilot projects and/or industry advocates seeing as raising awareness through the provision of information alone is not enough to shift the business as usual approach and change long-established perceptions

In that way, the engagement of the second study of this thesis to the discussion of barriers to small, low-carbon, (near) zero-energy housing was twofold. On an individual level, this study succeeded in demonstrating the importance of accounting for the perceptions of housing professionals and their potential impact on the identification of barriers to the implementation and uptake of small, low-carbon, (near) zero-energy housing. On a more general level, this study incorporated the human factor on the supply side of the housing market by including housing professionals in its investigation and considering them as actors in the process of change.

6.2.3 The Social Dimension – Market Demand

In the study "The demand for small, low-carbon, zero-energy, timber dwellings: A study of consumers' stated housing preferences", the goal was to address the social dimension by recognizing the role of the human factor in the process of change on the demand side of the housing market. In doing so, this study tested the assumption that there is a growing preference for smaller dwellings which was based on the increasing number of smaller households composed of one to two persons, elderly households, and lower income households. In recognizing individuals as actors for change, the study tackled this assumption from the consumers' perspectives and followed the stance of shaping supply by adopting a bottom-up approach in its investigation whereby consumers' housing preferences were evaluated and the following research sub-question was answered:

- **To what extent do smaller, low-carbon and zero-energy dwellings fulfil current housing preferences?** [pertains to chapter 4]

In a supply-led market, information around stated housing preferences provides insight into consumers' true housing aspirations and expectations. This stage of housing research is key as it establishes the foundation for accurately mapping out current housing demand which in turn contributes to increasing consumers' satisfaction levels. Through distributing a housing preferences questionnaire tailored based on the multi-attribute utility method (MAUT), the study established a scoring system of main housing characteristics which in turn enabled gauging the extent to which H4.0E dwelling profiles fulfil consumers' stated housing preferences in Flanders and in Almere. Study outcomes revealed that the smallest H4.0E dwelling profiles of less than 50 m^2 in size conclusively scored below the average level of attractiveness in both study locations, thus not fulfilling the current housing preferences of consumers. However, the medium H4.0E dwelling profiles with a size ranging between 50 and 65 m^2 scored just around the average level of attractiveness in both study locations suggesting that the possibility of timber dwellings of 50 to 80 m^2 satisfying consumers preferences cannot be excluded (Tables 6.4 and 6.5). Indeed, for a medium dwelling size of 50 to 80 m^2, MAUT outcomes demonstrated that housing characteristics such as a detached dwelling type and two bedrooms located in the corresponding most preferred residential area (suburban in Almere and rural in Flanders) do compensate for both the size and the timber frame. As such, in answering the research sub-question, this study's outcomes highlight the importance of distinguishing between smallest and smaller dwelling sizes. In the transition towards small, low-carbon, (near) zero-energy housing, although there is no demand for the smallest H4.0E dwellings, smaller H4.0E dwellings could potentially satisfy consumers' current housing preferences.

TABLE 6.4 Extreme dwelling profiles in Almere and in Flanders

Most preferred profile – Almere			Least preferred profile – Almere			Average level of attractiveness
Attribute level	Utility	Total	Attribute Level	Utility	Total	
Detached dwelling	12.2	**66.3**	Apartment dwelling	10.7	**35.4**	**50.9**
Suburban area	14.2		Rural area	12.3		
81 to 100 m^2	13.1		Less than 50 m^2	3.0		
Three bedrooms	11.8		One bedroom	2.8		
Bricks	15.1		Timber	6.7		
Most preferred profile – Flanders			**Least preferred profile – Flanders**			**Average level of attractiveness**
Attribute level	**Utility**	**Total**	**Attribute level**	**Utility**	**Total**	
Detached dwelling	16.8	**81.3**	Terraced dwelling	5.8	**26.2**	**53.8**
Rural area	20.5		Urban area	6.3		
More than 100 m^2	16.0		Less than 50 m^2	2.1		
Three bedrooms	12.2		One bedroom	2.6		
Bricks	15.2		Timber	8.1		

TABLE 6.5 H4.0E dwelling profiles scores in Almere and in Flanders

H4.0E profile – Almere Small House			H4.0E profile – Huldenberg Small House		
Attribute level	Utility	Total	Attribute Level	Utility	Total
Detached dwelling	12.22	**38.9**	Detached dwelling	16.75	**50.8**
Suburban area	14.19		Rural area	20.53	
45 m^2	2.97		43 m^2	2.11	
One bedroom	2.76		One bedroom	2.64	
Timber	6.72		Timber	8.11	
H4.0E profile – Almere Medium House			**H4.0E profile – Huldenberg Medium House**		
Attribute level	**Utility**	**Total**	**Attribute level**	**Utility**	**Total**
Detached dwelling	12.22	**51**	Detached dwelling	16.75	**53.9**
Suburban area	14.19		Rural area	20.53	
65 m^2	7.75		53 m^2	5.16	
Two bedrooms	10.09		One bedroom	2.64	
Timber	6.72		Timber	8.11	

From a broader perspective, study outcomes shed light on additional valuable insight that can inform the provision of small, low-carbon, (near) zero-energy dwellings. For instance, results revealed that residential area or study location is the factor that is most likely to influence dwelling size preferences rather than household size, age and income as was assumed. In other words, smaller dwellings are more likely to achieve higher preference scores in more urbanized contexts where residents are accustomed to denser and smaller living spaces. Seeing as dwelling size preferences did not vary according to household size, age or income, study outcomes refute the assumption that being part of smaller household, a senior household or a lower income household increases the preference for a smaller dwelling size. Instead, it validates the trend where households residing in more urbanized settings display a greater inclination towards embracing smaller living arrangements.

Additionally, findings show that the type of building material used in a dwelling does not affect the comfort and satisfaction levels of consumers unlike other housing characteristics such as dwelling size, dwelling type and number of bedrooms. That is to say, consumers are more likely to reject a small, low-carbon, (near) zero-energy dwelling based on its size, type, and/or number of bedrooms rather than based on its timber frame. Owner occupation was revealed to be consumers' ultimate goal in their housing pathways as it was a key factor influencing their willingness to move. This appeared as a barrier particularly preventing elderly households to relocate to smaller dwellings. Here, changing the cultural norm through establishing financial planning incentives, alternative methods of wealth transfer and ensuring housing stability and affordability by improving tenant regulations could motivate them to adjust their housing situation. Lastly, in light of the significant differences in preference scores between one and two-person households, a group that is usually combined in housing market research and by housing providers, study outcomes challenge the assumption that small households of one to two-persons have similar housing preferences. Instead, these outcomes suggest that one and two-person households should be considered two separate groups possibly at different life cycle stages for potentially more accurate predictions of housing needs.

6.2.4 The Technical Dimension

In the study "The assessment of downsizing and the use of timber as embodied carbon reduction strategies for new-build housing", the goal was to address the technical dimension. Following the normalization of a zero operational energy performance and the growing importance of reducing embodied energy, the study focuses on the material impact of small, low-carbon, (near) zero-energy dwellings through conducting a partial life cycle assessment. In line with the prioritization of the avoidance of energy and material consumption and sufficiency through downsizing, the study investigates the impact of downsizing, in addition to the use of timber, as embodied carbon reduction strategies. In doing so, the study addresses the need investigate the impact of house size on embodied carbon and brings clarity on the nature of this correlation. More importantly, having the small H4.0E dwellings as the subject of focus, the study addresses the need of bringing smaller dwellings into the discussion and investigate the potential impact, and benefits, of downsizing at the lower end of the range of housing sizes. As such, the following research sub-question was answered:

— **What is the impact of downsizing and the use of timber on the embodied carbon of a new-build dwelling?** [pertains to chapter 5]

The partial life cycle assessment (LCA) of three housing scenarios was conducted: the "Small House" (45 m^2), the "Medium House" (76 m^2), and the "Large House" (104 m^2). In investigating the material impact of these scenarios, two construction variations were modelled for each thus comparing a modular timber design to a traditional concrete alternative. The dwelling designs were based on three existing dwellings built in Almere, in the Netherlands, as part of the H4.0E project. Study outcomes confirmed that sufficiency through downsizing is the most effective embodied carbon reduction strategy seeing as reductions from downsizing (22 to 40%) exceed reductions from the use of timber (22 to 24%). In terms of embodied carbon savings from the use of timber, this study echoes previous research findings and supports the unanimity around the better performance of timber compared to more traditional construction materials such as concrete. Expectedly, the simultaneous application of both downsizing and the use of timber achieved the highest embodied carbon reductions with 42% for the Medium House and 53% for the Small House scenario (Figure 6.1). In terms of the nature of the correlation between house size and embodied carbon, a one to two ratio only occurs when timber and downsizing strategies are implemented simultaneously. Put differently, the embodied energy consumed by a single large concrete house is twice as much as the embodied energy consumed by a single small timber house as per the 53% reduction percentage obtained.

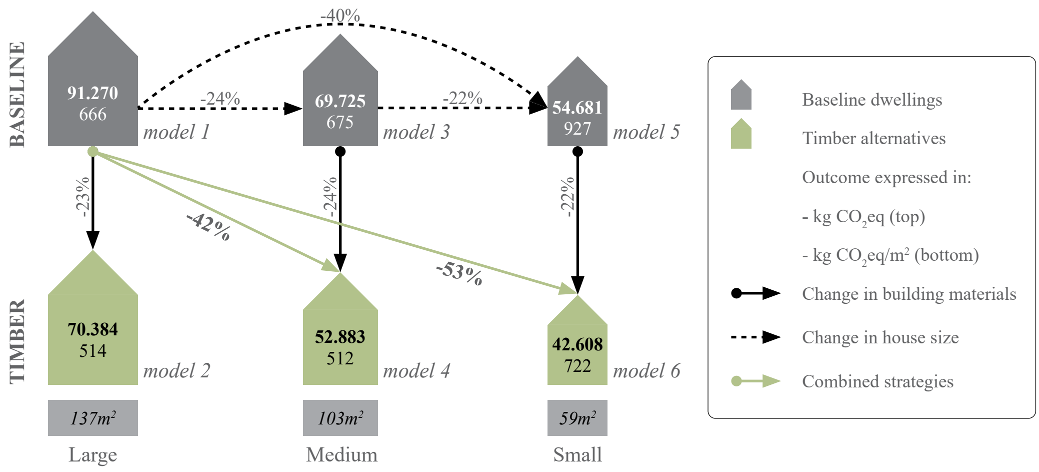

FIG. 6.1 Embodied carbon reduction percentages per strategy

Furthermore, this study's data analysis was conducted following a hierarchical approach that goes from the building level, covering the building element level and reaching the building component level. This hierarchical approach allowed a gradual gain of insight that increased in depth with every level of information which sheds light on several understandings that could inform the dwelling design process. Embodied carbon results per building element allowed gauging the impact of primary design choices through the identification of most carbon intensive building elements: the ground floor, the external walls, and the pitched roof. In turn, within each building element, embodied carbon results per building component allowed the identification of the most carbon intensive secondary design choices namely around the finishing materials such as the choice of roofing and flooring. A closer look into individual components enabled the identification of materials with shorter service lives requiring high maintenance and frequent replacement. Implementing design changes based on this gradually gained insight through modelling a better performing scenario confirmed further improvement with 29% of additional embodied carbon savings. Accordingly, the study demonstrated how a hierarchical approach allows designers and practitioners to use the building element and component level of information to make efficient design choices at an early stage thus improving the embodied carbon footprint of a dwelling and preventing unnecessary emissions simultaneously.

Lastly, on an overarching level of analysis, the partial LCA conducted in this study achieved higher embodied carbon outcomes compared to previous literature.
In the attempt of situating its outcomes in past literature, differences in study characteristics and scoping came to light leading to a lack of comparability of LCA outcomes. On the one hand, this confirmed the potential of truncation errors that result from adopting a limited LCA scope seeing as a broadened temporal system boundary was adopted in this study and a high level of detail and accuracy was included in its physical system boundary. On the other hand, this lack of comparability of outcomes underlined the importance of prioritizing transparency in LCA studies and emphasized the need in the global scientific community for clear, harmonized guidelines on how to both perform and document LCA outcomes.

6.3 General Conclusion

Through establishing a holistic and multidimensional outlook that covers different angles and integrates different disciplines, as was set out in the conceptual framework, this study sheds light on the complexity of the subject at hand, revealing that the answer to the main research question addressed is far from straightforward. Figure 6.2 provides a visual representation of the problem mapping resulting from the research that was conducted throughout this body of work.

– **To what extent are small, low-carbon, (near) zero-energy dwellings a housing solution in North-West Europe?**

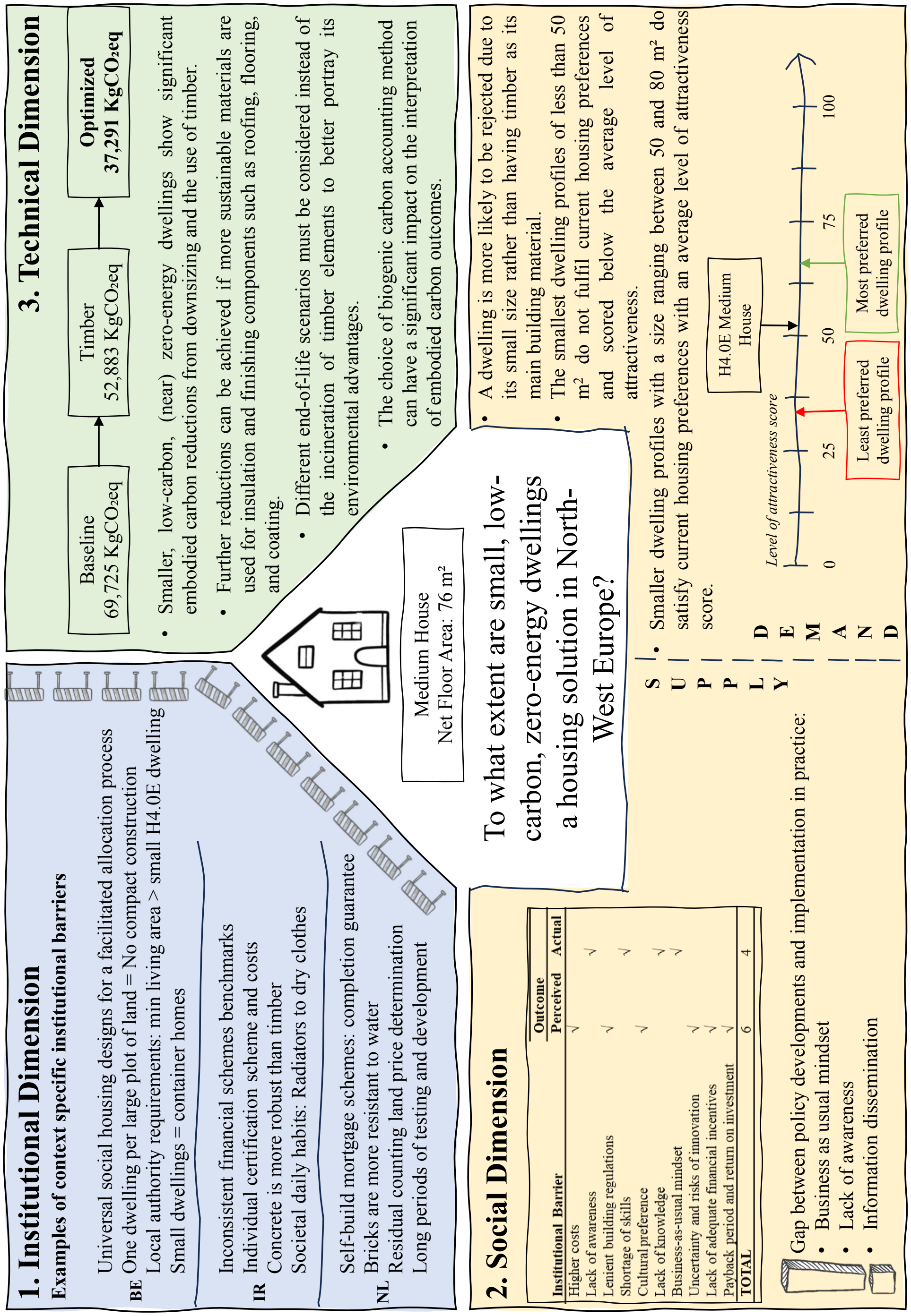

FIG. 6.2 Problem mapping

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From the institutional perspective, the investigation of barriers to the implementation and uptake of such dwellings revealed the need for significant changes in housing policies, financing, design requirements and perceptions in each study location specifically when it comes to promoting compact construction, timber construction and smaller dwelling sizes. Moreover, the investigation of institutional barriers highlighted a potential gap between the formulation of policies and their implementation in practice seeing as mismatches were identified between the perceptions of housing professionals and the latest policy developments. As such, under the social dimension, from the market supply perspective, the distinction between perceived and actual barriers underlined the need for innovation in information dissemination and awareness raising to overcome the prevailing business as usual mindset. From the market demand perspective under the social dimension, study outcomes revealed that the smallest dwelling sizes conclusively do not fulfil current housing preferences. However, the results do provide insight into potential trade-offs that would compensate for dwelling sizes that range between 50 and 80 m^2. Particularly, a detached dwelling as it was the most preferred dwelling type, located in a suburban or rural residential area in Almere and Flanders respectively and at least 2 number of bedrooms. Lastly, under the technical dimension, small, low-carbon, (near) zero-energy dwellings were demonstrated to be a better performing solution than traditional housing designs especially when it comes to their material impact. Expectedly, the smaller dwelling sizes achieve the lowest embodied carbon footprint[18] and outcomes underline additional measures that would result in further embodied carbon reductions. In sum, this visualisation of outcomes relays the following: although downsizing to a dwelling size of less than 50 m^2 results in the highest embodied carbon reduction and achieves the lowest material impact, this dwelling size would not fulfil current housing preferences and could lower the comfort and satisfaction levels of residents in the corresponding study locations. Moreover, while there is a need for current established housing policies, requirements and financial incentives to be adjusted to facilitate upscaling, there is a simultaneous need for the latest policy developments to be relayed effectively to local authorities and housing professionals to accelerate the shift towards small, low-carbon, (near) zero-energy dwellings.

The identification of challenges under each dimension led to a more comprehensive evaluation of the study focus gaining insight in the course of action needed at the institutional, the social and the technical levels. Accordingly, Figure 6.3 provides a visual representation of the different suggestions formulated throughout this research.

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18 Although the smallest H4.0E dwelling size achieves the most embodied carbon reductions, in Figure 6.1, the outcomes related to the medium dwellings size were represented seeing as this dwellings size is more likely to fulfil current consumer preferences.

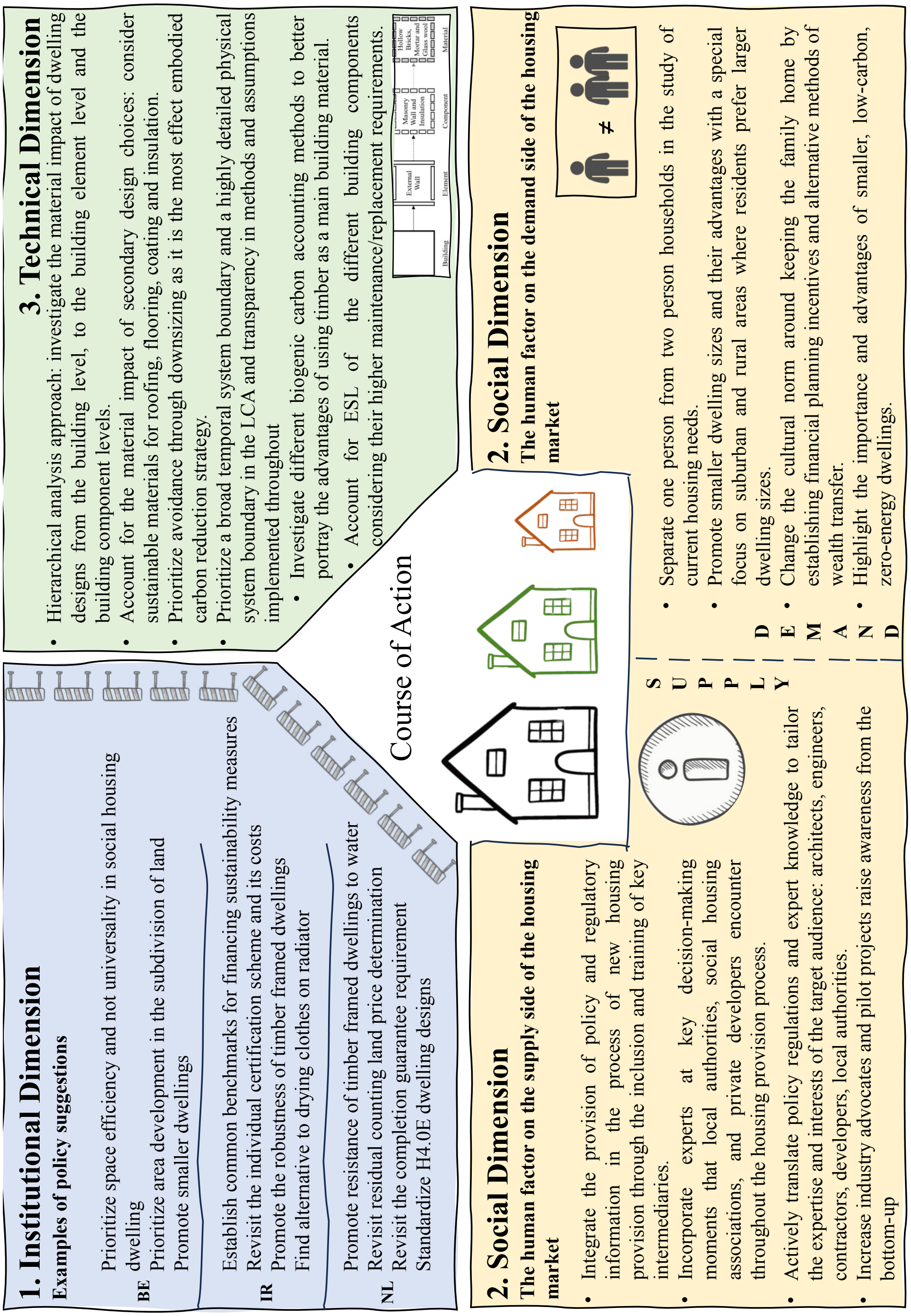

FIG. 6.3 Course of action

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6.4 Research limitations

6.4.1 Study specific limitations

On a specific level of analysis, each study within this research has its own limitations. In terms of the investigation of institutional barriers and the distinction between actual versus perceived barriers, the study restricted its analysis to qualitative data collected through focus groups and semi-structured interviews. While this type of data is necessary when implicit characteristics such as perceptions are being gauged, it does generate very context specific outcomes. As such, it is recognized that collecting quantitative data through a follow-up, complementary questionnaire would have allowed reaching a larger number of housing professionals and provided more insight into frequencies and perceived importance of identified barriers.

In terms of the investigation of current housing market preferences, the pandemic had a decisive influence on the study design and implementation. Significant delays caused a misalignment between the questionnaire distribution, which was done at different times in both study locations, and the design of H4.0E dwellings. As a result, a classic method was implemented and local housing preferences were gauged based on abstract dwelling profiles and simplified housing characteristics thus inhibiting the mimicking of real world housing decision making process. While the study still succeeded in achieving its goal of gauging the extent to which smaller, low-carbon, (near) zero-energy dwellings fulfil current housing preferences, it is recognized that collecting data based on more complex dwelling scenarios through different methods would have increased the accuracy in mimicking real world decision making. Moreover, the data collected in this study was restricted to respondents who are part of smaller households residing in Almere, Zoutleeuw, Huldenberg and Bertem and at least half of the respondents were within the senior age group. While this sample was sufficient to draw meaningful patterns in the data and provide a good representation of the population under investigation, it does limit the applicability of findings beyond the specific study. Conducting more recent studies that include larger samples spread over different locations and across different age groups would increase the generalizability of findings and better capture the dynamic aspect of the housing market. Additionally, in its selection of housing attributes and attribute levels this study excludes housing cost from its analysis because having low housing costs is very likely to achieve a high utility value that compensates for all other less preferred housing characteristics.

However, housing costs are acknowledged as an intrinsic aspect of the housing decision process and their inclusion are considered a limitation.

Lastly, in terms of investigating the material impact of the dwellings, the study consisted of a partial life cycle assessment excluding the operational energy from its temporal scope. While this was based on the normalization of a zero operational energy performance and the fact that it is now mandatory in many countries, it is recognized that accounting for it in the life cycle assessment would have provided a complete overview of the full life cycle performance. Additionally, the study also excluded furniture, sanitary elements and building services from its physical boundaries to reduce assumptions and increase the comparability of outcomes with previous studies. While it is recognized that including these elements would have contributed to a more comprehensive total embodied carbon footprint of a dwelling, it is worth noting that including them would have also further demonstrated the advantages of downsizing dwellings thus reinforcing the argument made in the study.

6.4.2 Overarching limitations

On a general level, the aim of this research has been to establish a holistic and multidimensional outlook in addressing its main research question around small, low-carbon, (near) zero-energy dwellings being a housing solution in North-West Europe. To that end, investigations have been carried out evaluating the implementation and uptake of such dwellings in three different geographic locations as part of the H4.0E project: Flanders, Ireland and the Netherlands. In Flanders, the focus was on providing housing solutions to small, low-income households on social renting waiting lists with a focus on modular and compact construction. The ownership of the H4.0E dwellings was reserved to the social letting agency that falls within the private housing sector but is also partially subsidized. In Ireland, the focus was on providing housing solutions to small, low-income households on social housing waiting lists. Seeing as the ownership of the H4.0E dwellings was reserved to local authorities, the designs of H4.0E dwellings in Ireland were primarily guided by the design requirements set by local authorities. In the Netherlands, the focus was on providing housing solutions to small, low to middle income households within the private housing sector with a focus on promoting self-building. In this case, the ownership of the H4.0E dwellings was reserved to the households and the design of the dwellings were also customized as per their requirements.

While having three different study contexts was insightful as it underlined the importance of contextual peculiarities and their impact on study outcomes, especially under the explorative investigation of institutional barriers, this aspect became in itself a limitation. For instance, NZEB policy documents highly varied per geographic location rendering the approach to distinguishing between actual and perceived barriers different in every country. Due to this lack of consistency in policy documents, in addition to the complexity of the research process, the investigation of actual and perceived barriers had to be restricted to a single context, in this case Ireland, to allow a detailed qualitative data analysis. Similarly, seeing as the types of tenure of the H4.0E dwellings differed per study location, dwelling designs and design goals also varied per study location. Considering this research intended to investigate the impact of house size on the embodied carbon of dwellings, similar dwelling designs of different sizes were needed to successfully conduct this analysis. Recalling the fact that H4.0E dwellings in the Netherlands all abide by the Wikihouse design concept and covered a wider range of dwelling sizes, the dwellings in Almere better fit the embodied carbon study goals. Last but not least, the distribution of the housing preferences questionnaire also differed per study location. In both Ireland and the Netherlands, this was done through a collaboration with a single municipality: Kilkenny and Almere while in Flanders it was conducted in collaboration with three different municipalities: Zoutleeuw, Huldenber, and Bertem. This significantly affected the number of respondents obtained per location and due to a low response rate in Ireland, this context was excluded from the analysis. Overall, that is to say that one of the main limitations of this research is its variations in study locations. While this did not obstruct the aim of achieving a holistic and multidimensional outlook to small, low-carbon, (near) zero-energy housing, it did prevent reaching generalisable outcomes thus restricting its geographical representativeness. Nevertheless, the importance of taking into account the impact of contextual peculiarities on study outcomes rather than prioritizing their generalization for more specific insights is the first argument put forth in this body of work.

6.5 Future Research Directions

6.5.1 Expanding the investigation of perceptions in context specific studies of institutional barriers

Within the institutional dimension, this research argued for the importance of adopting a context-specific approach in investigating the barriers to the implementation and uptake of sustainability measures such as small, low-carbon, (near) zero-energy dwellings. This approach underscores the idea that the contextual peculiarities of different study locations could potentially significantly influence the outcomes and effectiveness of such studies. It highlights that what may be a barrier in one location could differ significantly in another, necessitating tailored investigations. Moreover, this research highlighted the importance of preserving a link between policy development and policy implementation in industry and local practice. Within the social dimension, this study extends its focus to the supply side of the housing market by examining the perceptions of housing professionals. By doing so, it acknowledges the pivotal role of the human factor in shaping housing decisions. In its preliminary exploration, it has laid the groundwork for distinguishing between actual and perceived barriers, providing a valuable starting point for future investigations. Looking forward, future research can build upon this foundation by conducting similar investigations with more extensive and diverse samples of housing professionals, across various contextual settings. This will enable a deeper understanding of how professionals' perceptions align or diverge across different professional perspectives and study locations. Such insights can be invaluable for refining policies and strategies aimed at promoting sustainable housing practices, ultimately contributing to more effective and context-aware sustainability initiatives within the housing sector.

6.5.2 Exploring dwelling size preferences across different residential areas

Also within the social dimension, this research took into account the human factor on the demand side of the housing sector by investigating residents' current housing preferences. The findings from this investigation shed light on a specific aspect: the correlation between the type of residential area in which respondents currently reside and their preferences regarding dwelling size. It emerged that this particular factor, the current residential context, played a significant role in shaping residents' housing preferences, particularly with regard to the size of the dwelling they prefer. Seeing the residential areas covered in this research were suburban and rural, building upon this insight, future research can delve deeper into the nuances of housing preferences within different residential areas. By investigating more closely housing preferences across all residential areas researchers can gain a more comprehensive understanding of the interplay between location and dwelling size preferences and identify patterns and trends on how urban, suburban, or rural settings impact dwelling size preferences differently. In turn, this would provide valuable insights into strategic planning and policy development aimed at promoting smaller dwellings in specific areas. This knowledge can inform targeted approaches for encouraging the adoption of small, low-carbon housing solutions where they are most likely to resonate with residents and facilitate efforts to accelerate the shift toward sustainable housing practices by tailoring initiatives to the unique characteristics of different residential contexts. In that way, further research into the relationship between residential areas and dwelling size preferences would inform roadmaps for promoting smaller dwellings effectively thus accelerating the transition toward small, low-carbon, (near) zero-energy housing.

6.5.3 Expanding the inclusion of the human factor on the demand side

While this study addresses the human factor within the demand side of the housing market, it specifically focuses on understanding the housing preferences of residents. It's essential to note that within the realm of energy research, there have been various approaches to incorporating the human factor. One common approach involves studying residents' behaviour and practices concerning energy consumption within their homes. As such, it is worth highlighting that there's ample room for future research to broaden the scope of the human factor's inclusion. Through conducting post-occupancy evaluations, not only would residents' energy consumption practices within small, low-carbon, (near) zero-energy dwellings be investigated but also their overall comfort and satisfaction levels with these types of housing. By doing so, future research can provide a more comprehensive understanding of the human experience within small, low-carbon, (near) zero-energy dwellings. Examining residents' comfort and satisfaction levels can offer insights into how to effectively promote these dwellings and encourage their wider adoption. Furthermore, this could help identify specific aspects of these dwellings that residents appreciate and areas where improvements are needed. Conducting post-occupancy evaluations that incorporate comfort and satisfaction assessments can also assist in refining the design and construction of small, low-carbon, (near) zero-energy dwellings, ensuring that they align more closely with residents' preferences. Ultimately, this broader perspective on the human factor can contribute to more successful sustainable housing initiatives for a more effective uptake within the housing market.

6.5.4 Standardizing full life cycle assessments of small, low-carbon, (near) zero-energy dwellings

Within the technical dimension of this research, the primary focus lies on assessing the material impact of small, low-carbon, (near) zero-energy dwellings. This evaluation is conducted through a partial life cycle assessment. Within its physical system boundary, the investigation aimed for a high level of detail that covers all layers within the building elements including roofing, flooring, and coating among others. Nevertheless, to data gaps and the absence of standardized procedures and data for specific elements, the physical system boundary did exclude elements such as building service, sanitary elements and furniture. Additionally, in its temporal system boundary, this research chose to exclude the modules related to the operational energy performance of the dwellings. This decision was made to emphasize the material impact of the dwellings themselves, keeping the focus on the embodied carbon of the dwellings. While these exclusions were necessary for the current research objectives, they do result in an incomplete representation of the dwellings' overall environmental impact across their entire life cycle. To achieve a more comprehensive understanding, future research should aim for full life cycle assessments that would portray more accurate and complete carbon footprints of dwellings. More specifically, a zero operational energy performance should be ensured through collecting actual monitoring data. There should also be a concentrated effort on standardizing the process of the embodied carbon accounting of building services, sanitary elements and furniture and including them in LCA tools and databases.

6.5.5 Comparing the different life cycle assessment tools

This research conducts its partial life cycle assessment using the Belgian based TOTEM tool that tailors the environmental impact of materials according to the Belgian context. TOTEM also employs the static model for biogenic carbon accounting (-1/+1) where all timber elements are assumed to be incinerated in the of their life cycle. It is important to note that there are numerous other life cycle assessment (LCA) tools available for conducting such studies. While many of these tools access a common database, such as Ecoinvent, they can differ in various ways. Mainly, differences stem from the many assumptions that can be made throughout the application of the LCA methodology such as the biogenic carbon accounting. One key consideration is that the users/researchers often have limited control over the specific assumptions embedded within these LCA tools. Therefore, it becomes valuable for future research to engage in a comparative analysis of these tools. Such an analysis would serve to identify the potential discrepancies in results stemming from the distinct assumptions made by each tool and discern how these assumptions impact results for a more accurate interpretation of LCA outcomes. From a broader perspective, such a comparative analysis could guide practitioners and researchers in selecting the most suitable LCA tool for their specific context and research goals, considering the potential implications of tool-specific assumptions. In essence, by conducting a comparative analysis of various LCA tools and their assumptions, future research can contribute to a more comprehensive understanding of how different tools influence the interpretation of LCA outcomes. This knowledge is crucial for ensuring the accuracy and reliability of environmental assessments in support of sustainable decision-making.

6.5.6 Accounting for the economic dimension with the investigation of housing costs and affordability

While this research covers the institutional, social and technical dimensions of small, low-carbon, (near) zero-energy housing, it does not investigate the economic dimension with housing affordability falling out of the research scope. The priority was to investigate the extent to which such dwelling designs can be a solution by focusing on the perspectives other than costs considering the many design characteristics that fall outside the ‘norm’. These characteristics consist namely of the smaller dwelling sizes and the low-carbon building materials especially the timber frame. Additionally, depending on the study location, self-building and modular construction can also be added to this list of unusual characteristics. In the attempt to establish whether or not small, low-carbon, (near) zero-energy dwelling designs answer to established housing policies, current housing preferences and an improved energy performance, precedence was given to the institutional, social and technical dimensions. However, it is acknowledged that housing costs and/or housing affordability are an intrinsic aspect of the housing decision process. As such future research can expand upon this study by delving into the economic dimension. Analysing the affordability of small, low-carbon, (near) zero-energy housing designs would provide valuable insights into their feasibility as a housing solution, particularly in comparison to conventional housing options. This would involve assessing not only the initial construction costs but also the long-term financial implications, including operational and maintenance expenses. In that way, this would also address certain institutional barriers identified by housing professionals such as the higher initial costs and the payback period and return on investment barriers. Such an analysis would complement the multidimensional approach adopted in this research and lead to a more comprehensive perspective on the viability and potential adoption of these innovative dwelling designs in different contexts. By addressing this dimension, future research can contribute to an even broader understanding of the potential of small, low-carbon, (near) zero-energy dwellings as a housing solution in North-West Europe

Curriculum Vitae

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Education

2018-2023 PhD Researcher, Management in the Built Environment department, Urban Development Management section, Delft University of Technology

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2022 Energy and Climate Transformations - Third international conf. on Energy Research & Social Science (2022) University of Manchester - poster presentation.

2022 Housing for Zero Energy final conference (2022) Almere, The Netherlands - research presentation

2020 Barriers and drivers to the uptake of innovative, affordable, and zero-energy dwellings in Belgium and Ireland [online conference]. BEYOND 2020 – World Sustainable Built Environment conference.

List of publications

2020 Souaid, C., Van Der Heijden, H. M. H., & Elsinga, M. G. (2020). Barriers and drivers to the uptake of innovative, affordable, and zero-energy dwellings in Belgium and Ireland. In IOP Conference Series: Earth and Environmental Science (Vol. 588, No. 3, p. 032017). IOP Publishing

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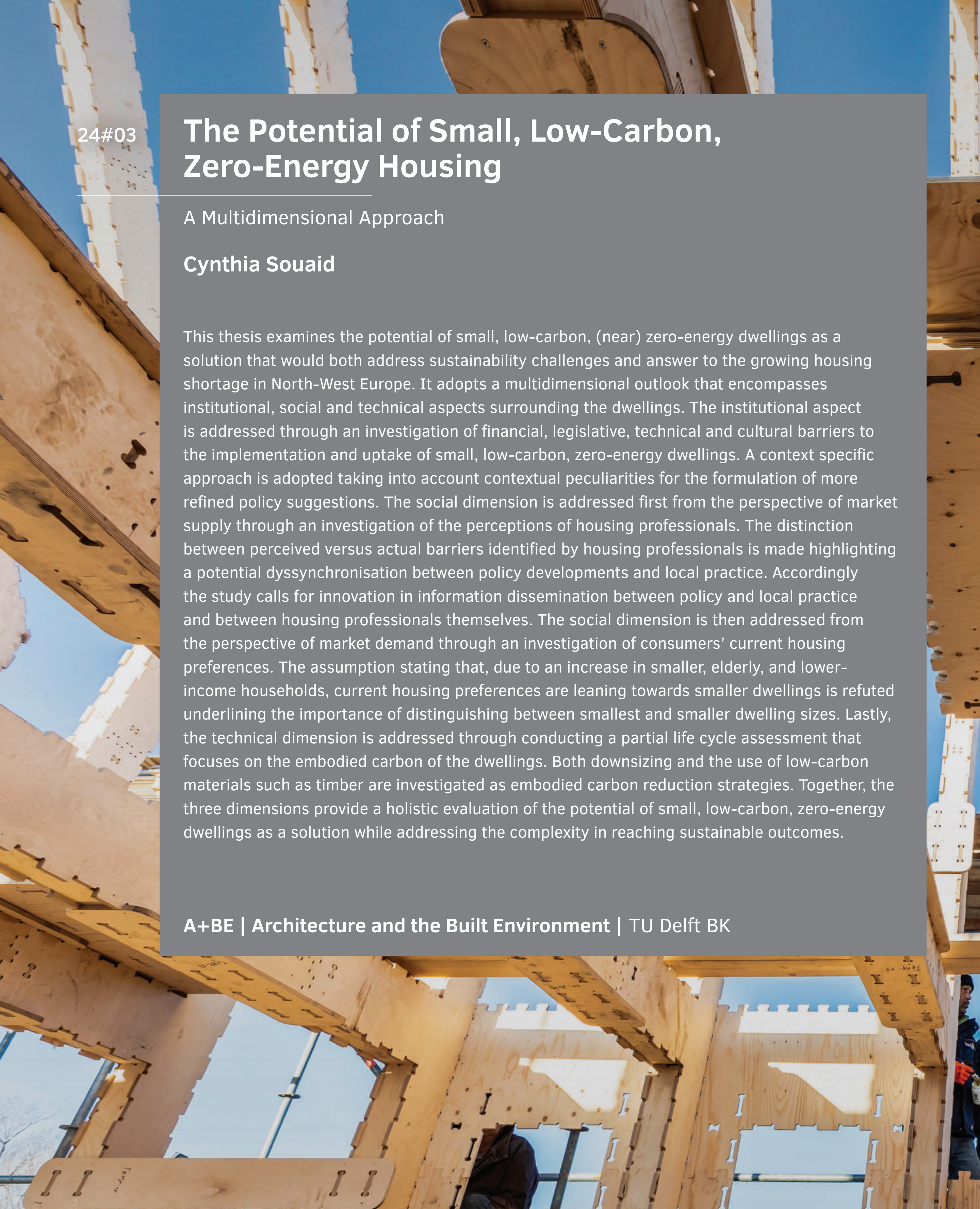
under review

Souaid, C., van der Heijden, H., & Elsinga, M. (2023). The demand for small, low-carbon, zero-energy, timber dwellings: A study of consumers' stated housing preferences. Housing Studies.

Souaid C., ten Caat, N., Meijer, A., Visscher, H., (2023). The assessment of downsizing and the use of timber as embodied carbon strategies for new-build housing. Building and Environment



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The Potential of Small, Low-Carbon, Zero-Energy Housing

A Multidimensional Approach

Cynthia Souaid

This thesis examines the potential of small, low-carbon, (near) zero-energy dwellings as a solution that would both address sustainability challenges and answer to the growing housing shortage in North-West Europe. It adopts a multidimensional outlook that encompasses institutional, social and technical aspects surrounding the dwellings. The institutional aspect is addressed through an investigation of financial, legislative, technical and cultural barriers to the implementation and uptake of small, low-carbon, zero-energy dwellings. A context specific approach is adopted taking into account contextual peculiarities for the formulation of more refined policy suggestions. The social dimension is addressed first from the perspective of market supply through an investigation of the perceptions of housing professionals. The distinction between perceived versus actual barriers identified by housing professionals is made highlighting a potential dyssynchronisation between policy developments and local practice. Accordingly the study calls for innovation in information dissemination between policy and local practice and between housing professionals themselves. The social dimension is then addressed from the perspective of market demand through an investigation of consumers' current housing preferences. The assumption stating that, due to an increase in smaller, elderly, and lower-income households, current housing preferences are leaning towards smaller dwellings is refuted underlining the importance of distinguishing between smallest and smaller dwelling sizes. Lastly, the technical dimension is addressed through conducting a partial life cycle assessment that focuses on the embodied carbon of the dwellings. Both downsizing and the use of low-carbon materials such as timber are investigated as embodied carbon reduction strategies. Together, the three dimensions provide a holistic evaluation of the potential of small, low-carbon, zero-energy dwellings as a solution while addressing the complexity in reaching sustainable outcomes.

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