UNIVERSITAT ROVIRA I VIRGILI

DECISION BUILDING INFORMATION MODELING (BIM)-SUPPORTED TOOLS FOR A FAIR TRANSITION TOWARDS MORE ENVIRONMENTALLY SUSTAINABLE BUILDINGS

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We state that the presented study, entitled, "Decision Building Information Modeling (BIM)-Supported Tools for a Fair Transition Towards More Environmentally Sustainable Buildings" Masoud Norouzi for the award of the degree of Doctor, has been carried out under our supervision at the Department of Chemical Engineering of this university.

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Dr. Dieter Boer

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‘He who is not grateful to people is not grateful to God (Allah)’
Prophet Muhammad

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Masoud Norouzi

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Summary

The Earth is currently facing significant environmental challenges, mostly due to human activities in the Anthropocene. Buildings are a major contributor to various environmental aspects, such as energy consumption, climate change, and resource depletion. In Europe, the building sector is responsible for about 40% of total energy consumption, 36% of all greenhouse gas emissions, 50% of mineral resources, 38% of the waste generated, and 33% of all water use. To address these challenges and promote sustainability, there is an urgent need for a rapid energy transition and to significantly reduce the environmental emissions in the building sector. The transition to more environmentally sustainable buildings involves multiple stakeholders and requires the simultaneous consideration of various factors. These strategies mainly include energy efficiency, circular economy principles, reliance on local and renewable resources, and the incorporation of green infrastructures into building design.

Decision Support Tools (DSTs) are used to help decision-makers facilitate a fair transition towards environmental sustainability in the building and construction sectors. The most common tool used to evaluate the environmental sustainability of products is Life Cycle Assessment (LCA). LCA methodology is an in-depth and reliable assessment that can be utilized to enhance building life-cycle performances. The whole-building LCA (WBLCA) technique offers a comprehensive perspective of building performance using standardized metrics. Neglecting the WBLCA perspective of a building throughout its lifespan might result in boundary shifting of the environmental load between different life cycle stages. However, the current application of LCA for whole buildings still faces some methodological challenges and implementation issues. Furthermore, understanding temporal perspectives of emissions and causal interrelations in the building system, and describing development from the present to the future, are fundamental parts of future scenarios. These factors suggest directions for sustainable technological development for aiding decision-making and policymaking. Additionally, to properly understand the environmental impacts of buildings, practitioners need to apply reliable data in their LCA workflow. The Environmental Product Declaration (EPD) scheme, although not perfect, is the most suitable methodological principle applicable during the building design process for providing practitioners with relevant environmental data.

The Architecture, Engineering, Construction, and Operations (AECO) sector explores a range of new technologies and approaches to investigate the energy and environmental performance of materials and activities and to help in the decision-making of sustainability in buildings. Building Information Modelling (BIM) and

Building Energy Modelling (BEM) methodologies have the potential to support decision-making processes through a set of applications and procedures that enable the generation and management of project information. The integration of these approaches into LCA methodology can enable a more precise application from the design phase to the end-of-life phase, as traditional LCA is a very time-consuming task. To model future and long-term solutions, it is highly necessary and valuable to conduct a dynamic LCA (DLCA) methodology.

The main objective of this thesis is to propose a design improvement framework that enhance the environmental performance of buildings towards sustainability by developing systematic and reliable LCA results with the incorporation of BIM, BEM, and EPD approaches. The study attempts to investigate the potential contribution of this framework by conducting a literature review and real case studies. This research study also aims to identify the main methodological challenges and implementation issues of using DSTs in the building sector, and propose solutions to overcome them (particularly considering the temporal perspectives).

To this end, six major contributions are made in this thesis. First, a literature review was conducted based on bibliometrics techniques (and more specifically science mapping) to track information flows and identify influential research elements in the field of interest. In the direction of potential opportunities in the current knowledge identified in the literature review, the possibility of some influential strategies and methods was considered in the next sections. Thus, in the second section, to highlight the co-benefits of improving energy efficiency in the buildings, the environmental impact of typical buildings that comply with the current building regulations and with the Passivhaus standard were compared. Third, thorough sensitivity analyses, the LCA methodology was combined with scenario-based modeling to investigate potential future paths considering long-term electricity mix projections. Fourth, lies in establishing a modeling framework for WBLCA that exploits the benefits of incorporating BIM, BEM, and EPD methodologies to achieve nearly-zero energy building (nZEB) targets. Fifth, and sixth, a DLCA was developed to investigate the potential future short-term paths of three different heating and ventilation options (such as compact heat pump) and consider long-term planning targets within the context of national regulations for the decarbonization of electricity mix and technological changes in waste management treatments of timber materials on the GHG emissions of an nZEB.

In summary, this thesis research concludes that the proposed framework can enhance the environmental performance of buildings by providing a systematic and reliable LCA approach with the implementation of BIM, BEM, and EPD methodologies. The framework can also provide practitioners with decision support tools for evaluating the environmental sustainability of building models while also considering future short- or long-term assessments. However, the study highlights the need for further research to overcome the methodological challenges and implementation issues of using DSTs in the building sector.

Resumen

Actualmente, la Tierra se enfrenta a importantes desafíos ambientales, principalmente debido a las actividades humanas en el Antropoceno. Los edificios son un importante contribuyente a diversos aspectos ambientales, como el consumo de energía, el cambio climático y la depleción de recursos. En Europa, el sector de la construcción es responsable de aproximadamente el 40% del consumo total de energía, el 36% de todas las emisiones de gases de efecto invernadero, el 50% de los recursos minerales, el 38% de los residuos generados y el 33% de todo el uso del agua. Para abordar estos desafíos y promover la sostenibilidad, es necesario una transición energética rápida y una reducción significativa de las emisiones ambientales en el sector de la construcción. La transición hacia edificios más sostenibles desde el punto de vista ambiental involucra a múltiples actores y requiere la consideración simultánea de diversos factores. Estas estrategias incluyen principalmente la eficiencia energética, los principios de la economía circular, la dependencia de recursos locales y renovables y la incorporación de infraestructuras verdes en el diseño de edificios.

Las Herramientas de Apoyo a la Toma de Decisiones (DST, por sus siglas en inglés) se utilizan para ayudar a los tomadores de decisiones a facilitar una transición justa hacia la sostenibilidad ambiental en los sectores de la construcción y la edificación. La herramienta más común utilizada para evaluar la sostenibilidad ambiental de los productos es la Evaluación del Ciclo de Vida (LCA, por sus siglas en inglés). La metodología LCA es una evaluación detallada y confiable que se puede utilizar para mejorar el rendimiento del ciclo de vida de los edificios. La técnica LCA de todo el edificio (WBLCA, por sus siglas en inglés) ofrece una perspectiva integral del rendimiento del edificio utilizando métricas estandarizadas. El descuido de la perspectiva WBLCA de un edificio a lo largo de su vida útil podría resultar en el desplazamiento de límites de carga ambiental entre diferentes etapas del ciclo de vida. Sin embargo, la aplicación actual de la LCA para edificios completos todavía enfrenta algunos desafíos metodológicos y problemas de implementación. Además, entender las perspectivas temporales de las emisiones y las interrelaciones causales en el sistema de construcción y describir el desarrollo desde el presente hacia el futuro son partes fundamentales de los escenarios futuros. Estos factores sugieren direcciones para el desarrollo tecnológico sostenible para ayudar en la toma de decisiones y en la formulación de políticas. Además, para comprender adecuadamente los impactos ambientales de los edificios, los profesionales deben aplicar datos confiables en su flujo de trabajo de LCA. El esquema de Declaración Ambiental de Producto (EPD, por sus siglas en inglés), aunque no es perfecto, es el principio metodológico más adecuado aplicable durante el proceso de diseño de edificios para proporcionar a los profesionales datos ambientales relevantes.

El sector de Arquitectura, Ingeniería, Construcción y Operaciones (AECO) explora una variedad de nuevas tecnologías y enfoques para investigar el rendimiento energético y ambiental de materiales y actividades, y para ayudar en la toma de decisiones de sostenibilidad en edificios. Las metodologías de Modelado de Información de Construcción (BIM) y Modelado de Energía de Edificios (BEM) tienen el potencial de apoyar los procesos de toma de decisiones a través de un conjunto de aplicaciones y procedimientos que permiten la generación y gestión de información del proyecto. La integración de estos enfoques en la metodología de Análisis de Ciclo de Vida (LCA) puede permitir una aplicación más precisa desde la fase de diseño hasta la fase de fin de vida, ya que el LCA tradicional es una tarea muy laboriosa. Para modelar soluciones futuras y a largo plazo, es altamente necesario y valioso realizar una metodología de LCA dinámico (DLCA).

El objetivo principal de esta tesis es proponer un marco de mejora del diseño que mejore el rendimiento ambiental de los edificios hacia la sostenibilidad mediante el desarrollo de resultados sistemáticos y fiables de LCA con la incorporación de enfoques BIM, BEM y EPD. El estudio intenta investigar la contribución potencial de este marco mediante la realización de una revisión de la literatura y estudios de casos reales. Este estudio de investigación también tiene como objetivo identificar los principales desafíos metodológicos y problemas de implementación del uso de DST en el sector de la construcción, y proponer soluciones para superarlos (particularmente considerando las perspectivas temporales).

Para ello, se hacen seis contribuciones principales en esta tesis. En primer lugar, se realizó una revisión de la literatura basada en técnicas bibliométricas (y más específicamente en el mapeo científico) para rastrear los flujos de información e identificar elementos de investigación influyentes en el campo de interés. En la dirección de las oportunidades potenciales en el conocimiento actual identificado en la revisión de la literatura, se consideró la posibilidad de algunas estrategias y métodos influyentes en las siguientes secciones. Así, en la segunda sección, para resaltar las co-beneficios de mejorar la eficiencia energética en los edificios, se comparó el impacto ambiental de edificios típicos que cumplen con las regulaciones de construcción actuales y con el estándar Passivhaus. Tercero, a través de análisis de sensibilidad exhaustivos, se combinó la metodología de LCA con el modelado basado en escenarios para investigar posibles caminos futuros considerando proyecciones de la mezcla eléctrica a largo plazo. Cuarto, radica en establecer un marco de modelado para WBLCA que aprovecha los beneficios de incorporar metodologías BIM, BEM y EPD para alcanzar objetivos de edificios de energía casi nula (nZEB). Quinto y sexto, se desarrolló un DLCA para investigar los posibles caminos futuros a corto plazo de tres opciones de calefacción y ventilación diferentes (como bomba de calor compacta) y considerar objetivos de planificación a largo plazo dentro del contexto de regulaciones nacionales para la descarbonización de la mezcla de electricidad y cambios tecnológicos en los tratamientos de gestión de residuos de materiales de madera sobre las emisiones de GEI de un nZEB.

En resumen, esta investigación concluye que el marco propuesto puede mejorar el rendimiento ambiental de los edificios al proporcionar un enfoque sistemático y confiable de LCA con la implementación de metodologías BIM, BEM y EPD. El marco también puede proporcionar a los profesionales herramientas de apoyo para la toma de decisiones para evaluar la sostenibilidad ambiental de los modelos de edificios, considerando evaluaciones futuras a corto o largo plazo. Sin embargo, el estudio destaca la necesidad de más investigación para superar los desafíos metodológicos y problemas de implementación del uso de DST en el sector de la construcción.

Resum

Actualment, la Terra està enfrontant importants desafiaments ambientals, en gran part a causa de les activitats humanes en l'Antropocè. Els edificis són un important contribuent a diversos aspectes ambientals, com ara el consum d'energia, el canvi climàtic i l'esgotament de recursos. A Europa, el sector de la construcció és responsable d'aproximadament el 40% del consum energètic total, el 36% de totes les emissions de gasos d'efecte hivernacle, el 50% dels recursos minerals, el 38% dels residus generats i el 33% de tot l'ús d'aigua. Per abordar aquests desafiaments i promoure la sostenibilitat, hi ha una necessitat urgent d'una transició energètica ràpida i de reduir significativament les emissions ambientals en el sector de la construcció. La transició cap a edificis més sostenibles des del punt de vista ambiental involucra diversos actors i requereix la consideració simultània de diversos factors. Aquestes estratègies inclouen principalment l'eficiència energètica, els principis d'economia circular, la dependència de recursos locals i renovables i la incorporació d'infraestructures verdes en el disseny dels edificis. Les eines de suport a la presa de decisions (DST) s'utilitzen per ajudar els responsables de la presa de decisions a facilitar una transició justa cap a la sostenibilitat ambiental en els sectors de la construcció i l'edificació. L'eina més comuna utilitzada per avaluar la sostenibilitat ambiental dels productes és l'Avaluació del Cicle de Vida (LCA). La metodologia LCA és una avaluació detallada i fiable que es pot utilitzar per millorar el rendiment del cicle de vida dels edificis. La tècnica de LCA de tot l'edifici (WBLCA) ofereix una perspectiva completa del rendiment dels edificis utilitzant mètriques estandarditzades. La negligència de la perspectiva WBLCA d'un edifici al llarg de la seva vida útil pot provocar el desplaçament del límit de la càrrega ambiental entre diferents etapes del cicle de vida. No obstant això, l'aplicació actual de LCA per a tots els edificis encara enfronta alguns reptes metodològics i problemes d'implementació. A més, per entendre adequadament els impactes ambientals dels edificis, els professionals necessiten aplicar dades fiables en el seu flux de treball de LCA. El sistema de Declaració Ambiental del Producte (EPD), tot i que no és perfecte, és el principi metodològic més adequat aplicable durant el procés de disseny d'edificis per proporcionar als professionals les dades ambientals rellevants.

El sector de l'Arquitectura, Enginyeria, Construcció i Operacions (AECO) explora una sèrie de noves tecnologies i enfocaments per investigar el rendiment energètic i ambiental dels materials i activitats, i ajudar en la presa de decisions de sostenibilitat en edificis. Les metodologies Building Information Modelling (BIM) i Building Energy Modelling (BEM) tenen el potencial de suportar els processos de presa de decisions a través d'un conjunt d'aplicacions i procediments que permeten la generació i gestió de la informació del projecte. La integració d'aquests enfocaments

en la metodologia LCA pot permetre una aplicació més precisa des de la fase de disseny fins a la fase de final de vida, ja que la LCA tradicional és una tasca molt laboriosa. Per modelar solucions futures i de llarg termini, és molt necessari i valuós realitzar una metodologia de LCA dinàmica (DLCA).

L'objectiu principal d'aquesta tesi és proposar un marc d'optimització del disseny que millori el rendiment ambiental dels edificis cap a la sostenibilitat, mitjançant el desenvolupament de resultats sistemàtics i fiables de LCA amb la incorporació dels enfocaments BIM, BEM i EPD. L'estudi intenta investigar la possible contribució d'aquest marc mitjançant una revisió de la literatura i estudis de casos reals. Aquest estudi de recerca també té com a objectiu identificar els principals reptes metodològics i problemes d'implementació de l'ús de DST en el sector de la construcció, i proposar solucions per superar-los (particularment considerant les perspectives temporals).

Per a això, s'han fet sis contribucions importants en aquesta tesi. En primer lloc, es va realitzar una revisió bibliogràfica basada en tècniques de bibliometria (i més concretament en cartografiat científic) per seguir els fluxos d'informació i identificar elements de recerca influents en el camp d'interès. En la direcció de les oportunitats potencials en el coneixement actual identificat en la revisió bibliogràfica, es va considerar la possibilitat d'algunes estratègies i mètodes influents en les seccions següents. Així, en la segona secció, per destacar els efectes beneficiosos de millorar l'eficiència energètica en els edificis, es van comparar els impactes ambientals dels edificis típics que compleixen amb les normatives de construcció actuals i amb l'estàndard Passivhaus. En tercer lloc, a través d'anàlisis de sensibilitat exhaustives, la metodologia LCA es va combinar amb la modelització basada en escenaris per investigar possibles camins futurs tenint en compte les projeccions a llarg termini de la mescla d'electricitat. El quart recau en l'establiment d'un marc de modelització per a WBLCA que aprofita els avantatges d'incorporar les metodologies BIM, BEM i EPD per aconseguir objectius d'edificis de quasi zero energia (nZEB). Cinquè i sisè, es va desenvolupar una DLCA per investigar els possibles camins futurs a curt termini de tres opcions diferents de calefacció i ventilació (com ara bombes de calor compactes) i considerar objectius de planificació a llarg termini dins del context de les normatives nacionals per a la descarbonització de la mescla d'electricitat i els canvis tecnològics en els tractaments de gestió de residus dels materials de fusta sobre les emissions de GEH d'un nZEB.

En resum, aquesta investigació de tesi conclou que el marc proposat pot millorar el rendiment ambiental dels edificis proporcionant un enfocament sistemàtic i fiable de LCA amb la implementació de les metodologies BIM, BEM i EPD. El marc també pot proporcionar als professionals eines de suport a la presa de decisions per avaluar la sostenibilitat ambiental dels models d'edificis, tenint en compte també les avaluacions futures a curt o llarg termini. No obstant, l'estudi destaca la necessitat de més recerca per superar els desafiaments metodològics i problemes d'implementació de l'ús de DST en el sector de la construcció.

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Chapter I

Introduction

I. Introduction

I.1 Background and motivation

Nowadays, we can see how the Earth is facing several important environmental challenges. Circumstances such as temperature rise and extreme climate events, shifting wildlife habitats, rising sea levels, and melting ice, being not only damaging considerably the ecosystem but also compromise the quality of life and well-being of future generations (Li et al., 2021; Mateus et al., 2023). These undesirable consequences are arising largely from the modern way of humankind's activities in the Anthropocene (*i.e.*, global warming and climate change), which have led to the urgent need for worldwide commitments and drawn focused attention to reducing the greenhouse gas (GHG) emissions (Luisa F Cabeza et al., 2014; Iddon and Firth, 2013). In 2020, GHG emissions dropped due to the COVID-19 forced confinement, representing a 26% decrease on average during the pandemic peak compared to the same period of the previous year (Le Quéré et al., 2020). However, this atypical slowdown in GHG emissions was only temporary without structural changes, and fossil fuel consumption and CO_2 emissions are expected to rebound quickly to the pre-crisis levels, and potentially even exceed these levels within a two-year horizon (López et al., 2023; L. V. Smith et al., 2021).

There is a close connection between energy, the environment, and sustainable development. Following the UN Sustainable Development Goals (SDGs) (United Nations, 2015a), the construction sector has the key role in the pathway towards sustainable and circular economic development as well as in reducing the environmental footprint (Ahmad et al., 2012; Takano et al., 2015; United Nations, 2015b). The acknowledgment of the significance of emissions from buildings was recognized during the 26th Conference of Parties (COP26), which has designated a specific day that focuses on 'Cities, Regions and Built Environment' (POST, 2021). Buildings account for a significant fraction of the issues such as energy consumption, climate change, and resource depletion (Cao et al., 2016). In Europe, the building sector is responsible for around 40% of total energy consumption, 36% of all greenhouse gas emissions, 50% of mineral resources, 38% of the waste generated, and 33% of all water use (Cusenza et al., 2022; European Commission, 2019). Under the main international instrument by the Paris Climate Agreement and then followed by European Green Deal, the Commission has set out a cross-sectional framework to reduce at least 55% of the greenhouse gas compared to 1990 levels by 2030, and an ambitious aim at net-zero emissions buildings by 2050 (VITO et al., 2018).

To promote sustainability and respond to existing climate change, the need for a rapid energy transition was discussed by the European policies, where the key solution will force the building sector to increase energy efficient by improving the performance of the building envelope and increasing the ratio of renewable energy (European Parliament, 2010; Mateus et al., 2023). The improving energy efficiency target by EU environmental policy is at least 32.5% compared to projections and increasing the share of renewable sources by at least 32%, both by 2030 (European Commission, 2018).

With the prospects of rising global demand for new residential buildings coupled with changes in consumption patterns, the relevance of a pathway to support fair sustainable, and resilient buildings have received increasing attention among researchers and practitioners in industry, society, and academia (Anastasiades et al., 2020). Sustainable construction involves designing and constructing buildings that are environmentally responsible, economically viable, and socially beneficial. Based on the literature review, the environmental aspect serves as a foundation for other aspects of sustainability (Ayarkwa et al., 2022; Obringer and Nateghi, 2021). Moreover, in conventional projects in today's practice, there is a pervasive emphasis on enhancing the economic performance of buildings, while environmental aspects are frequently relegated to a secondary priority or, in some instances, wholly disregarded (Forth et al., 2023). The transition towards more environmentally sustainable buildings involves multiple stakeholders, and several Decision Support Tools (DSTs). It requires the simultaneous consideration of various factors, including not only energy efficiency but also adopting the principles of circular economy, reliance on local and renewable resources, and the incorporation of green infrastructures into building design (Munaro et al., 2020; Norouzi et al., 2021a; Shahsavar et al., 2023).

Circular economy (CE) offers an opportunity to reduce the use of primary materials, and their associated buildings' environmental burdens (Abokersh et al., 2021; Bilal et al., 2020). Anastasiades et al. (2020) reviewed the lessons learned for translating sustainability and CE to bridge construction and concluded that "*where sustainability is the goal, circular economy is the means to this end*". However, Pomponi and Moncaster (2017) contended that the current CE researchers are inclined to ignore the effects and potential barriers of buildings that negatively impact the environment, thus creating a built environment transition to a CE is crucial (Mahpour, 2018). The adoption of circular economy-based strategies, such as reusing materials and the development of buildings to be reused or deconstructed, can serve as a means towards whole life-carbon emissions reductions (UKGBC, 2019). The authors found that there is a gap to contribute a scientific evolution study concerning the extent of embedding circular economy principles in the building and construction sector to seek the emerging research lines and the historical developments of the topic (Norouzi et al., 2021a). This lack of understanding knowledge is also aligned with the assertion of multiple studies (Mahpour, 2018; Munaro et al., 2020; Pomponi and Moncaster, 2017).

Among sustainable alternatives to conventional construction, certifications such as the Passive House (PH or Passivhaus) and "nearly-Zero Energy Buildings" (nZEB) have become the most widely used for architects (Schnieders and Hermelink, 2006). PH is a well-defined strategy among low-energy buildings (Lee et al., 2020), and is considered the most established standard for energy-efficient building design (Feist, 2011). The concept of PH refers to a house that requires less than one-tenth of the average heating energy (less than 15 kWh/m^2yr), use less than 1.5 L of oil or 1.5 m^3 of gas to heat one square meter of living area per year (Feist, 2011). This expectation is achieved by five essential principles (Moreno-Rangel et al., 2020):

i) Improve the envelope insulation.
ii) Thermal bridge-free construction.
iii) Utilization of airtightness.
iv) Equipped with a mechanical ventilation system with heat recovery (MVHR).
v) High-performance doors and windows.

Moreover, the deployment of energy-efficient appliances is critical for achieving the low-primary energy demand and the reduction of related GHG emissions, as more than 70% of total energy consumption in residential units is used for heating and cooling (Antoniadis and Martinopoulos, 2019; Rahif et al., 2022). Nevertheless, the choice of energy carrier for building heating and cooling sector is of particular relevance in the strategies for CO_2 emission reductions (Samsatli and Samsatli, 2019), where energy consumption in households' appliances still heavily relies on conventional fuels (*e.g.,* biomass, fossil fuels) (Khan et al., 2020; Samsatli and Samsatli, 2019). All those aspects highlight the future potential of low-energy buildings (*e.g.,* Passivhaus standard) while fostering the use of energy-efficient technologies, in reducing energy consumption and GHG emissions (Ligardo-Herrera et al., 2022).

Although energy efficiency measures in design and systems may effectively reduce the direct GHG emissions of building operation, it shifts the load emissions to the electricity mix production, and/or embodied impacts (Nematchoua et al., 2022; Rahif et al., 2022). The need to change the energy production mix over time by increasing the share of renewable sources among the technologies used has led to the development of a range of technological aspects to supply electricity (Ortiz-Rodríguez et al., 2010; Weidner and Guillén-Gosálbez, 2023; K. Zhu et al., 2019). Nevertheless, applying this aspect has so far been neglected in most initiatives (De

Wolf et al., 2017; Kiss et al., 2020) and the existing works of literature on climate change impact assessment in buildings usually exclude it (Negishi et al., 2018). Collinge et al. (2013) highlighted the interest in employing a dynamic approach for evaluating buildings, given their long lifespan and consequent potential changes in operation and, industrial and environmental systems over time. In this context, there is a high importance in properly taking into account the dynamics of environmental sustainability when comparing products, services, or systems (Beloin-Saint-Pierre et al., 2020).

Further strategies to achieve an nZEB should involve reducing the process emissions of embodied impacts of construction products in all stages of its life and in its broader sustainability assessment (Lützkendorf et al., 2014; Rodriguez et al., 2020). For example, low-energy buildings often have lower total operational emissions emitted but increased embodied emissions. In this context, some of the most influential strategies for improving environmental performance (mainly adopting CE principles) have been identified as increasing the use of sustainable building materials such as recycled or reused construction materials (Malmqvist et al., 2018; Norouzi et al., 2021b; Pomponi and Moncaster, 2016), extending building lifetime and material service life (Resch et al., 2020), technological improvements in production technology and end-of-life treatment (Fufa et al., 2017), and reducing waste processing impacts (Akanbi et al., 2018; Ghisellini et al., 2018). In addition, using timber or other “natural” materials may sequester and temporarily store embodied carbon or delay GHG emissions (Sodagar et al., 2010). However, there are different approaches for accounting for biogenic carbon storage in LCA, and these can lead to substantial differences in the LCA results (Fouquet et al., 2015). Another important trend is the incorporation of green infrastructures in building design, such as the use of solar panels (Elomari et al., 2022). These systems can not only improve energy efficiency but also help to reduce the carbon footprint of buildings and promote sustainable development.

Decision Support Tools (DSTs) are used to help decision-makers to facilitate a fair transition toward environmental sustainability in the building and construction sectors. DSTs are the array of computer-based tools developed to support a wide range of applications in sustainable building design and operation, mainly including (Wong-Parodi et al., 2020):

i) Environmental impact assessment (EIA) tools (*i.e.*, life cycle assessment (LCA)).
ii) Building performance simulation (BPS) tools.

The most common tool applied to evaluate the environmental sustainability of a product, process or service is LCA (Anastasiades et al., 2020; Buyle et al., 2013;

Dinas et al., 2017). LCA methodology is an in-depth and reliable assessment that can be utilized to enhance buildings' life-cycle performances (Najjar et al., 2019). The reviews by Igos et al. (2019) and more recently by Roberts et al. (2020) highlight the key challenges and general topic of uncertainty that may arise in LCA models hindering. They suggest related methods to mitigate them through uncertainty and sensitivity analyses at various stages of the building design process. However, these uncertainties are often not quantified and communicated in the literature. For example, Feng et al. (2022) revealed that a mere 10% of building LCA papers referenced uncertainty and incorporated an uncertainty analysis in their findings (*e.g.,* 426 out of 5890 papers published between 2000 and 2020). The need for a life-cycle perspective when implementing and assessing the potential impacts of buildings is also essential to design more efficient and environmentally friendly complex products, such as building products, elements, and buildings as a whole (Luisa F. Cabeza et al., 2014; Soares et al., 2017a). The whole-building LCA (WBLCA) technique serves to cover environmental performance and offers an all-encompassing perspective of building performance using science-based, standardized metrics (Kylili et al., 2017; Weißenberger et al., 2014). Neglecting the WBLCA perspective of a building throughout its service life might result in problem-shifting of the environmental load between different life cycle stages in the process of decision-making (Norouzi et al., 2022). However, the current application of LCA for a whole building still faces some methodological challenges and implementation issues, due to both the complexity of building systems (such as the variability in building and material lifespans, location-specific conditions, and diverse building materials), and the design quality (such as choice of impact categories, and level of transparency) (Abd Rashid and Yusoff, 2015; Khasreen et al., 2009; Song et al., 2020).

The Architecture, Engineering, Construction, and Operations (AECO) sector explores a range of new technologies and approaches to investigate the energy and environmental performance of materials and activities and to help in the decision-making of sustainability in buildings. With the increasing awareness of this issue, the key area of green innovation which provides changing the characteristics of the AECO sector is the development of Building Information Modelling (BIM) and Building Energy Modelling (BEM) methodologies. These emerging technologies have been receiving great attention from both academics and software developers in recent years, being one of the most effective ways to fair transition towards more sustainable buildings (Gao et al., 2019). BIM and BEM have the potential to support decision-making processes through a set of applications and procedures that enable the generation and management of project information. These tools can help to select competent and sustainable models for buildings, from the design phase until the end-of-life phase (Olawumi and Chan, 2018; Olusola et al., 2017).

I.2 General and specific objectives

This thesis intends to investigate a possible contribution to the most influential challenge regarding environmental sustainability problems in the building sectors from both literature review and real case study projects. Thus, the main goal is to propose a design improvement framework to enhance the environmental performance of residential buildings by developing systematic and reliable LCA results with the implementation of digital platforms and well-known decision support tools (DSTs) such as BIM, BEM, and EPD. The specific sub-objectives of the research are outlined in the following paragraphs:

i) To identify and provide a holistic perspective, bringing together the historical developments and current status, and highlighting the emerging topics, hot research lines and potential for decision support tools of the topic applications in buildings to achieve environmental targets and to improve sustainability.
ii) To assess the environmental impact of typical buildings designed to meet the current Irish Building Regulations and the Passivhaus standard.
iii) To develop and verify a detailed simulation to account for the overall effect of the variations in electricity grid composition during the building lifespan on the environmental results based on sensitivity analysis.
iv) To develop a detailed modeling framework for WBLCA to exploit the benefits of incorporating BIM, BEM, and EPD methodologies towards nZEB.
v) To assess the sustainable potential for mitigating the carbon footprint of a timber-frame low-energy dwelling in terms of three efficient heating and ventilation options such as heat pump integration into a dynamic LCA.
vi) To analyze the influence of technological progress of the waste treatment of timber materials on the building's embodied impacts.

The capability of the decision support tools developed in this thesis is implemented via real building case studies to demonstrate their potential in facilitating decisions and policymakers towards more environmentally sustainable choices.

I.3 Literature review

Various review methods are available for examining the written publications, including critical review, literature review, meta-analysis, systematic search, and review paper (Grant and Booth, 2009). The bibliometrics technique is a systematic quantitative method of literature reviews that follows a transparent, and systematic process to collect information in a reproducible manner (Pollack and Adler, 2015). This technique can be useful for transdisciplinary research in enabling researchers to evaluate emerging trends in their respective fields of research, identifying potential opportunities in the current literature, and providing additional ways for future works in terms of geography, theory, and methodology used (Pickering and Byrne, 2014). Bibliometrics techniques differ in their output and purpose and can be grouped into three categories: bibliometric indicators (*e.g.*, (Waltman, 2016)), bibliometric statistics (*e.g.*, (Dong et al., 2012)), and science mapping (*e.g.*, (Zupic and Čater, 2015)). Thus, to track information flows and identify influential research elements of the published articles, a literature review using these three techniques is conducted. In addition, this investigation is followed with a content analysis (as a qualitative analysis approach) to provide deep and new information related to the field of interest.

The standard procedure of bibliometrics comprises document collection, data processing, visualization, and analysis. According to the research of Aria and Cuccurullo (2017), and Zupic and Čater (2015), we propose an adapted methodological framework using the bibliometric indicators, bibliometric statistics, and science mapping methods (see Figure I.1).

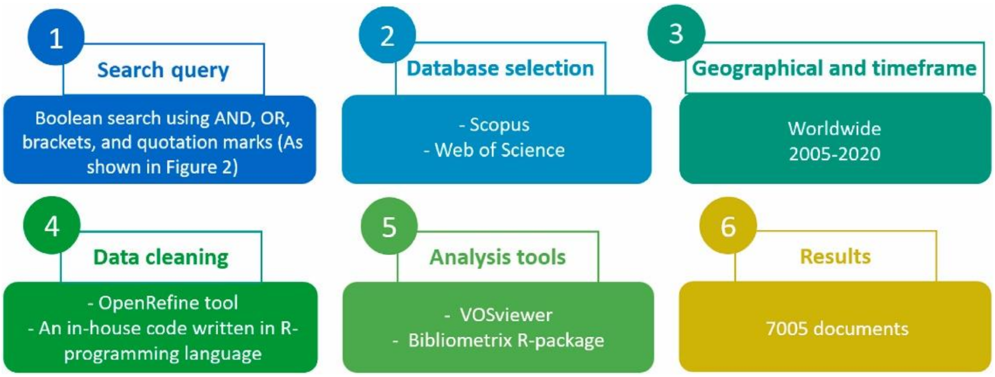

Figure I.1: The methodological framework of the bibliometrics technique.

The detailed background on bibliometrics techniques (and more specifically science mapping), as well as a description of the workflow of this empirical framework adopted to analyze the sustainability and circular economy in the buildings, followed by a discussion of the results, are presented in Chapter II.

I.4 Environmental impact assessment (EIA) tool

Environmental impacts are addressed in the current thesis as a concept that covers ecological aspects of the sustainability of buildings. Environmental impact assessment (EIA) is a planning tool that is traditionally applied in the scientific and political spheres to identify, predict, and communicate information about the environmental effects of a system, plan, or proposal. LCA is commonly used in decision-making contexts, as it can play an invaluable role in improving EIA (Manuilova et al., 2009).

I.4.1 Life cycle assessment (LCA)

LCA is a powerful method to calculate the environmental impact of a product or process, considering the whole life cycle, from cradle to grave or even cradle to cradle (Buyle et al., 2013). All aspects considering the natural environment, human health, and resource depletion are considered simultaneously with the life cycle perspective. Hence, the LCA approach can be used to identify and quantify environmental impacts associated with a process/product from raw material extraction to disposal, energy, and material consumption, as well as the generated wastes (Gasia et al., 2021; Guinée et al., 2011). LCA intends to analyze the unique impact of a product, process or service on environmental loads throughout its various life cycle phases. Currently, two international standards, namely ISO 14040 and 14044 (ISO 14040, 2006; ISO 14044, 2006) set out four steps, making the LCA methodology possible to compare different studies: (i) Goal and scope definition; (ii) life cycle inventory (LCI); (iii) life cycle impact assessment (LCIA); and (iv) interpretation. These steps are shown in Figure I.2 and explained in detail in the next subsections.

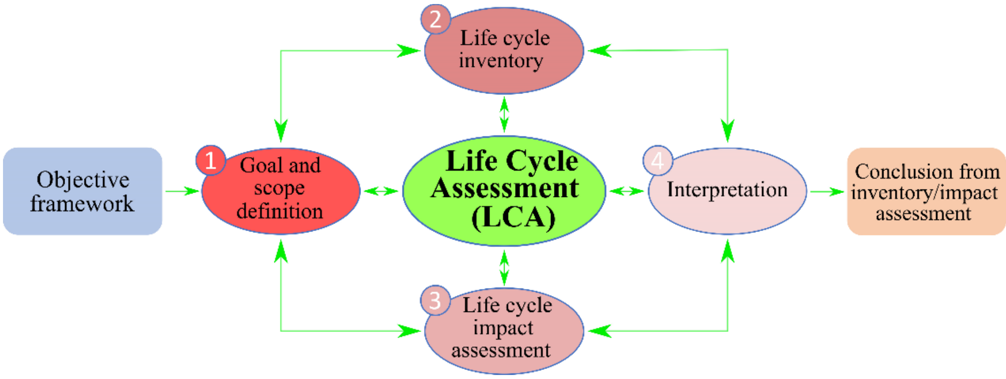

Figure I.2: Phases of the LCA methodology (Sharma et al., 2011).

I.4.1.1 <u>Goal and scope definition</u>

The first step, goal and scope definition, establishes the purpose, functional unit, system boundaries, cut-off criteria, scenario development procedure, and limitations of the study. This step can substantially affect the results of LCI and LCIA, as well as the interpretation of the whole study (Song et al., 2020). It determines the context of the study, and how and by whom life cycle stages, unit processes, inflows, and outflows are to be included (or excluded). As specified in the ISO 14044 standard (ISO 14044, 2006), the criteria used to define the impact categories and category indicators must be also identified and explained in the goal and scope definition phase. These impact categories are consistent with the purpose of the LCA study.

In the building sector, the European EN 15978 and 15804 standards for the "Sustainability of Construction Works – Assessment of Buildings" (CEN, 2019, 2011) describe four building life cycle stages (see Figure I.3):

i) The product stage (modules A1-A3): From raw material supply to manufacturing.
ii) The construction process stage (module A4): Transport to the building site, and module A5: on-site construction.
iii) the use stage (modules B1-B7): Use, maintenance, repair, replacement, refurbishment, and operational energy and water use.
iv) The end-of-life stage (modules C1-C4): From de-construction, waste processing, to final disposal.
v) The benefits and loads beyond the system boundary (module D).

The systemic approaches for LCA are known as "cradle-to-gate" which includes A1-A3; "cradle-to-site", which includes A1-A5, or "cradle-to-grave", which includes A1-B7. When the evaluation covers the possibilities of recycling and reuse, it is called "cradle-to-cradle" which includes modules A1-D (ISO 14044, 2006). As illustrated in Figure I.3, it must also determine which elements from the building system will be included in the calculation. Due to the complexity of the LCA process and lack of the necessary data in the inventory which will be explained more extensively in section III.2.1.2 of Chapter III, the incorporation of the whole model boundaries is however not involved in the case study studied. ISO 14044 allows to apply this modification to the process, but only if they do not substantially alter the overall conclusions of the study (*i.e.*, ignoring the stages that lack adequate data and are not linked to significant impacts, such as B3 (repair) and B5 (refurbishment)). However, throughout Chapter IV of the thesis, the system boundaries correspond to the term "cradle-to-cradle" of the building's life cycle (see section IV.2.2.2).

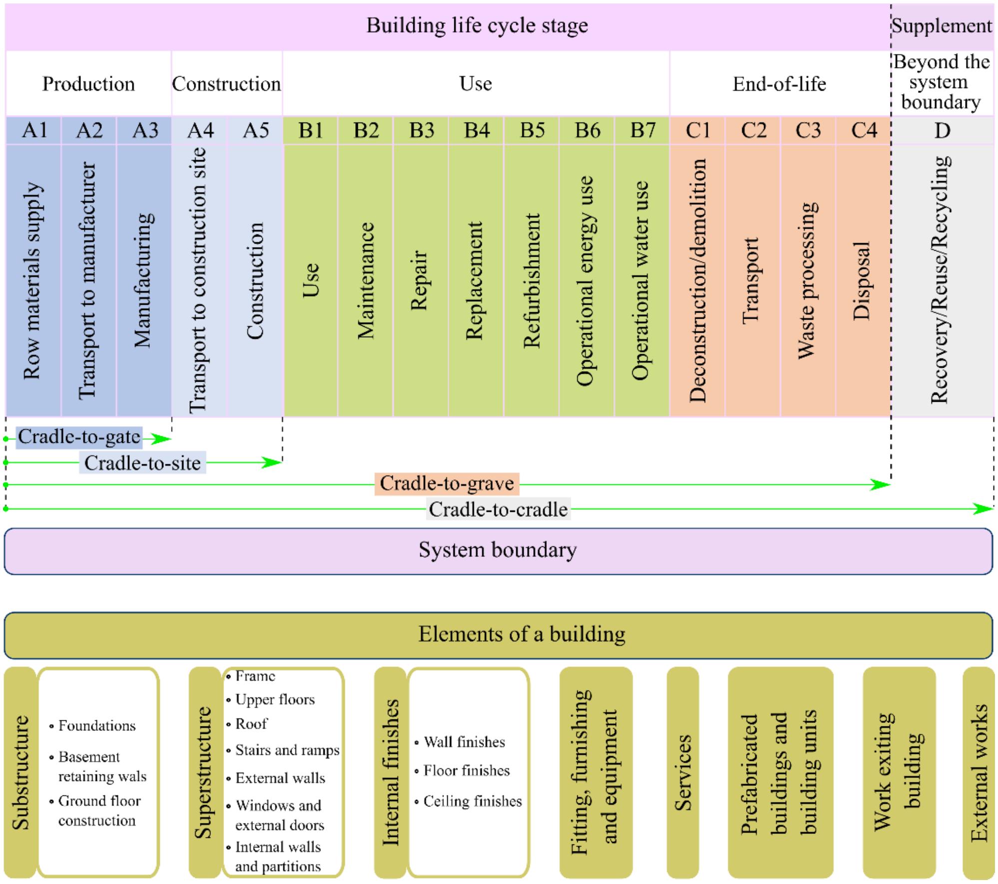

Figure I.3: LCA-related system boundaries and elements of a building, based on (CEN, 2019, 2011; RICS, 2017).

I.4.1.2 Inventory analysis

Inventory analysis (LCI) deals with the collection and synthesis of information on the input and outputs of the system by creating a flow diagram. These inputs are usually energy consumption, water usage, transportation, and usage of raw materials, while the outputs are waste and emission into water, air and soil, and manufactured goods, byproducts, products, and services.

The inventory for a building LCA should include a comprehensive data system that lists all processes and sub-processes, along with their respective inputs and outputs. However, one of the main challenges in conventional projects in today's practice is how to identify construction products with LCI data following a trusted and transparent approach (Gelowitz and McArthur, 2017). It is a fundamental issue and certain precautions are needed to correctly perform an LCA. This is because this stage, until recently, takes significant time and effort to gather all the data needed.

The environmental burdens for the LCI are quantified for each subsystem as follows (Eq. I-1):

$$LCI_j = \sum_{i=1}^{I} bc_{j,i}\, x_i \qquad \text{Eq. I-1}$$

where $bc_{j,i}$ represent the burden j from subsystem or activity i, and x_i is a mass or energy flow associated.

Based on the source of data for performing building LCAs, either generic (adapted from general databases, for example, Ecoinvent (Wernet et al., 2016)) or product-specific data in the form of environmental product declarations (EPD) or a combination of them have been used for the LCI stage (Lasvaux et al., 2015).

Generic data sources are obtained by sector average LCI data based on typical material production data and construction procedures. Generic LCI databases are predominantly provided by industries resources, scientific knowledge, technical literature, and internal patent information, and can be used for describing environmental impacts in a national or regional context (Palumbo et al., 2020). There are several commercial and open-access databases providing access to generic LCI data, such as GaBi (Sphera Solutions, 2023), Ecoinvent (Wernet et al., 2016), and ICE (Hammond et al., 2011). The Ecoinvent database is a comprehensive and internationally recognized LCI dataset. The database provides detailed information on the environmental impacts associated with more than 15000 industrial processes, including energy production, agriculture, transportation, and manufacturing related (Wernet et al., 2016). The GaBi database (Sphera Solutions, 2023) is developed by Thinkstep AG. This database is the similar and provides extensive data on the environmental impacts of various products and processes, including energy, water use, waste, emissions, and materials. The Inventory of Carbon and Energy (ICE) database is an open-source database developed by the University of Bath that provides a comprehensive summary of Embodied Energy Coefficients (EEC) and Embodied Carbon Coefficients (ECC) for most common construction materials (Ecology, 2019).

Environmental Product Declarations (EPDs), which are provided by manufacturers and producers as a method of reporting and sharing environmental data. It contains detailed product-specific LCA data of materials and components based on the application of the LCA methodologies. At present, there are various open-access databases on the internet in the framework of a program to store these EPDs that are publicly available and free to download from their website: The International EPD System (EPD International AB, 2023), Wood for Good Lifecycle Database (Wood for Good, 2023), ECO Platform (EcoPlatform, 2023), and GreenBookLive (BRE Group, 2023).

Although generic databases are useful for providing LCI data to evaluate the environmental impact of buildings, they have a significant limitation: they are based on industry-average values and may not reflect differences in the environmental impact of specific materials obtained from different suppliers and locations (Häkkinen et al., 2015; Meex et al., 2018). The use of specific data (*i.e.*, EPDs) to obtain better quality and more reliable results rather than generic data, is recommended by the International Reference Life Cycle Data (European Commission Joint Research Centre, 2010). In section I.4.4, the incorporation of EPD as a data environmental source will be further explored. This thesis investigates the impact of using different data granularity (generic and specific) to conduct an LCA. We refer the reader to section III.2 of Chapter III which uses Ecoinvent with SimaPro software (Pré Consultants, 2022), and section IV.2.2.1 of Chapter IV for the case of EPD which describes the model employed providing general choice recommendations for both approaches.

I.4.1.3 Impact assessment

In the impact assessment (LCIA) phase, the results of LCI are evaluated. The global/local environmental impacts of various flows of material and energy are assigned to the different impact categories, which expressing the different impact potentials and consumption of resources to be connected to a common unit. There are several categories that are commonly used, such as climate change (potential global warming due to emissions of GHG to the air), ozone layer depletion, human health, resources, etc. After the classification of the impacts, the contribution of each of the constituents is calculated by using the standard characterization factors for a reference substance using I-2 (Toniolo et al., 2020):

$$I_m = \sum_{j=1}^{J} ec_{k,j}\, LCI_j \qquad \text{I-2}$$

where I_m is the environmental impact of substance m with reference to the impact category j, $ec_{k,j}$ represents the characterization factor k for the burden LCI_j. The objective of this calculation step is to transform those elementary flows into impact indicators in accordance with the goal and scope definition.

Although a usual LCA study covers a range of measurable indicators, recent studies showed a high correlation between impact categories utilized in EPDs based on the EN 15804 standard (Lasvaux et al., 2015). Therefore, for the sake of clarity for decision-makers, Global Warming Potential (GWP) is often used as a reasonable proxy for other impact categories, even if some burden shifts in the different environmental contributors to the buildings' environmental performance are likely to occur (Häfliger et al., 2017; Lasvaux et al., 2015). This indicator is what is commonly referred to as the "carbon footprint" or "whole life-carbon" of the product, involving the conversion of various GHGs to CO_2 equivalents of warming ($kgCO_2eq$) over a predefined time horizon (RICS, 2017). This thesis investigates the impact of different impact categories for quantifying the LCA of a building in Chapter III while using only GWP (*i.e.,* carbon footprint) as a single environmental impact category to conduct an LCA in Chapter IV.

I.4.1.4 Interpretation

The final step of an LCA consists of the interpretation of results from both the life cycle inventory analysis and life cycle impact assessment. It includes the identification of the main sources of impact based on the results of LCI and LCIA and suggests limitations and recommendations to improve the performance of the alternatives. In addition, the results of an LCA consist of a report with all assumptions, etc. made during the assessment, which makes the establishment of sensitivity analyses in the interpretation of the results, as required by ISO 14044 (ISO 14044, 2006).

I.4.2 Challenges of implementing LCA in building practice

Current approaches to the LCA method face several limitations and challenges, which should therefore be addressed to improve the accuracy and applicability of LCA in buildings. Giesekam and Pomponi (2017) identify the lack of guidance on three main knowledge gaps in building LCA, namely, carbon sequestration in biogenic materials, uncertainty analysis, and data quality. One of the important sources of this uncertainty is the temporal and/or spatial variations of commodity flows and emissions (Collet et al., 2014). However, the current LCA standards do not consistently factor in variations in building usage, energy supply (including from renewable sources), building and environmental regulations, and other changes occurring over the lifespan of the building (Anand and Amor, 2017). Thus, we call for additional transparency reporting these parameters which are briefly introduced in section I.4.2.1 of Chapter I, while details are left to the papers (See section III.2.2 of Chapter III and section IV.2.4.1 in the Chapter IV).

Khasreen et al. and De Wolf et al. also stressed the importance of a globally or nationality-accepted framework to enhance comparability of building LCAs, as well as the transparency of goal and scope definitions (due to the limited descriptions on system boundary, functional unit, reference service life, etc.), and accuracy of datasets (De Wolf et al., 2017; Khasreen et al., 2009). This growing awareness has led to a range of LCA guidelines for assessment methods being introduced in recent years. As explained in section IV.2.1 in Chapter IV, this challenge can be effectively addressed through the implementation of standard practices such as EN 15978 (CEN, 2011) and EN 15804 (CEN, 2019), and following the standardized development approaches initiated by the Royal Institution of Chartered Surveyors (RICS) to provides a concise, clear and thorough interpretation when assessing the environmental impact of a building. The differences in study objectives, methodologies used to achieve them, and data utilized make it difficult to compare the results of different studies from one country to another (Resch and Andresen, 2018). Therefore, to further interpretation of the results, there is an important need to compare the obtained LCA results with the reliable national benchmark values. In this thesis, the validity of the results is analyzed with the benchmark values in a quantitative way in two building case studies:

- With respect to the reliable reference values of the Royal Institute of British Architects (RIBA) 2030 Climate Change (RIBA, 2021) that can be used as benchmarks for comparing the LCA results (see section III.2.3 of Chapter III).
- The buildings' embodied carbon and operational energy performances are compared to the London Energy Transformation Initiative (LETI) Climate Emergency Design Guide (LETI, 2020a), as a reliable reference value (see section IV.2 of Chapter IV).

I.4.2.1 Dynamic aspects

Despite the fact that a growing body of current building LCA literature promises high precision of impacts, few studies focus on temporal consideration effects and often they are using inadequate scope and inventory. The identification of dynamic variables and an accurate description of their temporal variations in LCA studies is crucial (Su et al., 2019). The importance of this matter is particularly critical in the context of buildings that endure for decades, and sometimes centuries. However, there is still little focus on temporal issues and uncertainty associated with future scenarios in the existing studies, such as disposal and recycling (Beloin-Saint-Pierre et al., 2020; Lueddeckens et al., 2020). This less well-conceived addressing and fail in describing long-term structural and technological progress are particularly attributed to the LCA inherent methodology, and complex process associated with the specific nature of buildings (*i.e.*, long life cycle, large environmental impacts, and complex application) (Buyle et al., 2013; Luisa F Cabeza et al., 2014). Thus, as the current LCA's ISO standard does not offer explicit guidance on modeling future and long-term solutions, it is highly necessary and valuable to conduct a dynamic LCA

(DLCA) methodology to provide more accurate, reliable, and meaningful results (Bisinella et al., 2021; Matthews et al., 2019). The DLCA methodology explicitly recognizes the significance of temporal factors in the evaluation of potential environmental consequences. Thus, it is an emerging research area in the international environmental management area (Su et al., 2021), and there is a particular need to implement a more in-depth studied system into its modeling framework.

Conducting a comprehensive DLCA analysis is a multidisciplinary research topic and it relies heavily on secondary data from scientific articles, industrial and governmental reports, and regulatory documents. Therefore, it requires a broad range of skills and knowledge. In this thesis, we focus on three main building-related dynamic variables, including energy evolution, technological evolution, and waste recycling rates (Fnais et al., 2022; Fouquet et al., 2015; Negishi et al., 2019). In order to model DLCA, the following two typical approaches have been proposed for buildings: the dynamic matrix model (Collinge et al., 2013), and the data transformation–based model (Su et al., 2019). Although these assessment methodologies have specific advantages, it remains unclear how to identify dynamic variables and scientifically quantify them (Su et al., 2021). Therefore, they do not provide deep discussion regarding the temporal attributes of dynamic variables. As such, the modeling frameworks should follow a high degree of adaptability to enable the exploration of various evolution values in a simplified manner (Su et al., 2021). This would facilitate the identification of the sensitivity of results to particular parameters.

Future scenario analysis is a management-engineering method to predict and evaluate potential future situations based on expert-based strategy, policy-based transition, and natural resource management (Bisinella et al., 2021). The general concept behind scenario-based modeling is that investigating numerous possible future situations can better cover the case-specific issue and are to be more justifiable than providing many predictions on what the future will look like for a system as complex as human activities (Beloin-Saint-Pierre et al., 2020). The modeling of scenario analysis should allow the application of a systematic procedure and be formulated contextually and with the help of stakeholders in the field. By incorporating future scenarios into LCA, it is possible to provide a structured framework for a reliable long-term assessment by aligning the uncertainty of LCAs. This can further identify the potential developments from the present to the future of products and systems throughout their entire life cycle (Mendoza Beltran et al. 2018). In this thesis, a combination of scenario-based modeling into LCA methodology is applied to explore potential future paths considering short- or long-term planning under the restriction of global/national regulations. A detailed description of this research method can be found in the respective papers in two different building case studies:

- With respect to changes in the electricity production mix in a real Irish case study (see section III.2.2 of Chapter III).
- Alternative designs of heating and ventilation systems, the effect of future electricity decarbonization, and improvement in the technological evolution and waste recycling rates of timber materials in a real British case study (see section IV.2.2 of Chapter IV).

I.4.3 Biogenic carbon storage in products

Biogenic CO_2 emissions are defined as the carbon that is absorbed from the atmosphere during the growth of biomass via photosynthesis and then released back into the atmosphere due to the combustion or decomposition of biologically-based materials (*e.g.,* timber) (Norouzi et al., 2023). As biogenic carbon storage is sequestered from, and stored, outside the atmosphere for a period of time (*e.g.,* until the building's EoL), the possibility of achieving carbon sink effects is recognized as one of the most effective options for zero-carbon buildings (CCC, 2018; Lukić et al., 2021). However, it was still challenging to report modeling approaches of biogenic carbon accounting, as the current LCIA methods do not present a consistent model for the treatment of this factor (Fouquet et al., 2015). Thus, we call for additional transparency in reporting of utilized modeling methods for parameter evolutions in accordance with established best practices in the built environment.

Figure I.4 shows the framework scheme of the biogenic carbon flows throughout the life cycle of bio-based materials analyzed. There are two main approaches to assess the impact of biogenic carbon when timber originates from sustainably managed forests and the calculation is based on static characterization factors (Lukić et al., 2021):

i) According to the product environmental footprint (PEF) standard (European Commission, 2017), timber is regarded as "carbon neutral", which is referred to the "0/0" approach. Here, there is no consideration since any biogenic carbon uptake (0) initially will be released back (0) into the atmosphere (Hoxha et al., 2020).
ii) As specified in EN 15804 standard (CEN, 2019), biogenic carbon uptake is presented as additional information on climate change, using the "-1/+1" approach. The carbon uptake (-1) is accounted separately as a negative emission during the material production stage (A1-A3), and release (+1) of biogenic carbon and the transfers of biogenic carbon between different product systems throughout the life cycle of a building (Hoxha et al., 2020).

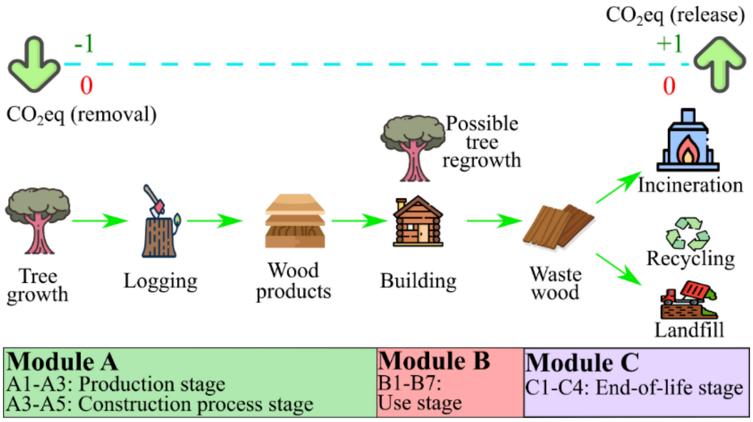

Figure I.4: Schematic representation of accounted biogenic carbon.

In this thesis, both approaches are applied to the case studies:

- With respect to both 0/0 and -1/+1 approaches in the Chapter III (section III.2.2);
- For the case of the -1/+1 approach in Chapter IV (see section IV.2.2).

The amount of biogenic carbon in wood products is calculated according to EN 16449 (EN 16449, 2014), which is given below in II-3:

$$P_{co2} = \frac{44}{12} \times cf \times \frac{\rho_\omega \times v_\omega}{1 + \frac{\omega}{100}} \qquad \text{II-3}$$

where, P_{co2} is the biogenic carbon oxidized as carbon dioxide emission from the product system into the atmosphere (kg); cf is the carbon fraction of woody biomass (oven dry mass); ω is the moisture content of the product (*e.g.*, 12 %); ρ_ω is the density of woody biomass of the product at that moisture content (kg/m^3); and v_ω is the volume of the solid wood product at that moisture content (m^3).

I.4.4 Environmental Product Declaration (EPD) – the future of sustainability communication of products

An Environmental Product Declaration (EPD) is an "*independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impact of products*" and has been provided by the manufacturers (The International EPD System, 2022). Users and purchasers involved in the construction and building chain can use EPDs, as a credible way to compare products' environmental performance for different manufacturers under certain conditions. It also encourages companies to promote their products and services as sustainable and manufacturing in environmentally friendly processes. products. As a result, the EPDs provide the buildings' products with internationally acknowledged background data (Abouhamad and Abu-Hamd, 2021). This can be partly linked to the application of building sustainability assessment methods (BSAMs), which use LCA principles to assess the environmental impacts of buildings. Hence, EPD is one of the most recommended methods to provide accurate LCA-based information over their life cycle along with a summary of the analysis methodology, assumptions, and data sources of building materials.

EPDs are built on the detailed process-based LCA data for a specific product which is verified by the Product Category Rules (PCRs) to make the result of the LCA comparable (Del Borghi, 2013; ISO 14025, 2010; Minkov et al., 2015). The quantified environmental information and impact categories of EPDs are based on the LCA procedures mentioned in ISO 14040 standard (ISO 14040, 2006). However, as a core specific so-called PCR, the European Standard EN in the sustainability of construction works (disclosed in ISO 14025, and EN 15804 standards) define rules for conducting the LCA of building products within the framework of EPDs (Achenbach et al., 2016). As shown in Figure I.5, an EPD, referred to in ISO 14025 (ISO 14025, 2010) as a 'type III environmental declaration', is carried out in the following procedure:

i) Select or develop the appropriate product category rule, conduct and verify the product LCA.
ii) Develop the environmental information and compile it into the EPD reporting format.
iii) Verification by a third-party document.
iv) Register the EPD by submitting the final document to an EPD dataset.

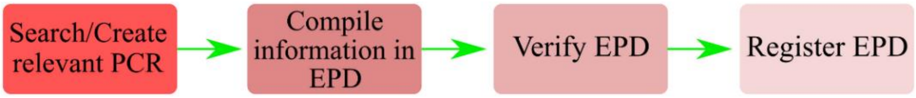

Figure I.5: EPD development process (ISO 14025, 2010).

To simplify the application of these criteria, a method similar to the comparison matrices developed by Gelowitz and McArthur, is adopted in this research (Gelowitz and McArthur, 2017). However, the full use of EPD data at different stages of the building to conduct comprehensive LCAs presents several challenges (Almeida et al., 2023; AzariJafari et al., 2021). These challenges include variations in the delivery format, methodologies, and system limits applied in different product categories. Such variations make it difficult to compare EPDs and generate uncertainties for the users (Broer et al., 2022). On the other hand, EPDs primarily evaluate the sustainability of civil construction products and materials, where specific methodologies are mandatory for evaluating the material production stage (modules A1-A3). Other phases are optional since most EPD executors are companies that manufacture materials, hence they have more control over these phases (Broer et al., 2022). There is an update of the standard issued in July 2022, which makes the evaluation of the end-of-life phases of materials mandatory (Broer et al., 2022). To ensure the consistency of the assessment, EPDs must undergo regular revisions in accordance with the standard (Almeida et al., 2023). Moreover, there is an important shortcoming in interpreting results from EPDs, as standard EN 15978 does not provide a standardized method (Božiček et al., 2021). Therefore, a systematic methodology is necessary to incorporate these techniques and provide reliable and comprehensive results for whole building life cycle assessment. In this sense, according to the life cycle stages and modules from the EN 15978 standard (CEN, 2011) shown in Figure I.6, the dataset used for LCA impacts in assessments at the building level can be derived from the environmental data for products, provided in the available documentation report of EPDs. When the LCI data situation is unclear, appropriate assumptions in the form of scenario development should be made in various ways to allow implement different methodologies (*e.g.*, treatment of biogenic carbon and timing of emissions, modules A4, A5, C1, and C2). A framework to use the data from EPDs throughout the planning phases is suggested in this thesis. For more information, we refer the reader to section IV.2.2 of Chapter IV which describes the model employed providing detailed choice recommendations.

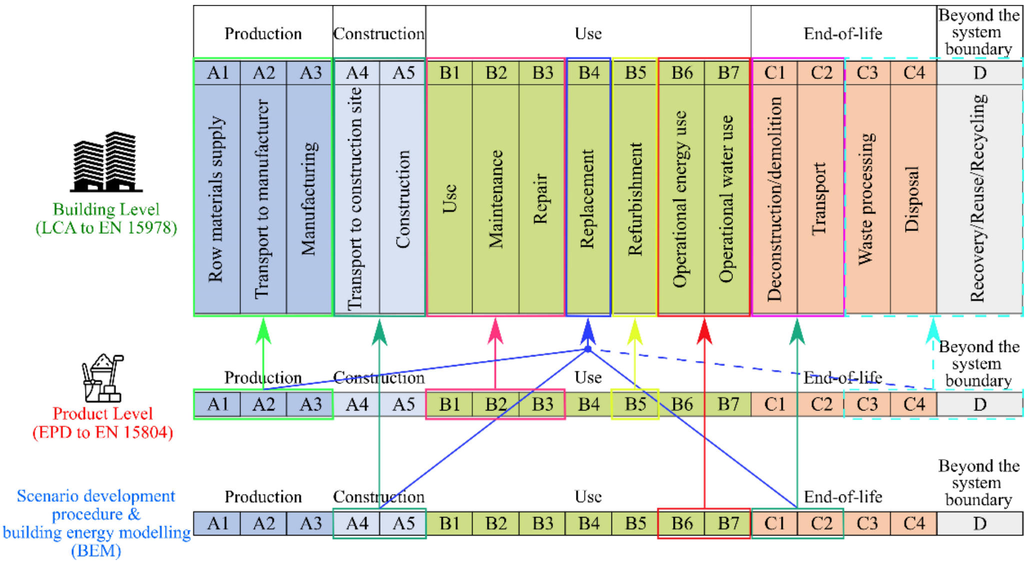

Figure I.6: Life cycle stages and modules, and the correlations between product and building levels.

I.5 Building performance simulation (BPS) tools

The input of computer-aided building techniques and innovations in the construction industry has been argued as the best approach for the built environment to adapt the current design and delivery practices in sustainable smart cities and buildings (Al-Homoud, 2001; Olawumi and Chan, 2018). For this effectiveness, wider use of implementing sustainable solutions using adaptable technologies and simulation tools could potentially support design decisions with numerous benefits to stakeholders.

Building performance simulation (BPS) is an integral part of assessing and planning building performance which has become increasingly important in the built environment. There are several applications of digital BPS tools to help the implementation of sustainable practices in the building and construction industry, including:

i) Life cycle assessment (LCA) and carbon footprint (Shadram et al., 2016; Soust-Verdaguer et al., 2017).
ii) Sustainable material selection (Govindan et al., 2016).
iii) Waste management (Akinade et al., 2015).
iv) Energy consumption and performance (Abanda and Byers, 2016; Kuo et al., 2016).

Due to the accumulation of life cycle information of a building and the complexity of building structures, the utilization of methodologies such as BIM and BEM among others can be effectively used for assessing LCA results and energy simulation in the buildings (Santos et al., 2019a). Despite the numerous studies on environmental impact assessment in buildings, the vast majority of these building-related LCA practices have conducted their analysis primarily on integrating the BIM with BPS tools or assessment of materials' environmental impacts through LCA tools in isolation. Such a framework assessing these factors together in an integrated way could support environmentally sustainable assessment of the buildings. Thus, the overall research purpose of this thesis is to develop a BIM-supported method for assessing the environmental performance of buildings. Figure I.7 shows the general overview of the thesis purpose and how these goals are related. In the next sections, the integration of BIM into LCA and BEM will be further explored.

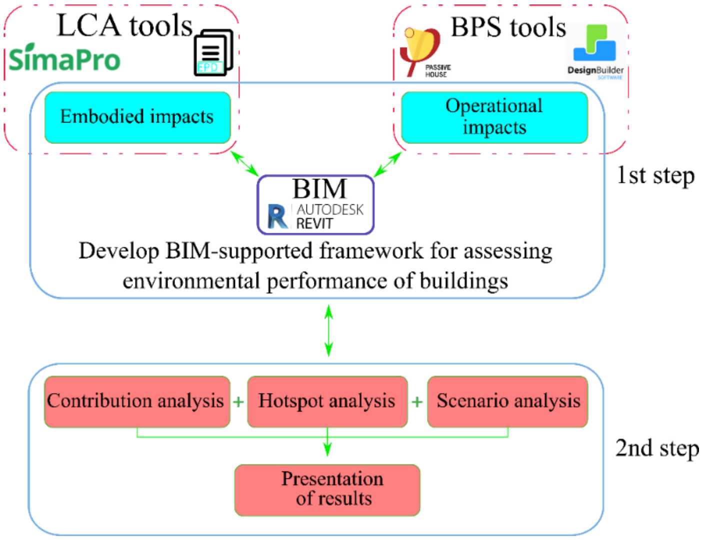

Figure I.7: A simplified and schematic overview of the combined approach of building performance simulation tools and LCA.

I.5.1 Interoperability between BIM and BEM

According to a well know definition given by the Associated General Contractors of America (AGC), BIM methodology is the "*development and use of computer software to simulate the construction and operation of a facility*" (Gao et al., 2019). BIM can be used to generate a data-rich, object-oriented, intelligent, and model-based representation that provides benefits and essential information about building design to share among different stakeholders and is used during all stages of the building's lifecycle (Mohajer and Aksamija, 2019). On the other hand, BEM intends to quantify buildings' energy performance to help designers and architects through its simulation, using predefined criteria about the building composition and utilization (Gerrish et al., 2017). There are various existing BPS tools explored to develop the guidelines for BIM and BEM (Sousa, 2012). A summary of these common tools can be referred to Bahar et al. (2013) and Crawley et al. (2008).

Generally, the methodology framework of the BEM tools to perform building energy simulation can be divided into the following steps (Gao et al., 2019):

i) Concept design, including site development, building orientation, the initial building services, and the structural system.
ii) Preliminary design, including building envelope, lighting, thermal comfort design, HVAC options, water and wastewater systems, materials selection, preliminary thermal, daylighting, and energy modeling efforts.

iii) Developed design, including building envelope details, final space layout, air-conditioning and ventilation system integration, structural design integration, electrical systems integration, hydraulic systems integration, final materials selection, detailed thermal, and detailed energy modeling).
iv) Detailed design, including updated design and construction plans, and the requirements and protocols for construction documentation. Then, the architecture model generated in this step includes consent and tender drawings and specifications for each discipline, and finally the energy analysis.

Current practice in the BEM technology followed the above consecutive structure where the engineer manually generates a building energy model using design documents (*e.g.*, CAD drawings, building information of mechanical loads, and systems specifications), the simulation results acquired after spending a lot of time and resources might become pointless (Ahn et al., 2014; Bazjanac et al., 2011; Unites States General Services Administration (GSA), 2015). This means that this conventional approach does not benefit from the effort of parametric modeling in the BIM authorizing tool. In this sense, an emerging approach, named Building Information Modelling based Building Energy Modelling (BIM-based BEM) uses the pre-designed BIM model (including the important information of building geometry, construction typology, materials' properties, and HVAC system) to create the input for BEM tools. Thus, interoperability between BIM and BEM could provide a robust and time-saving method of transferring data, enabling the advantages of the low-cost, easy-to-use, synchronized, and reproducible model (Gao et al., 2019; Sanhudo et al., 2018). Generally, interoperability is defined as the ability between at least two software tools to communicate, exchange, and enable the distribution of data (Bahar et al., 2013; Rezaei et al., 2014).

The BIM-based BEM process consists of three main parts: (i) BIM tool; (ii) model schema exchange format; and (iii) BEM software. This integrated approach is semi-automated using relevant open-BIM data schemas such as Green Building XML (gbXML) (G.B. Foundation, 2023) and Industry Foundation Classes (IFC) (Liebich, 2013) that facilitate integration and achieve interoperability among various software tools and platforms commonly used in the building industry (Noack et al., 2016).

IFC was developed and maintained by buildingSMART (buildingSMART, 2023). The purpose is to provide a common data model for process improvement of geometric as well as semantic data exchange, ensuring interoperability without loss of information in both construction and facility management sectors. It offers a vendor-neutral standard that includes a comprehensive set of object information representations, such as geometric representations and properties, topology, relations between components and spaces, special structures, costs, schedules, and many other parameters in a strictly object-oriented manner (Forth et al., 2023). IFC is designed to be used by model-based applications throughout the full life cycle of buildings, from design to construction to operation and maintenance. One of the key advantages of IFC is its ability to accurately represent building information in a highly structured manner (Porsani et al., 2021). This allows more efficient data exchange between different software applications, resulting in reducing the possibility of errors and accurate energy simulations.

On the other hand, the gbXML is a public, non-profit schema that was initially developed by Green Building Studio and later acquired by Autodesk. Unlike IFC, which has a broader application area in the AECO industry (Cemesova et al., 2013), gbXML focuses on exchanging building information used by energy simulation tools (Noack et al., 2016). The gbXML schema is based on the extension markup language (XML) specification, which intends to represent relevant building information, such as the building geographic coordinates, the building envelope, components, thermal zones, mechanical equipment simulation, and material thickness, needed for preliminary energy analysis (Forth et al., 2023).

The aim of developing these extensions is to allow the direct import of geometric BIM models into different simulation tools and lead to a significant reduction of duplication effort in modeling. However, the quality of data transfer between applications depends on the implementation of these data formats and their adoption by practitioners (Sanhudo et al., 2018). The most significant limitations in both, IFC-based and gbXML-based processes, have been identified and are listed in an earlier study (Gao et al., 2019).

BIM–BEM interoperability issues can appear in any or all of the simulation applications (Porsani et al., 2021). From these tools, Autodesk Revit (Autodesk, 2021) enables model data export in two formats: gbXML and IFC. Some examples of the integrated BIM-based BEM approach are between design tools (*i.e.*, Autodesk Revit (Autodesk, 2021), and PassivBIM (Cemesova et al., 2015)) and the commonly used BEM tools (*i.e.*, DesignBuilder (DesignBuilder, 2021), and Passive House Planning Package (PHPP) (Passivhaus Institut, 2015)). Figure I.8 illustrates how these aforementioned tools and their relevant data schemas are employed in this thesis to simulate the performance of specific buildings, which allows the input of 3D models to be integrated with the output of BIM software.

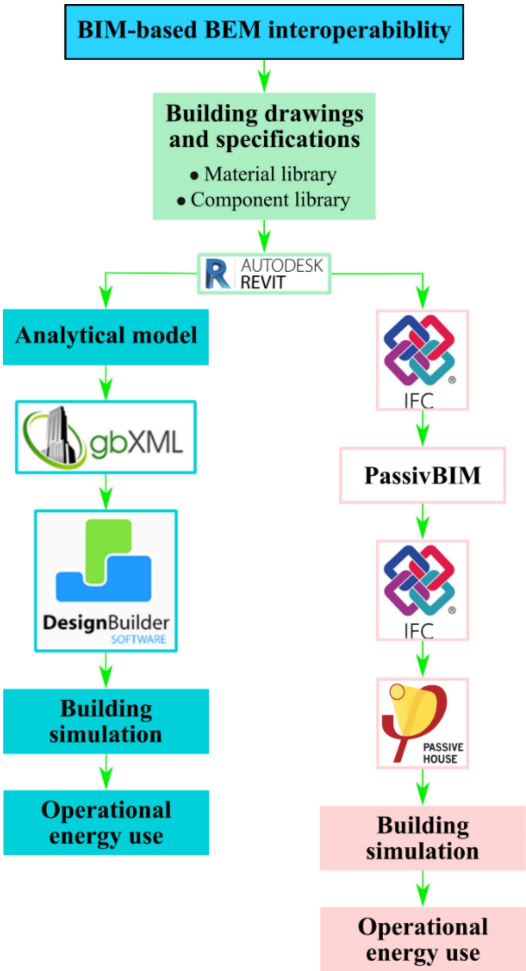

Figure I.8: A workflow of the combined approach of BIM-based BEM.

Revit, a computer-aided design software, is capable of constructing a 3D building model based on the characteristics of an existing one. The key feature of Revit is the use of parametric building components as the basis for the building component. The software enables users to create complex and basic building components without having to know how to create them through complex programming coding. Furthermore, Revit offers the opportunity to work with other analytical tools and can export 3D models into these third-party applications in a variety of formats, thus facilitating more flexibility in collaboration and efficient information exchange.

The PHPP is a powerful and accurate energy modeling tool that supports designers in incorporating different elements of buildings into the design process (*i.e.*, R- or U-values, thermal bridges, airtightness, ventilation sizing, windows, solar orientation, climate, and energy gains and losses) (Moran et al., 2014). The use of this tool is a mandatory part of the design and certification process of producing a building that complies with the Passivhaus standard (Feist, 2011).

The PassivBIM system focuses on establishing the geometry, constructions and materials, and space types of a building during the transition from a Revit tool to PHPP (Cemesova et al., 2015).

A detailed individual discussion of these tools is beyond the scope of this thesis which will focus on the BIM-based BEM process. Therefore, in section III.2 of Chapter III (using Autodesk Revit, PassivBIM, and PHPP) and in section IV.2 Chapter IV (Autodesk Revit, and DesignBuilder) contain an overview of the methodology behind the development of interoperability between BIM and energy simulation tools.

I.5.2 BIM-LCA integration to mainstream LCA

As previously mentioned in section I.4.1, when utilizing predefined environmental data in the form of EPDs or generic data, the time-consuming steps of LCA is the collection of detailed material information and quantities (Meex et al., 2018). As a result, using a BIM-based LCA model could benefit the AECO industry in terms of promoting supply chain integration and sharing required information relative to traditional practices. In response to the need for BIM-based LCA tools, there are three main approaches explored in the literature on BIM integration with LCA analysis (Santos et al., 2020b, 2019b):

i) Incorporating a range of BIM tools for project modeling to conduct LCA analysis.
ii) Connecting the BIM model as a source of data of LCA databases to obtain the total environmental impacts (*e.g.*, bill of quantities, and material information).
iii) Automating simulations and improving information exchanges of the entire workflow between BIM models and different software environments.

Llatas et al. (2020) found that the studies' focus has recently shifted towards incorporating sustainability-related information from BIM models based on the third approach (*e.g.*, Tally), but data interoperability remains a challenging issue. In this context, several studies noted that there is a lack of useful information within BIM models which prevents automatic building simulation (Iacovidou et al., 2018; Olawumi et al., 2018; Zadeh et al., 2017). According to Bueno and Fabricio and Roberts et al., there are inconsistencies in the results of the plug-in and detailed evaluation models, despite attempts to standardize the study's scope. These researchers suggest that these differences derive from the plug-in tool's simplifications (Bahar et al., 2013; Crawley et al., 2008). De Wolf et al. (2017)

demonstrate that numerous LCA tools are impeded by limited transparency and a lack of updated background information, and thus they should be adapted to align with designer demands. Moreover, Soust-Verdaguer et al. (2017) suggest that future work should focus on ensuring interoperability between BIM and LCA rather than developing plug-ins for specific BIM software packages. The application of extract, transform, and load (ETL) technology was also suggested to overcome BIM-LCA interoperability issues and manage large datasets in several fields (Shadram et al., 2016). These domains include those with information from multiple sources in different formats and using different data models. Consequently, by employing ETL technology and middleware corrective tools, it is possible to facilitate the integration of BIM data into life cycle energy analysis (*e.g.*, BEM) and minimize the amount of effort and time required by manually re-entry of BIM data into LCA tools.

Thus, it is still difficult to perform a comprehensive BIM-based LCA analysis considering the current approaches where BIM is mostly used for geometric and material extraction, and thus further developments should be made to strengthen the knowledge of BIM integration with LCA (Fnais et al., 2022). Frequently, to conduct an LCA analysis, users utilize external post-processing tools such as spreadsheets (*e.g.*, Microsoft Excel), to export the values and then perform LCA calculation (Mora et al., 2020).

In this thesis, due to the lack of complex programming routines or the need to determine the system boundary to modify the database in several directions to allow different methodologies (further details will be discussed in Chapters III and IV), the BIM-based LCA following the flexible method applied in the second approach is used through building case studies (see Figure I.9).

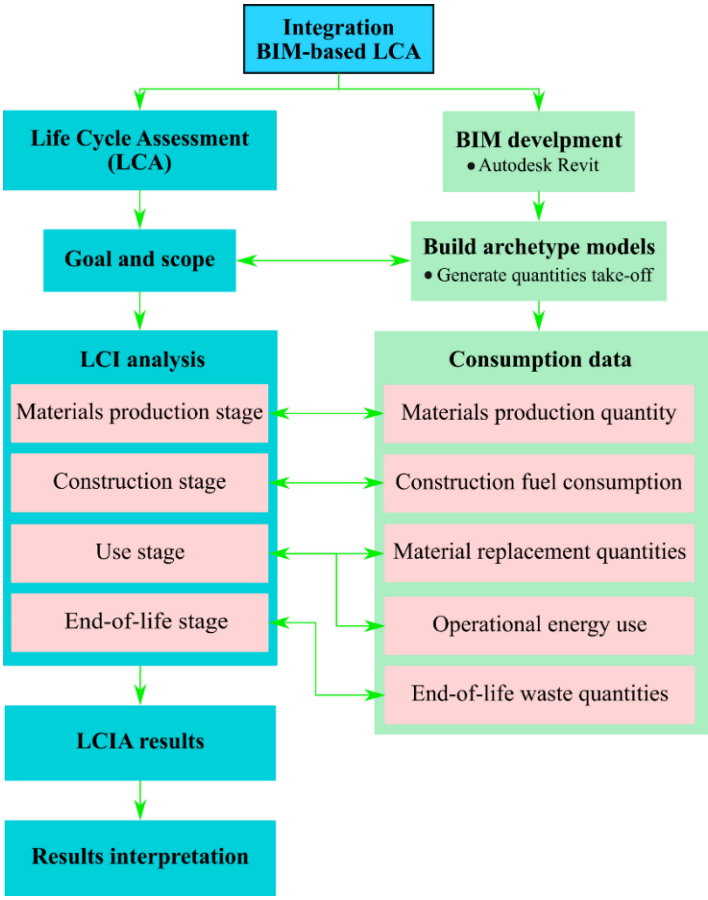

Figure I.9: Integration BIM-based LCA method.

I.5.3 Whole Building Life Cycle Assessment (WBLCA): An integrated approach with BIM, BEM, and EPD

In this section, the detailed framework for integrating WBLCA with BIM, BEM, and EPD is developed for residential buildings based on EN 15978 standard (CEN, 2011).

The application of BIM and BEM into WBLCA has demonstrated to provide new opportunities to support data collection throughout the building-level LCA development, and integrating EPD in the proposed framework can lead to a more comprehensive and accurate assessment of the environmental performance of buildings. Figure I.10 presents the WBLCA development framework consists of the following steps:

- Step 1 (Data collection): Here, the data for the assessment are collected. The EPD inventory or scenario development procedure provides data about the embodied environmental performance of different materials and components from different suppliers. In WBLCA development, the building is modeled using BIM, and the lists of the constituent materials for each component of the building and the quantities are elaborated over its life cycle. This database consists of the embodied impacts associated with the materials used in construction, data on various transportation modes, information concerning the environmental performance of different fuel types, and end-of-life impacts.

- Step 2 (BIM-based BEM development): The second step develops an integrated process within BIM software linked to a BEM model, which simulates the energy used during building operation. The energy simulation of the building relies on several factors such as occupancy patterns, climate, and maintenance schedules.
- Step 3 (Impact assessment): In this step, the environmental impacts of the building are assessed using the LCI developed in steps 1 and 2. The impact assessment step could also include the evaluation of some temporal considerations (*i.e.,* DLCA) of environmental indicators.
- Step 4 (Results interpretation): Here, the results of the assessment are interpreted and communicated. The WBLCA results are categorized according to the purpose of the LCA research at various levels, such as building part, element, component, or product. The results can be used to identify areas for improvement and to communicate the environmental performance of the building to stakeholders. Additionally, the WBLCA results can be limited to a set of indicators and presented through diverse information modules. For instance, the results are depicted as overall LCA outcomes, resource category contributions, construction element contributions, and fuel type contributions. The contribution analysis revealed the critical factors that were addressed for further enhancement of WBLCA performance through revisions in BIM model. The proposed framework is further explained in section IV.2.2 of Chapter IV and evaluated a whole life-carbon using a real British low-energy dwelling. The approach of "carbon footprint" or "whole life-carbon" analysis, which evaluates the global warming potential of a product or process throughout its life cycle, is derived from the LCA principles (RICS, 2017).

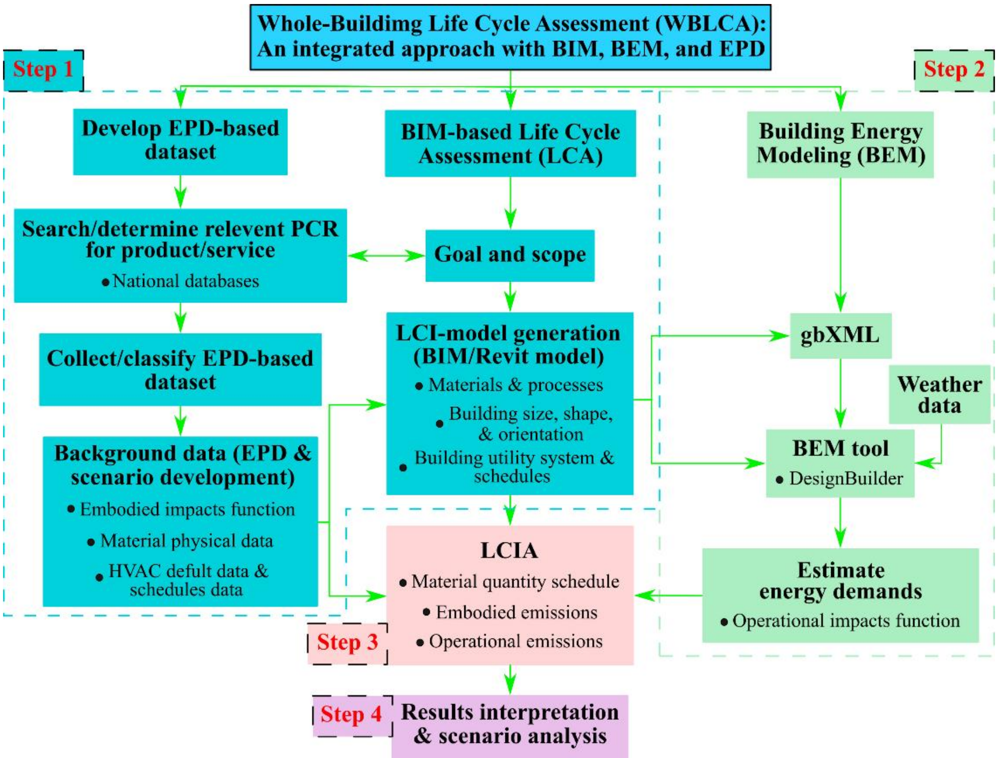

Figure I.10: An integrated WBLCA approach with BIM, BEM, and EPD.

I.6 Thesis outline

This research is derived from a paper-based Ph.D. thesis, where the development and validation chapter of this thesis is represented as journal papers. Together, these papers form a connected storyline continues in the second chapter, which focuses on analyzing and reviewing scientific literature. Then, the detailed contribution and methodology followed in each objective is presented in the different chapters. The next one is a summary of the methodology and conclusions followed in this research.

I.6.1 Literature review on sustainable and circular buildings (article 1)

The second chapter reviews the literature related to serving the purpose of identifying the current challenges, state-of-the-art strategies examined in the building environmental performance evaluation, and the methods used in developing the planning framework. To this end, a comprehensive scientific evolution study of the circular and sustainability in the building and construction sector is implemented to detect new trends and highlight the evolution of the research topic. Around 7000 documents published during the period 2005 to 2020 at Web of Science and Scopus were collected and analyzed. Using an in-house code written in R-programming language (Team, 2018), the duplicate records are removed, and the data cleaning is implemented during preprocessing. The bibliometric indicators, network citation, and multivariate statistical analysis are obtained using Bibliometrix R-package (Aria and Cuccurullo, 2017) and VOSviewer (van Eck and Waltman, 2013). Figure I.11 shows a graphical summary for article 1.

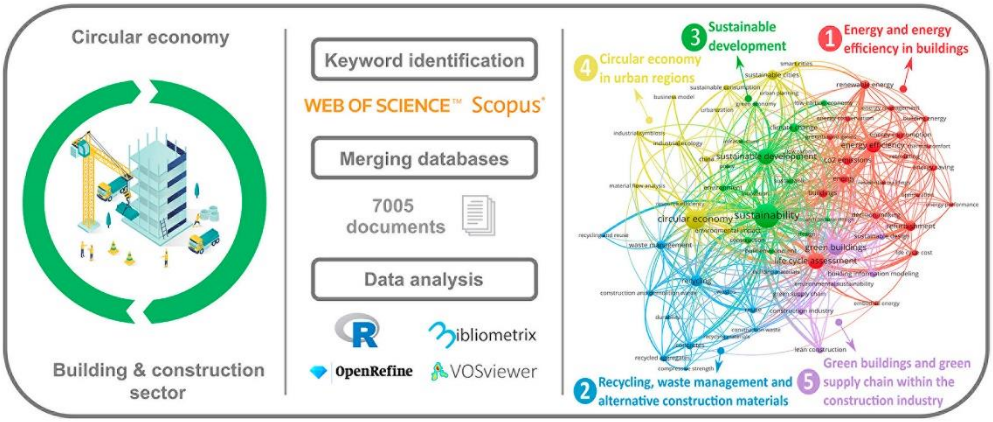

Figure I.12: Graphical abstract of article 1: Circular economy in the building and construction sector: A scientific evolution analysis (Norouzi et al., 2021a).

The co-occurrence analysis showed five keyword clusters in the field of interest and how these are currently considered in building studies. The three main aspects are focused on during a literature review:

i) Energy and energy efficiency in buildings (*e.g.*, employing Passivhaus standard (Feist, 2011)).
ii) Recycling, waste management, and alternative construction materials.
iii) Sustainability, and sustainable development.

The analysis showed that researchers pay close attention to "energy efficiency", "life cycle assessment", "renewable energy", "resource efficiency", "building information modeling", and "recycling" in the past five years. All these aspects are found to have an important influence on sustainable and circular buildings, though the extent of influence depends on the considered region, and time step.

The detailed findings of the literature review and decision support tools are presented in Chapter II.

I.6.2 Low-energy buildings in combination with grid decarbonization (article 2)

In this chapter, the proposed BIM-based LCA and BEM method is illustrated through an Irish building case study. To test this framework, an LCA is implemented to assess the environmental performance of several most commonly low-energy/passive house buildings. The building case studies were designed to meet the current Irish Building Regulations (as assessed by SAP 2009 (DECC, 2009)), and to comply with SAP 2012 (BRE, 2014), and two different types in accordance with the Passivhaus standard (Feist, 2011). Each of the different case studies uses a combination of different technologies to deliver energy (*e.g.*, thermal properties, and installation of renewable technologies).

The quantity take-off approach from Autodesk Revit (Autodesk, 2021), as a BIM tool, is used to calculate the embodied impacts. The energy performance analysis of the dwelling is conducted using the interoperability of Revit, and PHPP (Passivhaus Institut, 2015), as a dynamic BEM tool. PassivBIM (Cemesova et al., 2015) is used as a free plugin for Autodesk Revit that allows for the exchange of data between the two software packages through an IFC format (Liebich, 2013). To convert the building materials and energy consumption (*i.e.*, the output of the BIM and BEM tool) into environmental impacts, a primary emission factor obtained from the generic LCI database (*i.e.*, Ecoinvent (Wernet et al., 2016) using Simapro (Pré Consultants, 2022)) is used. The outcomes are broken down into building subparts and illustrate the embodied emissions attributed to material production, transportation, replacements, and waste treatment alongside the amount for each of the constituent components. Moreover, a sensitivity analysis is conducted to evaluate the effect of electricity decarbonization on the dwellings' GWP. Several different future electricity mix scenarios have been used and compared to a static scenario where the current electricity mix remains constant. Figure I.13 shows a graphical summary for article 2.

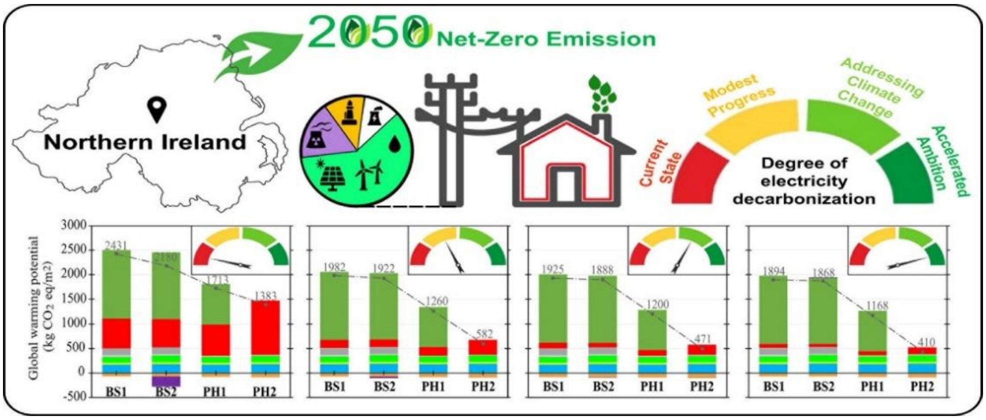

Figure I.14: Graphical abstract of article 2: Low-energy buildings in combination with grid decarbonization, life cycle assessment of passive house buildings in Northern Ireland (Norouzi et al., 2022).

The results indicate that adopting the passivhaus standard can lead to a substantial reduction in environmental impacts, with an average decrease of 30% (and a maximum reduction of 50%) across all categories, except abiotic depletion potential (ADP), where dwellings comply with the current building regulations exhibited a better performance. As expected, the decarbonization of electricity generation leads to a significant reduction of GWP in all cases, with the highest value achieved for the passive house using the highest share of electricity, with a 58%-70% GWP reduction compared to the static scenario. Moreover, electricity decarbonization increases the relative share of the production stage to the overall building emission. To understand if the analyzed case studies will contribute to matching the environmental targets, the buildings' environmental and operational energy performances were also compared to the RIBA 2030 Climate Challenge (RIBA, 2021).

The detailed methodology of the proposed LCA method and results are provided in Chapter III.

I.6.3 Whole-building LCA (i.e., carbon footprint) of low-energy buildings by incorporating BIM, BEM, and EPD (article 3)

Based on the literature review in Chapter II, the proposed WBLCA method is applied to improve new building designs. With the integration of EPD and BIM-based LCA analysis, comprehensive and reliable LCA results would be generated. In this chapter, a WLCA is explored to address the main influential concerns regarding mitigating the carbon footprint of a UK timber-frame low-energy dwelling. The research further aimed to investigate the potential greenhouse gas (GHG) emission reduction in terms of three different heating and ventilation options, and to analyze the influence of the decarbonization of the electricity production as well as the technological progress of waste treatment of timber on the building's environmental performance. To this end, the whole life-carbon of the building case studies is evaluated for the assumed prospective scenarios, and they are compared to the LCA results of the baseline scenario, where the existing technology and context remained constant over time.

This study focuses on these aspects illustrated through a typical semi-detached house, one of the most common types in the UK. The quantity take-off approach from the BIM software (Autodesk Revit) is applied to the export of building physical data (*e.g.*, building geometries and properties of construction elements) to other modules. The energy performance analysis of the dwelling is conducted using Revit and translated into gbXML (G.B. Foundation, 2023), as the data exchange format that can be used by the dynamic BEM tool (DesignBuilder (2021)). Impact assessment in this publication is based on the primary emission factors obtained from the specific LCI database (*i.e.*, EPD) and scenario development procedures are used when data is not clear. Figure I.15 shows a graphical summary for article 3.

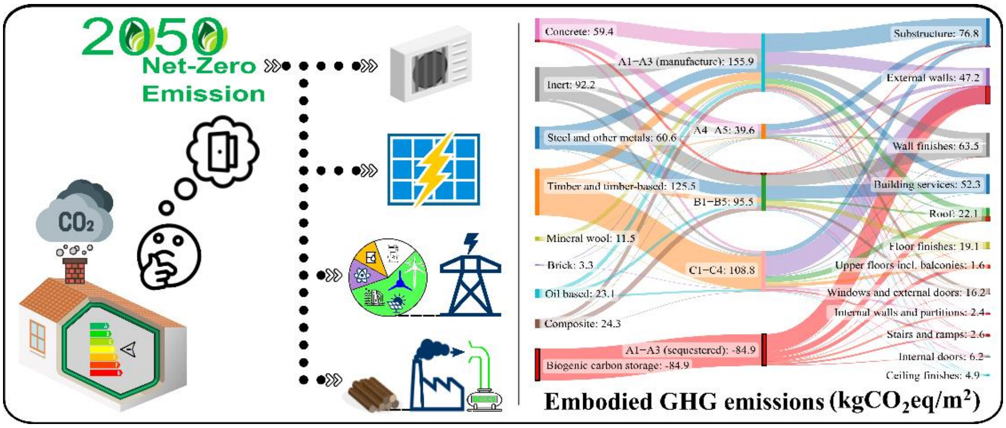

Figure I.16: Graphical abstract of article 3: Carbon footprint of low-energy buildings in the United Kingdom: Effects of mitigating technological pathways and decarbonization strategies (Norouzi et al., 2023).

The results of the analysis show that using a compact heat pump would lead to a significant emission reduction of the dwelling, by 19%; while GHG emission savings can be reinforced if the assessed systems are employed simultaneously with grid decarbonization, exhibiting a 25%-60% reduction compared to the baseline scenario. Moreover, technological changes in the waste treatments of timber products could substantially reduce the buildings' embodied emissions, representing 3%-23%. To further interpretation of the results obtained, the buildings' embodied carbon and operational energy performances were also compared to the LETI Climate Emergency Design Guide (LETI, 2020a).

The detailed methodology of the proposed design improvement framework and results are provided in Chapter IV.

I.7 General conclusions

This chapter provides an overview of the conclusions derived from the research outcome and summarizes the theoretical and practical contributions made in this thesis. The aim of the research works presented in this thesis was to develop a design improvement framework to enhance the environmental performance of buildings and be capable of assisting decision-making steps in building construction. To achieve this goal, the thesis aimed to identify aspects and examine tools of environmental impact assessment of buildings that may be influential but are seldom accounted for by practitioners. This was accomplished through a series of case studies, long-term scenario analysis, and testing the effects of various methodological settings and assumptions in the environmental impact results. It should be noted that each case study provides detailed discussions and particular conclusions within their respective chapters.

- The general theoretical and practical contributions, and some practical advice for AECO practitioners, clients, and governments are presented herein. It is found that the utilization of BIM-supported assessment of buildings' life cycle performance promotes the development of environmentally sustainable buildings. The adoption of this interoperability feature (*i.e.*, their ability to exchange and interpret information correctly) is significant in enhancing the effectiveness of the simulation process among the stakeholders. Furthermore, it brings the automation process one step closer to achieving building environmental sustainability outcomes directly from BIM.
- As uncertainties are inherently linked with future projections (*e.g.*, electricity evolution, and end-of-life options) the combination of the future scenario analysis and LCA methodologies is recommended for the studied parameters to obtain robust design decisions. By adopting this approach, the developed scenario can effectively address the issue examined and identify potential paths that are more meaningful to evaluate through an LCA, instead of measuring sensitivity and uncertainty using statistical techniques offered by an inadequately specified scenario. In line with this, adapting static LCA (*i.e.*, baseline scenario, where the existing technology and context remained constant over time) plus dynamic assessment (*i.e.*, modeling temporal perspective variables using various future scenarios) as demonstrated herein proves to enhance the effectiveness of the method for evaluating the buildings' performance over their lifespan.
- The investigation of this thesis advocates that the more consistent model for the treatment of biogenic carbon storage could be the −1/+1 approach, where the carbon uptake occurs independently as a negative emission of material production stage (A1-A3) and the carbon release occurs at the end-of-life (C3) stage as positive emission. This follows the latest version of EN 15804 (CEN, 2019) for EPDs. Biogenic carbon storage is often the most significant flow related to a timber product and has a dramatic impact on cumulative carbon values. However, if included within the material production stage, as is common practice in some standards (Hawkins et al., 2021), the resulting embodied carbon value may appear to be relatively small or even negative. Thus, it may discourage the adoption of resource-efficient design and instead propose the use of very high amounts of wood products in construction, which results in possible negative impacts on landscapes and other environmental indicators.

- Another aspect, which is interesting to reflect on, is how energy mix evolution will have an influence on energy consumption-related emissions of the buildings due to climate regulations. Sensitivity analyses reveal that the benefits of the PV system on the local changes in the electricity demand over a UK building's life cycle may not always be feasible. However, the installation of PV panels is affecting the energy production on a larger scale and not only in a specific country. Usually, renewable energy production is always maintained at its highest level, and fluctuations in demand impact fossil fuel-based electricity production from elsewhere. Thus, even in those countries with cleaner electricity production (*e.g.*, Norway), electricity savings can result in the displacement of fossil fuel production in other parts of Europe. That is why the installation of PV systems should be promoted, even in countries with a future renewable energy infrastructure such as the UK.
- Moreover, the analyses of this research thesis across multiple building case studies shows that the benefits of low-energy buildings (*i.e.*, through energy efficiency measures) may prove less significant over time considering shifts in background energy systems and with the increase in temperatures in a heating-dominated climate (*e.g.*, European countries). Hence, it is of high importance for policymakers and governmental agencies to update regulations and building codes to account for the impact of embodied emissions on the environmental performance of new and retrofitting building projects. These standards should include limits on embodied emission impacts (*e.g.*, $kgCO_2/m^2$) in addition to limits on operational energy consumption (*e.g.*, kWh/m^2/year). Enhanced regulations concerning embodied impact would motivate contractors to select materials with better-embodied emission performance (*e.g.*, using lighter and less emissions-intensive materials), and offer applying circularity principles through the reuse and recycling of building components in both new and retrofit buildings.
- In the pursuit of minimizing a building's environmental performance, AECO professionals should assess the embodied impacts of materials/components from suppliers by considering their EPDs, the transportation distance, and the mode of transport utilized.
- AECO professionals should allocate significant attention to identifying optimal combinations of emission efficiency measures through the whole building life cycle perspective during the design phase, as it has the potential to significantly reduce the building's life cycle emissions over its lifespan.

- Through an empirical study using BIM-based LCA tools, it has been demonstrated that it is feasible to estimate and compare LCA results during the design process, even from an early design stage, which differs from the traditional LCA process. The use of BIM-based LCA tools allow the user to run the LCA process simultaneously, despite the design was not yet completed. As a result, this approach enables more precise and well-structured decisions to be made more, and reducing the possible impacts of miscalls from the early design phase.
- Understanding involved dynamic variables and causal interrelations in the building sector and describing development from the present to the future are regarded as fundamental parts of future scenarios. Thus, as demonstrated herein, it seems likely to increase the usefulness of the method used in assessing the performance of buildings, particularly advising on directions for sustainable technological development for aiding decision-making and policymaking processes. Such common application can be observed in the utilization of global climate and energy reports, or shared socioeconomic pathways.

I.8 Future work

In the course of this thesis, numerous issues and possible ways have been revealed to extend findings. The main potential improvements and new ideas are presented in this chapter, which may warrant further investigation in future works.

- The BIM-supported framework developed in this thesis demonstrates that the process and the application of the tools is a useful design-phase approach for enhancing a building's environmental performance from a life-cycle perspective. However, the development of interfaces using middleware corrective applications that employ ETL technology and visual programming languages, such as Dynamo and Grasshopper, presents a new potential solution for facilitating the evaluation and optimization of buildings' life cycle performance. By employing these interfaces, it is feasible to incorporate any missing information from the model before it is simulated. Adopting such a strategy is important to make the information exchange between BIM tools, databases, BPS tools, and optimization algorithms.
- Achieving a real-time connection between LCA tools and BIM authoring tools would lead to significant development in the AECO industry. This connection allows any editing made on the BIM model to be immediately reflected in the energy simulation and environmental impact outcomes. Therefore, it eliminates the need to export/import data between different software tools and enables designers to make modifications to establish a

highly efficient design. To achieve a real-time connection, a well-defined file schema between software tools (*e.g.*, gbXML) or plug-ins must be developed within the BIM environment for the LCA software while maintaining the results' accuracy. However, this future research and data related to energy modeling need to include all energy end uses, considering the evolution of the energy mix for a representative hourly time step, and leverage the increasing availability of geographical information systems (GIS) data to evaluate and visualize building lifecycle processes that occur inside and outside the buildings in greater detail.

- Over the last decade, there has been a steady increase in the number EPDs for buildings. The production of EPDs is standardized through ISO 14025 and EN 15804 (CEN, 2019; ISO 14025, 2010), which are harmonized by different programme operators (*i.e.*, institutions that provide EPDs). At the time of writing, there are still significant efforts that are needed to make the EPD scheme for building product design. It is considered a significant shortcoming, as the standard EN 15978 (CEN, 2011) does not provide a standardized method for interpreting results from EPDs. Building designers need guidance when working with LCA data and EPDs. Without such guidance, there is a risk of misinterpretation or disregard of results, which reduces the importance, credibility, and utility of EPDs in reducing the environmental impact of the building sector. One of the possible ways is to develop a widespread platform to access to different EPDs for products to ensure better comparability between EPDs of various programme operators.
- In this thesis, we have captured the dynamic effects on electricity mix, and technological progress and recycling rate of timber materials of two prototypical dwellings (Irish masonry and British semi-detached low-energy buildings) and showed that, for these building types, applying these scenarios will be significantly important. Some future research remains:
  i) We focused on these building types because they are the most common types in this region. However, it will be important to analyze other types of houses with greater loads and smaller surface area (*e.g.*, collective housing), as well as commercial, and industrial buildings, that might be much more sensitive to the effects of dynamic driving factors.
  ii) Building studies should be capable of adapting to changes in local climate conditions caused by an increase in future GWP. This means requiring more cooling and less heating in the future. Weather data that considers future patterns can be important in designing future buildings.
  iii) Other dynamic aspects such as occupant behavioral considerations could also be considered to improve the representation of this research approach. As all these aforementioned focus areas were not included in

this study, they should be an object of further investigation to ensure building sustainability.

- The current thesis emphasizes energy consumption and environmental aspects. As another future possibility, it suggests exploring the economic and social dimensions of sustainability when investigating LCA. This would enable decision-makers to take into account not only the environmental impacts but also the economic and social aspects of sustainability. These factors can influence the effectiveness of the tools in achieving a more general framework of sustainability goals.

I.9 Nomenclature

ADP	Abiotic depletion potential
AECO	Architecture, Engineering, Construction, and Operations
BEM	Building Energy Modelling
BIM	Building Information Modeling
BoQ	Bill-of-Quantities
BPS	Building Performance Simulation
CE	Circular Economy
CO_2	Carbon Dioxide
COP26	26th Conference of Parties
DSTs	Decision Support Tools
EC	Embodied Carbon
ECC	Embodied Carbon Coefficients
EEC	Embodied Energy Coefficients
EIA	Environmental Impact Assessment
EoL	End-of-Life
EPD	Environmental Product Declaration
FU	Functional Unit
gbXML	Green Building Extensible Markup Language
GHG	Greenhouse Gas
GIS	Geographical Information Systems
GWP	Global Warming Potential
HVAC	Heating, Ventilation and Air Conditioning
ICE	Inventory of Carbon and Energy
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
kg	Kilogram
LCA	Life Cycle Assessment
LCT	Life Cycle Thinking

LETI	London Energy Transformation Initiative
LOD	Level of Development
MVHR	Mechanical, ventilation system with heat recovery
nZEB	nearly-Zero Energy Buildings
PH	Passive House or Passivhaus
PHPP	Passive House Planning Package
PV	Photovoltaic
RIBA	Royal Institute of British Architects
RICS	Royal Institution of Chartered Surveyors
RSP	Reference Service Period
SAP	Standard Assessment Procedure
SDGs	Sustainable Development Goals
WBLCA	Whole-Building Life Cycle Assessment

I.10 References

Abanda, F.H., Byers, L., 2016. An investigation of the impact of building orientation on energy consumption in a domestic building using emerging BIM (Building Information Modelling). Energy 97, 517–527. https://doi.org/10.1016/J.ENERGY.2015.12.135

Abd Rashid, A.F., Yusoff, S., 2015. A review of life cycle assessment method for building industry. Renew. Sustain. Energy Rev. 45, 244–248. https://doi.org/10.1016/J.RSER.2015.01.043

Abokersh, M.H., Norouzi, M., Boer, D., Cabeza, L.F., Casa, G., Prieto, C., Jiménez, L., Vallès, M., Abokersh, M.H., Norouzi, M., Boer, D., Cabeza, L.F., Casa, G., Prieto, C., Jiménez, L., Vallès, M., 2021. A framework for sustainable evaluation of thermal energy storage in circular economy. Renew. Energy 2021, Vol. 175, Pages 686--701 175, 686–701. https://doi.org/10.1016/J.RENENE.2021.04.136

Abouhamad, M., Abu-Hamd, M., 2021. Life Cycle Assessment Framework for Embodied Environmental Impacts of Building Construction Systems. Sustain. 2021, Vol. 13, Page 461 13, 461. https://doi.org/10.3390/SU13020461

Achenbach, H., Diederichs, S.K., Wenker, J.L., Rüter, S., 2016. Environmental product declarations in accordance with EN 15804 and EN 16485 — How to account for primary energy of secondary resources? Environ. Impact Assess. Rev. 60, 134–138. https://doi.org/10.1016/J.EIAR.2016.04.004

Ahmad, S.A., Hassan, M.Y., Abdullah, H., Rahman, H.A., Majid, M.S., Bandi, M., 2012. Energy efficiency measurements in a Malaysian public university, in: PECon

2012 - 2012 IEEE International Conference on Power and Energy. https://doi.org/10.1109/PECon.2012.6450281

Ahn, K.U., Kim, Y.J., Park, C.S., Kim, I., Lee, K., 2014. BIM interface for full vs. semi-automated building energy simulation. Energy Build. 68, 671–678. https://doi.org/10.1016/J.ENBUILD.2013.08.063

Akanbi, L.A., Oyedele, L.O., Akinade, O.O., Ajayi, A.O., Davila Delgado, M., Bilal, M., Bello, S.A., 2018. Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2017.10.026

Akinade, O.O., Oyedele, L.O., Bilal, M., Ajayi, S.O., Owolabi, H.A., Alaka, H.A., Bello, S.A., 2015. Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS). Resour. Conserv. Recycl. 105, 167–176. https://doi.org/10.1016/J.RESCONREC.2015.10.018

Al-Homoud, M.S., 2001. Computer-aided building energy analysis techniques. Build. Environ. 36, 421–433. https://doi.org/10.1016/S0360-1323(00)00026-3

Almeida, R., Chaves, L., Silva, M., Carvalho, M., Caldas, L., 2023. Integration between BIM and EPDs: Evaluation of the main difficulties and proposal of a framework based on ISO 19650:2018. J. Build. Eng. 68, 106091. https://doi.org/10.1016/J.JOBE.2023.106091

Anand, C.K., Amor, B., 2017. Recent developments, future challenges and new research directions in LCA of buildings: A critical review. Renew. Sustain. Energy Rev. 67, 408–416. https://doi.org/10.1016/J.RSER.2016.09.058

Anastasiades, K., Blom, J., Buyle, M., Audenaert, A., 2020. Translating the circular economy to bridge construction: Lessons learnt from a critical literature review. Renew. Sustain. Energy Rev. 117, 109522. https://doi.org/10.1016/J.RSER.2019.109522

Antoniadis, C.N., Martinopoulos, G., 2019. Optimization of a building integrated solar thermal system with seasonal storage using TRNSYS. Renew. Energy 137, 56–66. https://doi.org/10.1016/j.renene.2018.03.074

Aria, M., Cuccurullo, C., 2017. bibliometrix: An R-tool for comprehensive science mapping analysis. J. Informetr. https://doi.org/10.1016/j.joi.2017.08.007

Autodesk, 2021. Revit for MEP Engineering. Industries. URL https://www.autodesk.com/products/revit/mep (accessed 7.15.22).

Ayarkwa, J., Joe Opoku, D.G., Antwi-Afari, P., Man Li, R.Y., 2022. Sustainable building processes' challenges and strategies: The relative important index approach. Clean. Eng. Technol. 7, 100455. https://doi.org/10.1016/J.CLET.2022.100455

AzariJafari, H., Guest, G., Kirchain, R., Gregory, J., Amor, B., 2021. Towards comparable environmental product declarations of construction materials: Insights from a probabilistic comparative LCA approach. Build. Environ. 190, 107542. https://doi.org/10.1016/J.BUILDENV.2020.107542

Bahar, Y.N., Pere, C., Landrieu, J., Nicolle, C., 2013. A Thermal Simulation Tool for Building and Its Interoperability through the Building Information Modeling (BIM) Platform. Build. 2013, Vol. 3, Pages 380-398 3, 380–398. https://doi.org/10.3390/BUILDINGS3020380

Bazjanac, V., Maile, T., Rose, C., O'donnell, J.T., Mrazović, N., Morrissey, E., Welle, B.R., 2011. An assessment of the use of building energy performance simulation in early design. IBPSA Build. Simul.

Beloin-Saint-Pierre, D., Albers, A., Hélias, A., Tiruta-Barna, L., Fantke, P., Levasseur, A., Benetto, E., Benoist, A., Collet, P., 2020. Addressing temporal considerations in life cycle assessment. Sci. Total Environ. 743, 140700. https://doi.org/10.1016/J.SCITOTENV.2020.140700

Bilal, M., Khan, K.I.A., Thaheem, M.J., Nasir, A.R., 2020. Current state and barriers to the circular economy in the building sector: Towards a mitigation framework. J. Clean. Prod. 276, 123250. https://doi.org/10.1016/J.JCLEPRO.2020.123250

Bisinella, V., Christensen, T.H., Astrup, T.F., 2021. Future scenarios and life cycle assessment: systematic review and recommendations. Int. J. Life Cycle Assess. 2021 2611 26, 2143–2170. https://doi.org/10.1007/S11367-021-01954-6

Božiček, D., Kunič, R., Košir, M., 2021. Interpreting environmental impacts in building design: Application of a comparative assertion method in the context of the EPD scheme for building products. J. Clean. Prod. 279, 123399. https://doi.org/10.1016/J.JCLEPRO.2020.123399

BRE, 2014. SAP 2012 - The Government' s Standard Assessment Proceedure for Energy Rating of Dwellings. Technical Report rev June 2014. Buiding Res. Establ. (on behalf DECC). Watford.

BRE Group, 2023. GreenBook Live. BRE Glob. URL https://www.greenbooklive.com/index.jsp (accessed 3.15.23).

Broer, R., Simjanovic, J., Toth, Z., 2022. Implementing the Paris Agreement and Reducing Greenhouse Gas Emissions throughout the Life Cycle of Buildings: European Public Policies, Tools And Market Initiatives.. Build. Perform. Inst. Eur. URL https://scholar.google.com/scholar_lookup?title=Implementing the Paris Agreement and Reducing Greenhouse Gas Emissions throughout the Life Cycle of Buildings%3A European Public Policies%2C Tools and Market Initiatives&publication_year=2022&author=Building (accessed 2.27.23).

Bueno, C., Fabricio, M.M., 2018. Comparative analysis between a complete LCA study and results from a BIM-LCA plug-in. Autom. Constr. 90, 188–200. https://doi.org/10.1016/J.AUTCON.2018.02.028

buildingSMART, 2023. buildingSMART Technical_Industry Foundation Classes (IFC) – An Introduction. Build. Int. URL https://technical.buildingsmart.org/standards/ifc/ (accessed 3.2.23).

Buyle, M., Braet, J., Audenaert, A., 2013. Life cycle assessment in the construction sector: A review. Renew. Sustain. Energy Rev. 26, 379–388. https://doi.org/10.1016/J.RSER.2013.05.001

Cabeza, Luisa F, Rincón, L., Vilariño, V., Pérez, G., Castell, A., 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.08.037

Cabeza, Luisa F., Rincón, L., Vilariño, V., Pérez, G., Castell, A., 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.08.037

Cao, X., Dai, X., Liu, J., 2016. Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. Energy Build. 128, 198–213. https://doi.org/10.1016/J.ENBUILD.2016.06.089

CCC, 2018. Reducing UK emissions - 2018 Progress Report to Parliament. Clim. Chang. Comm. URL https://www.theccc.org.uk/publication/reducing-uk-emissions-2018-progress-report-to-parliament/ (accessed 8.14.22).

Cemesova, A., Hopfe, C.J., McLeod, R.S., 2015. PassivBIM: Enhancing interoperability between BIM and low energy design software. Autom. Constr. 57, 17–32. https://doi.org/10.1016/J.AUTCON.2015.04.014

Cemesova, A., Hopfe, C.J., Rezgui, Y., 2013. An approach to facilitating data exchange between bim environments and a low energy design tool.

CEN, 2019. 15804: 2012+A2: 2019—Sustainability of Construction. Eur. Comm. Stand. URL https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=15804%3A+2012%2B+A2%3A+2019—Sustainability+of+Construction+Works—Environmental+Product+Declarations—Core+Rules+for+the+Product+Category+of+…&btnG= (accessed 9.17.22).

CEN, 2011. EN 15978:2011 - Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method. Eur. Comm. Stand. URL https://scholar.google.com/scholar_lookup?title=EN 15978%3A2011 - Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method&publication_year=2011&author=%2FTC 350 CEN (accessed 9.17.22).

Collet, P., Lardon, L., Steyer, J.P., Hélias, A., 2014. How to take time into account in the inventory step: A selective introduction based on sensitivity analysis. Int. J. Life Cycle Assess. 19, 320–330. https://doi.org/10.1007/S11367-013-0636-7/TABLES/3

Collinge, W.O., Landis, A.E., Jones, A.K., Schaefer, L.A., Bilec, M.M., 2013. Dynamic life cycle assessment: Framework and application to an institutional building. Int. J. Life Cycle Assess. 18, 538–552. https://doi.org/10.1007/S11367-012-0528-2/FIGURES/6

Crawley, D.B., Hand, J.W., Kummert, M., Griffith, B.T., 2008. Contrasting the capabilities of building energy performance simulation programs. Build. Environ. 43, 661–673. https://doi.org/10.1016/j.buildenv.2006.10.027

Cusenza, M.A., Guarino, F., Longo, S., Cellura, M., 2022. An integrated energy simulation and life cycle assessment to measure the operational and embodied energy of a Mediterranean net zero energy building. Energy Build. 254, 111558. https://doi.org/10.1016/J.ENBUILD.2021.111558

De Wolf, C., Pomponi, F., Moncaster, A., 2017. Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. Energy Build. 140, 68–80. https://doi.org/10.1016/J.ENBUILD.2017.01.075

DECC, 2009. The Government’s Standard Assessment Procedure for Energy Rating of Dwellings. Watford, UK Build. Res. Establ. URL https://www.bregroup.com/sap/standard-assessment-procedure-sap-2009/ (accessed 4.19.21).

Del Borghi, A., 2013. LCA and communication: Environmental Product Declaration. Int. J. Life Cycle Assess. 18, 293–295. https://doi.org/10.1007/S11367-012-0513-9/TABLES/1

DesignBuilder, 2021. DesignBuilder Version 6.1.8.021. Des. Softw. Ltd. URL https://designbuilder.co.uk// (accessed 9.12.22).

Dinas, A., Nikolaidis, T.N., Baniotopoulos, C.C., 2017. Sustainable Restoration Criteria for a Historical Steel Railway Bridge. Procedia Environ. Sci. 38, 578–585. https://doi.org/10.1016/J.PROENV.2017.03.131

Dong, B., Xu, G., Luo, X., Cai, Y., Gao, W., 2012. A bibliometric analysis of solar power research from 1991 to 2010. Scientometrics 93, 1101–1117. https://doi.org/10.1007/S11192-012-0730-9/TABLES/7

Ecology, C., 2019. Embodied energy and carbon–The ICE database. URL https://circularecology.com/embodied-carbon-footprint-database.html (accessed 3.15.23).

EcoPlatform, 2023. ECO Portal. ECO Platf. AISBL. URL https://www.eco-platform.org/eco-portal-access-point-to-digital-product-data.html (accessed 3.12.23).

Elomari, Y., Norouzi, M., Marín-Genescà, M., Fernández, A., Boer, D., 2022. Integration of Solar Photovoltaic Systems into Power Networks: A Scientific Evolution Analysis. Sustain. 2022, Vol. 14, Page 9249 14, 9249. https://doi.org/10.3390/SU14159249

EN 16449, 2014. EN 16449:2014–Wood and wood-based products - Calculation of the Biogenic Carbon Content of wood and Conversion to Carbon Dioxide. Eur. Stand. URL https://www.en-standard.eu/csn-en-16449-wood-and-wood-based-products-calculation-of-the-biogenic-carbon-content-of-wood-and-conversion-to-carbon-dioxide/ (accessed 9.16.22).

EPD International AB, 2023. The International EPD System. Int. EPD Syst. URL https://www.environdec.com/home (accessed 3.12.23).

European Commission, 2019. LEVEL(S) - Taking action on the TOTAL impact of the construction sector. Luxemb. Publ. Off. Eur. Union, 2019. https://doi.org/10.2779/458570

European Commission, 2018. Directive (EU) 2018/844 of the European Parliament and of the Council. URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.156.01.0075.01.ENG (accessed 1.31.21).

European Commission, 2017. Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3. URL https://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm (accessed 4.10.21).

European Commission Joint Research Centre, 2010. International Reference Life Cycle Data System (ILCD) Handbook: Specific Guide for Life Cycle Inventory Data Sets. EUR 24709 EN; Publ. Off. Eur. Union Luxemb. URL https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/international-reference-life-cycledata-system-ilcd-handbook-specific-guide-life-cycle#:~%7B%7D:text=Abstract%3A,footprinting%2CandGreenPublicProcurement (accessed 4.19.21).

European Parliament, 2010. European Parliament and Council, 2010a. Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings. Off. J. Eur. Union. URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2010.153.01.0001.01.ENG&toc=OJ%3AL%3A2010%3A153%3AFULL

Feist, W., 2011. Certified Passive House—Certification Criteria for Residential Passive House Buildings. Passiv. House Institute, Darmstadt, Ger. URL https://scholar.google.com/scholar?cluster=13112177155049035575&hl=en&as_sdt=2005&sciodt=0,5 (accessed 9.5.22).

Feng, H., Zhao, J., Zhang, H., Zhu, S., Li, D., Thurairajah, N., 2022. Uncertainties in whole-building life cycle assessment: A systematic review. J. Build. Eng. 50, 104191. https://doi.org/10.1016/J.JOBE.2022.104191

Fnais, A., Rezgui, Y., Petri, I., Beach, T., Yeung, J., Ghoroghi, A., Kubicki, S., 2022. The application of life cycle assessment in buildings: challenges, and directions for future research. Int. J. Life Cycle Assess. 2022 275 27, 627–654. https://doi.org/10.1007/S11367-022-02058-5

Forth, K., Abualdenien, J., Borrmann, A., 2023. Calculation of embodied GHG emissions in early building design stages using BIM and NLP-based semantic model healing. Energy Build. 284, 112837. https://doi.org/10.1016/J.ENBUILD.2023.112837

Fouquet, M., Levasseur, A., Margni, M., Lebert, A., Lasvaux, S., Souyri, B., Buhé, C., Woloszyn, M., 2015. Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment. Build. Environ. 90, 51–59. https://doi.org/10.1016/J.BUILDENV.2015.03.022

Fufa, S.M., Wiik, M., Schlanbusch, R.D., Andresen, I., 2017. The influence of estimated service life on the embodied emissions of zero emission buildings (ZEBs) when choosing low-carbon building products.

G.B. Foundation, 2023. gbXML - An industry supported standard for storing and sharing building properties between 3D Architectural and Engineering Analysis Software. Green Build. XML Schema, Inc. URL https://www.gbxml.org/ (accessed 3.2.23).

Gao, H., Koch, C., Wu, Y., 2019. Building information modelling based building energy modelling: A review. Appl. Energy 238, 320–343. https://doi.org/10.1016/J.APENERGY.2019.01.032

Gasia, J., Fabiani, C., Chàfer, M., Pisello, A.L., Manni, A., Ascani, M., Cabeza, L.F., 2021. Life cycle assessment and life cycle costing of an innovative component for refrigeration units. J. Clean. Prod. 295, 126442. https://doi.org/10.1016/J.JCLEPRO.2021.126442

Gelowitz, M.D.C., McArthur, J.J., 2017. Comparison of type III environmental product declarations for construction products: Material sourcing and harmonization evaluation. J. Clean. Prod. 157, 125–133. https://doi.org/10.1016/J.JCLEPRO.2017.04.133

Gerrish, T., Ruikar, K., Cook, M., Johnson, M., Phillip, M., 2017. Using BIM capabilities to improve existing building energy modelling practices. Eng. Constr. Archit. Manag. 24, 190–208. https://doi.org/10.1108/ECAM-11-2015-0181/FULL/PDF

Ghisellini, P., Ripa, M., Ulgiati, S., 2018. Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.11.207

Giesekam, J., Pomponi, F., 2017. Briefing: Embodied carbon dioxide assessment in buildings: guidance and gaps. Proc. Inst. Civ. Eng. Eng. Sustain. 171, 334–341. https://doi.org/10.1680/JENSU.17.00032/ASSET/IMAGES/SMALL/JENSU171-0334-F2.GIF

Govindan, K., Madan Shankar, K., Kannan, D., 2016. Sustainable material selection for construction industry – A hybrid multi criteria decision making approach. Renew. Sustain. Energy Rev. 55, 1274–1288. https://doi.org/10.1016/J.RSER.2015.07.100

Grant, M.J., Booth, A., 2009. A typology of reviews: an analysis of 14 review types and associated methodologies. Heal. Inf. Libr. J. 26, 91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x

Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life cycle assessment: Past, present, and future. Environ. Sci. Technol. 45, 90–96. https://doi.org/10.1021/ES101316V/ASSET/IMAGES/LARGE/ES-2010-01316V_0003.JPEG

Häfliger, I.F., John, V., Passer, A., Lasvaux, S., Hoxha, E., Saade, M.R.M., Habert, G., 2017. Buildings environmental impacts' sensitivity related to LCA modelling choices of construction materials. J. Clean. Prod. 156, 805–816. https://doi.org/10.1016/J.JCLEPRO.2017.04.052

Häkkinen, T., Kuittinen, M., Ruuska, A., Jung, N., 2015. Reducing embodied carbon during the design process of buildings. J. Build. Eng. 4, 1–13. https://doi.org/10.1016/J.JOBE.2015.06.005

Hammond, G., Jones, C., Lowrie, F., Tse, P., Association, B.S.R. and I., Bath, U. of, 2011. Embodied carbon : the Inventory of Carbon and Energy (ICE), BSRIA guide TA - TT -. BSRIA, Bracknell SE -. https://doi.org/LK - https://worldcat.org/title/730400073

Hawkins, W., Cooper, S., Allen, S., Roynon, J., Ibell, T., 2021. Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure. Structures 33, 90–98. https://doi.org/10.1016/J.ISTRUC.2020.12.013

Hoxha, E., Passer, A., Ruschi, M., Saade, M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., Habert, G., 2020. Biogenic carbon in buildings: a critical overview of LCA methods. Build. Cities 1, 504–524. https://doi.org/10.5334/BC.46

Iacovidou, E., Purnell, P., Lim, M.K., 2018. The use of smart technologies in enabling construction components reuse: A viable method or a problem creating solution? J. Environ. Manage. 216, 214–223. https://doi.org/10.1016/J.JENVMAN.2017.04.093

Iddon, C.R., Firth, S.K., 2013. Embodied and operational energy for new-build housing: A case study of construction methods in the UK. Energy Build. https://doi.org/10.1016/j.enbuild.2013.08.041

Igos, E., Benetto, E., Meyer, R., Baustert, P., Othoniel, B., 2019. How to treat uncertainties in life cycle assessment studies? Int. J. Life Cycle Assess. 24, 794–807. https://doi.org/10.1007/S11367-018-1477-1/TABLES/3

ISO 14025, 2010. ISO 14025: Environmental labels and declarations–Type III environmental declarations–Principles and procedures. ISO—International Organ. Stand. Geneva, Switz. URL https://scholar.google.com/scholar?q=ISO E., 14025. Environmental labels and declarationsType IIIenvironmental declarationsPrinciples and procedures. .#d=gs_cit&t=1676923785082&u=%2Fscholar%3Fq%3Dinfo%3AtjLnkvP9wbcJ%3Ascholar.google.com%2F%26output%3Dcite (accessed 2.20.23).

ISO 14040, 2006. Environmental Management — Life Cycle Assessment — Principles and Framework. Int. Organ. Stand. Switz. URL https://www.iso.org/standard/37456.html (accessed 8.20.22).

ISO 14044, 2006. Environmental Management — Life Cycle Assessment — Requirements and Guidelines. Int. Organ. Stand. Switz. URL https://www.iso.org/standard/72357.html (accessed 9.20.22).

Khan, H., Khan, I., Binh, T.T., 2020. The heterogeneity of renewable energy consumption, carbon emission and financial development in the globe: A panel quantile regression approach. Energy Reports 6, 859–867. https://doi.org/10.1016/J.EGYR.2020.04.002

Khasreen, M.M., Banfill, P.F.G., Menzies, G.F., 2009. Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. Sustain. 2009, Vol. 1, Pages 674-701 1, 674–701. https://doi.org/10.3390/SU1030674

Kiss, B., Kácsor, E., Szalay, Z., 2020. Environmental assessment of future electricity mix – Linking an hourly economic model with LCA. J. Clean. Prod. 264, 121536. https://doi.org/10.1016/J.JCLEPRO.2020.121536

Kuo, H.J., Hsieh, S.H., Guo, R.C., Chan, C.C., 2016. A verification study for energy analysis of BIPV buildings with BIM. Energy Build. 130, 676–691. https://doi.org/10.1016/J.ENBUILD.2016.08.048

Kylili, A., Ilic, M., Fokaides, P.A., 2017. Whole-building Life Cycle Assessment (LCA) of a passive house of the sub-tropical climatic zone. Resour. Conserv. Recycl. 116, 169–177. https://doi.org/10.1016/J.RESCONREC.2016.10.010

Lasvaux, S., Habert, G., Peuportier, B., Chevalier, J., 2015. Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies. Int. J. Life Cycle Assess. 2015 2011 20, 1473–1490. https://doi.org/10.1007/S11367-015-0938-Z

Le Quéré, C., Jackson, R.B., Jones, M.W., Smith, A.J.P., Abernethy, S., Andrew, R.M., De-Gol, A.J., Willis, D.R., Shan, Y., Canadell, J.G., Friedlingstein, P., Creutzig, F., Peters, G.P., 2020. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nat. Clim. Chang. 2020 107 10, 647–653. https://doi.org/10.1038/s41558-020-0797-x

Lee, J., McCuskey Shepley, M., Choi, J., 2020. Exploring the localization process of low energy residential buildings: A case study of Korean passive houses. J. Build. Eng. https://doi.org/10.1016/j.jobe.2020.101290

LETI, 2020. LETI Climate Emergency Design Guide, how new buildings can meet UK climate change targets. London Energy Transform. Initiat. URL https://www.leti.uk/cedg (accessed 10.20.22).

Li, H., Luo, Z., Xu, X., Cang, Y., Yang, L., 2021. Assessing the embodied carbon reduction potential of straw bale rural houses by hybrid life cycle assessment: A four-case study. J. Clean. Prod. 303. https://doi.org/10.1016/J.JCLEPRO.2021.127002

Liebich, T., 2013. IFC4—The new buildingSMART standard. IC Meet. Helsinki, Finl. bSI Publ. URL https://scholar.google.com/scholar?q=T. Liebich, IFC4the new buildingSMART standard, in: IC Meeting, bSI Publications Helsinki, Finland. (accessed 3.1.23).

Ligardo-Herrera, I., Quintana-Gallardo, A., Stascheit, C.W., Gómez-Navarro, T., 2022. Make your home carbon-free. An open access planning tool to calculate energy-related carbon emissions in districts and dwellings. Energy Reports 8, 11404–11415. https://doi.org/10.1016/J.EGYR.2022.08.263

Llatas, C., Soust-Verdaguer, B., Passer, A., 2020. Implementing Life Cycle Sustainability Assessment during design stages in Building Information Modelling: From systematic literature review to a methodological approach. Build. Environ. 182, 107164. https://doi.org/10.1016/J.BUILDENV.2020.107164

López, L.R., Dessì, P., Cabrera-Codony, A., Rocha-Melogno, L., Kraakman, B., Naddeo, V., Balaguer, M.D., Puig, S., 2023. CO2 in indoor environments: From environmental and health risk to potential renewable carbon source. Sci. Total Environ. 856, 159088. https://doi.org/10.1016/J.SCITOTENV.2022.159088

Lueddeckens, S., Saling, P., Guenther, E., 2020. Temporal issues in life cycle assessment—a systematic review. Int. J. Life Cycle Assess. 25, 1385–1401. https://doi.org/10.1007/S11367-020-01757-1/TABLES/1

Lukić, I., Premrov, M., Passer, A., Žegarac Leskovar, V., 2021. Embodied energy and GHG emissions of residential multi-storey timber buildings by height – A case with structural connectors and mechanical fasteners. Energy Build. 252, 111387. https://doi.org/10.1016/J.ENBUILD.2021.111387

Lützkendorf, T., Foliente, G., Balouktsi, M., Wiberg, A.H., 2014. Net-zero buildings: incorporating embodied impacts. https://doi.org/10.1080/09613218.2014.935575 43, 62–81. https://doi.org/10.1080/09613218.2014.935575

Mahpour, A., 2018. Prioritizing barriers to adopt circular economy in construction and demolition waste management. Resour. Conserv. Recycl. 134, 216–227. https://doi.org/10.1016/J.RESCONREC.2018.01.026

Malmqvist, T., Nehasilova, M., Moncaster, A., Birgisdottir, H., Nygaard Rasmussen, F., Houlihan Wiberg, A., Potting, J., 2018. Design and construction strategies for reducing embodied impacts from buildings – Case study analysis. Energy Build. 166, 35–47. https://doi.org/10.1016/J.ENBUILD.2018.01.033

Manuilova, A., Suebsiri, J., Wilson, M., 2009. Should Life Cycle Assessment be part of the Environmental Impact Assessment? Case study: EIA of CO2 Capture and Storage in Canada. Energy Procedia 1, 4511–4518. https://doi.org/10.1016/J.EGYPRO.2009.02.269

Mateus, R.A.S., Oliveira, T., Neves, C., 2023. Sustainable technology: Antecedents and outcomes of households' adoption. Energy Build. 284, 112846. https://doi.org/10.1016/J.ENBUILD.2023.112846

Matthews, N.E., Stamford, L., Shapira, P., 2019. Aligning sustainability assessment with responsible research and innovation: Towards a framework for Constructive Sustainability Assessment. Sustain. Prod. Consum. 20, 58–73. https://doi.org/10.1016/J.SPC.2019.05.002

Meex, E., Hollberg, A., Knapen, E., Hildebrand, L., Verbeeck, G., 2018. Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design. Build. Environ. 133, 228–236. https://doi.org/10.1016/J.BUILDENV.2018.02.016

Minkov, N., Schneider, L., Lehmann, A., Finkbeiner, M., 2015. Type III Environmental Declaration Programmes and harmonization of product category rules: status quo and practical challenges. J. Clean. Prod. 94, 235–246. https://doi.org/10.1016/J.JCLEPRO.2015.02.012

Mohajer, M.F., Aksamija, A., 2019. Integration of Building Energy Modeling (BEM) and Building Information Modeling (BIM): Workflows and Case Study. Build. Technol. Educ. Soc. 2019, 37. https://doi.org/https://doi.org/10.7275/bn9j-e183

Mora, T.D., Bolzonello, E., Cavalliere, C., Peron, F., 2020. Key Parameters Featuring BIM-LCA Integration in Buildings: A Practical Review of the Current Trends. Sustain. 2020, Vol. 12, Page 7182 12, 7182. https://doi.org/10.3390/SU12177182

Moran, F., Blight, T., Natarajan, S., Shea, A., 2014. The use of Passive House Planning Package to reduce energy use and CO2 emissions in historic dwellings. Energy Build. 75, 216–227. https://doi.org/10.1016/J.ENBUILD.2013.12.043

Moreno-Rangel, A., Sharpe, T., McGill, G., Musau, F., 2020. Indoor air quality in passivhaus dwellings: A literature review. Int. J. Environ. Res. Public Health. https://doi.org/10.3390/ijerph17134749

Munaro, M.R., Tavares, S.F., Bragança, L., 2020. Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment. J. Clean. Prod. 260. https://doi.org/10.1016/j.jclepro.2020.121134

Najjar, M., Figueiredo, K., Hammad, A.W.A., Haddad, A., 2019. Integrated optimization with building information modeling and life cycle assessment for generating energy efficient buildings. Appl. Energy 250, 1366–1382. https://doi.org/10.1016/J.APENERGY.2019.05.101

Negishi, K., Lebert, A., Almeida, D., Chevalier, J., Tiruta-Barna, L., 2019. Evaluating climate change pathways through a building's lifecycle based on Dynamic Life Cycle Assessment. Build. Environ. 164, 106377. https://doi.org/10.1016/J.BUILDENV.2019.106377

Negishi, K., Tiruta-Barna, L., Schiopu, N., Lebert, A., Chevalier, J., 2018. An operational methodology for applying dynamic Life Cycle Assessment to buildings. Build. Environ. 144, 611–621. https://doi.org/10.1016/J.BUILDENV.2018.09.005

Nematchoua, M.K., Sendrahasina, R.M., Malmedy, C., Orosa, J.A., Simo, E., Reiter, S., 2022. Analysis of environmental impacts and costs of a residential building over its entire life cycle to achieve nearly zero energy and low emission objectives. J. Clean. Prod. 373, 133834. https://doi.org/10.1016/J.JCLEPRO.2022.133834

Noack, F., Katranuschkov, P., Scherer, R.J., Dimitriou, V., Firth, S., Hassan, T., Ramos, N., Pereira, P., Malo, P., Fernando, T., 2016. Technical challenges and approaches to transfer building information models to building energy. eWork Ebus. Archit. Eng. Constr. - Proc. 11th Eur. Conf. Prod. Process Model. ECPPM 2016 521–528.

Norouzi, Masoud, Chàfer, M., Cabeza, L.F., Jiménez, L., Boer, D., 2021a. Circular economy in the building and construction sector: A scientific evolution analysis. J. Build. Eng. 44. https://doi.org/10.1016/J.JOBE.2021.102704

Norouzi, M., Colclough, S., Jiménez, L., Gavaldà, J., Boer, D., 2022. Low-energy buildings in combination with grid decarbonization, life cycle assessment of passive house buildings in Northern Ireland. Energy Build. 261, 111936. https://doi.org/10.1016/J.ENBUILD.2022.111936

Norouzi, M., Haddad, A.N., Jiménez, L., Hoseinzadeh, S., Boer, D., 2023. Carbon footprint of low-energy buildings in the United Kingdom: Effects of mitigating technological pathways and decarbonization strategies. Sci. Total Environ. 882, 163490. https://doi.org/10.1016/J.SCITOTENV.2023.163490

Norouzi, Mohsen, Rafienia, M., Poorazizi, E., Setayeshmehr, M., 2021b. Adipose-derived Stem Cells Growth and Proliferation Enhancement Using Poly (lactic-co-glycolic acid) (PLGA)/Fibrin Nanofiber Mats. J. Appl. Biotechnol. Reports 8, 361–369. https://doi.org/10.30491/JABR.2020.223551.1199

Obringer, R., Nateghi, R., 2021. What makes a city ‘smart’ in the Anthropocene? A critical review of smart cities under climate change. Sustain. Cities Soc. 75, 103278. https://doi.org/10.1016/J.SCS.2021.103278

Olawumi, T.O., Chan, D.W.M., 2018. Identifying and prioritizing the benefits of integrating BIM and sustainability practices in construction projects: A Delphi survey of international experts. Sustain. Cities Soc. 40, 16–27. https://doi.org/10.1016/J.SCS.2018.03.033

Olawumi, T.O., Chan, D.W.M., Wong, J.K.W., Chan, A.P.C., 2018. Barriers to the integration of BIM and sustainability practices in construction projects: A Delphi survey of international experts. J. Build. Eng. 20, 60–71. https://doi.org/10.1016/J.JOBE.2018.06.017

Olusola, O.S., Oluwatosin, O.T., Alabi, A., 2017. Achieving Value for Money (VFM) in Construction Projects. Civ. Environ. Res.

Ortiz-Rodríguez, O., Castells, F., Sonnemann, G., 2010. Life cycle assessment of two dwellings: One in Spain, a developed country, and one in Colombia, a country under development. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2010.02.021

Palumbo, E., Soust-Verdaguer, B., Llatas, C., Traverso, M., 2020. How to Obtain Accurate Environmental Impacts at Early Design Stages in BIM When Using Environmental Product Declaration. A Method to Support Decision-Making. Sustain. 2020, Vol. 12, Page 6927 12, 6927. https://doi.org/10.3390/SU12176927

Passivhaus Institut, 2015. Passive house planning package (PHPP), version 9, user handbook. Darmstadt Passiv. House Inst. URL https://passivehouse.com/04_phpp/04_phpp.htm (accessed 7.6.21).

Pickering, C., Byrne, J., 2014. The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers. High. Educ. Res. Dev. 33, 534–548. https://doi.org/10.1080/07294360.2013.841651

Pollack, J., Adler, D., 2015. Emergent trends and passing fads in project management research: A scientometric analysis of changes in the field. Int. J. Proj. Manag. 33, 236–248. https://doi.org/10.1016/j.ijproman.2014.04.011

Pomponi, F., Moncaster, A., 2017. Circular economy for the built environment: A research framework. J. Clean. Prod. 143, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Pomponi, F., Moncaster, A., 2016. Embodied carbon mitigation and reduction in the built environment – What does the evidence say? J. Environ. Manage. 181, 687–700. https://doi.org/10.1016/J.JENVMAN.2016.08.036

Porsani, G.B., de Lersundi, K.D.V., Gutiérrez, A.S.O., Bandera, C.F., 2021. Interoperability between Building Information Modelling (BIM) and Building Energy Model (BEM). Appl. Sci. 2021, Vol. 11, Page 2167 11, 2167. https://doi.org/10.3390/APP11052167

POST, 2021. Reducing the whole life carbon impact of buildings. Parliam. Off. Sci. Technol. UK Parliam. Postbr. 44. URL https://researchbriefings.files.parliament.uk/documents/POST-PB-0044/POST-PB-0044.pdf (accessed 9.10.22).

Pré Consultants, 2022. SimaPro. PRé Sustain. B.V. URL https://simapro.com/ (accessed 9.20.22).

Rahif, R., Norouziasas, A., Elnagar, E., Doutreloup, S., Pourkiaei, S.M., Amaripadath, D., Romain, A.C., Fettweis, X., Attia, S., 2022. Impact of climate change on nearly zero-energy dwelling in temperate climate: Time-integrated discomfort, HVAC energy performance, and GHG emissions. Build. Environ. 223, 109397. https://doi.org/10.1016/J.BUILDENV.2022.109397

Resch, E., Andresen, I., 2018. A Database Tool for Systematic Analysis of Embodied Emissions in Buildings and Neighborhoods. Build. 2018, Vol. 8, Page 106 8, 106. https://doi.org/10.3390/BUILDINGS8080106

Resch, E., Lausselet, C., Brattebø, H., Andresen, I., 2020. An analytical method for evaluating and visualizing embodied carbon emissions of buildings. Build. Environ. 168, 106476. https://doi.org/10.1016/J.BUILDENV.2019.106476

Rezaei, R., Chiew, T.K., Lee, S.P., Shams Aliee, Z., 2014. Interoperability evaluation models: A systematic review. Comput. Ind. 65, 1–23. https://doi.org/10.1016/J.COMPIND.2013.09.001

RIBA, 2021. 2030 Climate Challenge. URL https://www-architecture-com.sabidi.urv.cat/about/policy/climate-action/2030-climate-challenge (accessed 12.28.21).

RICS, 2017. Whole life carbon assessment for the built environment. R. Inst. Chart. Surv. Parliam. Sq. London SW1P 3AD. URL https://www.rics.org/globalassets/rics-website/media/news/whole-life-carbon-assessment-for-the--built-environment-november-2017.pdf (accessed 9.14.22).

Roberts, M., Allen, S., Coley, D., 2020. Life cycle assessment in the building design process – A systematic literature review. Build. Environ. 185, 107274. https://doi.org/10.1016/J.BUILDENV.2020.107274

Rodriguez, B.X., Huang, M., Lee, H.W., Simonen, K., Ditto, J., 2020. Mechanical, electrical, plumbing and tenant improvements over the building lifetime: Estimating material quantities and embodied carbon for climate change mitigation. Energy Build. 226, 110324. https://doi.org/10.1016/J.ENBUILD.2020.110324

Samsatli, S., Samsatli, N.J., 2019. The role of renewable hydrogen and inter-seasonal storage in decarbonising heat – Comprehensive optimisation of future renewable energy value chains. Appl. Energy 233–234, 854–893. https://doi.org/10.1016/J.APENERGY.2018.09.159

Sanhudo, L., Ramos, N.M.M., Poças Martins, J., Almeida, R.M.S.F., Barreira, E., Simões, M.L., Cardoso, V., 2018. Building information modeling for energy retrofitting – A review. Renew. Sustain. Energy Rev. 89, 249–260. https://doi.org/10.1016/J.RSER.2018.03.064

Santos, R., Costa, A.A., Silvestre, J.D., Pyl, L., 2019a. Informetric analysis and review of literature on the role of BIM in sustainable construction. Autom. Constr. 103, 221–234. https://doi.org/10.1016/J.AUTCON.2019.02.022

Santos, R., Costa, A.A., Silvestre, J.D., Pyl, L., 2019b. Integration of LCA and LCC analysis within a BIM-based environment. Autom. Constr. 103, 127–149. https://doi.org/10.1016/J.AUTCON.2019.02.011

Santos, R., Costa, A.A., Silvestre, J.D., Vandenbergh, T., Pyl, L., 2020. BIM-based life cycle assessment and life cycle costing of an office building in Western Europe. Build. Environ. 169, 106568. https://doi.org/10.1016/J.BUILDENV.2019.106568

Schnieders, J., Hermelink, A., 2006. CEPHEUS results: Measurements and occupants' satisfaction provide evidence for Passive Houses being an option for sustainable building. Energy Policy. https://doi.org/10.1016/j.enpol.2004.08.049

Shadram, F., Johansson, T.D., Lu, W., Schade, J., Olofsson, T., 2016. An integrated BIM-based framework for minimizing embodied energy during building design. Energy Build. 128, 592–604. https://doi.org/10.1016/J.ENBUILD.2016.07.007

Shahsavar, A., Ghadamian, H., Saboori, H., 2023. Building energy and environmental sustainability. Build. Energy Flex. Demand Manag. 3–15. https://doi.org/10.1016/B978-0-323-99588-7.00006-7

Sharma, A., Saxena, A., Sethi, M., Shree, V., Varun, 2011. Life cycle assessment of buildings: A review. Renew. Sustain. Energy Rev. 15, 871–875. https://doi.org/10.1016/J.RSER.2010.09.008

Smith, L.V., Tarui, N., Yamagata, T., 2021. Assessing the impact of COVID-19 on global fossil fuel consumption and CO2 emissions. Energy Econ. 97, 105170. https://doi.org/10.1016/J.ENECO.2021.105170

Soares, N., Bastos, J., Pereira, L.D., Soares, A., Amaral, A.R., Asadi, E., Rodrigues, E., Lamas, F.B., Monteiro, H., Lopes, M.A.R., Gaspar, A.R., 2017. A review on current advances in the energy and environmental performance of buildings towards a more sustainable built environment. Renew. Sustain. Energy Rev. 77, 845–860. https://doi.org/10.1016/J.RSER.2017.04.027

Sodagar, B., Rai, D., Jones, B., Wihan, J., Fieldson, R., 2010. The carbon-reduction potential of straw-bale housing. http://dx.doi.org/10.1080/09613218.2010.528187 39, 51–65. https://doi.org/10.1080/09613218.2010.528187

Song, X., Carlsson, C., Kiilsgaard, R., Bendz, D., Kennedy, H., 2020. Life Cycle Assessment of Geotechnical Works in Building Construction: A Review and Recommendations. Sustain. 2020, Vol. 12, Page 8442 12, 8442. https://doi.org/10.3390/SU12208442

Sousa, J., 2012. Energy simulation software for buildings: Review and comparison, in: CEUR Workshop Proceedings. pp. 57–68.

Soust-Verdaguer, B., Llatas, C., García-Martínez, A., 2017. Critical review of bim-based LCA method to buildings. Energy Build. 136, 110–120. https://doi.org/10.1016/J.ENBUILD.2016.12.009

Sphera Solutions, 2023. Product Sustainability Software & Data. GaBi Database. URL https://sphera.com/product-sustainability-software/ (accessed 3.20.23).

Su, S., Li, X., Zhu, Y., 2019. Dynamic assessment elements and their prospective solutions in dynamic life cycle assessment of buildings. Build. Environ. 158, 248–259. https://doi.org/10.1016/J.BUILDENV.2019.05.008

Su, S., Zhang, H., Zuo, J., Li, X., Yuan, J., 2021. Assessment models and dynamic variables for dynamic life cycle assessment of buildings: a review. Environ. Sci. Pollut. Res. 28, 26199–26214. https://doi.org/10.1007/S11356-021-13614-1/FIGURES/3

Takano, A., Hafner, A., Linkosalmi, L., Ott, S., Hughes, M., Winter, S., 2015. Life cycle assessment of wood construction according to the normative standards. Eur. J. Wood Wood Prod. https://doi.org/10.1007/s00107-015-0890-4

Team, R.C., 2018. R: A Language and Environment for Statistical Computing. R Found. Stat. Comput. Vienna, Austria.

The International EPD System, 2022. The Environmental Product Declaration-EPD International. Int. EPD Syst. URL https://www.environdec.com/library (accessed 4.10.22).

Toniolo, S., Tosato, R.C., Gambaro, F., Ren, J., 2020. Life cycle thinking tools: Life cycle assessment, life cycle costing and social life cycle assessment. Life Cycle Sustain. Assess. Decis. Methodol. Case Stud. 39–56. https://doi.org/10.1016/B978-0-12-818355-7.00003-8

UKGBC, 2019. Net Zero Carbon Buildings: A Framework Definition. UK Green Build. Counc. london. URL https://www.ukgbc.org/ukgbc-work/net-zero-carbon-buildings-a-framework-definition/ (accessed 9.10.22).

United Nations, 2015a. About the sustainable development goals.. Sustain. Dev. Goals. URL https://www.un.org/sustainabledevelopment/sustainable-development-goals/ (accessed 1.6.21).

United Nations, 2015b. Open Working Group proposal for Sustainable Development Goals. Sutainable Dev. - Knowl. Platf. URL https://sustainabledevelopment.un.org/focussdgs.html (accessed 2.25.21).

Unites States General Services Administration (GSA), 2015. Guide: 05-Energy performance. Unites States Gen. Serv. Adm. URL https://scholar.google.com/scholar_lookup?title=05-Energy performance&publication_year=2015&author=B. Guide (accessed 2.13.23).

van Eck, N.J., Waltman, L., 2013. {VOSviewer} manual. Leiden: Univeristeit Leiden.

VITO, KU Leuven, TU Graz, 2018. PEF4Buildings—Study on the Application of the PEF Method and related guidance documents to a newly office building (ENV.B.1/ETU/2016/0052LV) 428. https://doi.org/10.2779/23505

Waltman, L., 2016. A review of the literature on citation impact indicators. J. Informetr. 10, 365–391. https://doi.org/10.1016/J.JOI.2016.02.007

Weidner, T., Guillén-Gosálbez, G., 2023. Planetary boundaries assessment of deep decarbonisation options for building heating in the European Union. Energy Convers. Manag. 278, 116602. https://doi.org/10.1016/J.ENCONMAN.2022.116602

Weißenberger, M., Jensch, W., Lang, W., 2014. The convergence of life cycle assessment and nearly zero-energy buildings: The case of Germany. Energy Build. 76, 551–557. https://doi.org/10.1016/J.ENBUILD.2014.03.028

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Wong-Parodi, G., Mach, K.J., Jagannathan, K., Sjostrom, K.D., 2020. Insights for developing effective decision support tools for environmental sustainability. Curr. Opin. Environ. Sustain. 42, 52–59. https://doi.org/10.1016/J.COSUST.2020.01.005

Wood for Good, 2023. Wood for Good Lifecycle Database. BRE. URL https://woodforgood.com/lifecycle-database/ (accessed 3.15.23).

Zadeh, P.A., Wang, G., Cavka, H.B., Staub-French, S., Pottinger, R., 2017. Information Quality Assessment for Facility Management. Adv. Eng. Informatics 33, 181–205. https://doi.org/10.1016/J.AEI.2017.06.003

Zhu, K., Victoria, M., Brown, T., Andresen, G.B., Greiner, M., 2019. Impact of CO2 prices on the design of a highly decarbonised coupled electricity and heating system in Europe. Appl. Energy 236, 622–634. https://doi.org/10.1016/J.APENERGY.2018.12.016

Zupic, I., Čater, T., 2015. Bibliometric Methods in Management and Organization. Organ. Res. Methods 18, 429–472. https://doi.org/10.1177/1094428114562629

Chapter II

Literature review on sustainable and circular buildings

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II. Literature review on sustainable and circular buildings

Circular economy in the building and construction sector: A scientific evolution

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Keywords: Circular economy; Building; Construction sector; Science mapping; Bibliometric analysis; Sustainable development

II.1 Introduction

The building and construction sector is a key area that has significant impacts on the economy and environment (Zuo and Zhao, 2014). This sector contributes to the economy (about 9% of the EU's Gross Domestic Product (GDP)), provides direct and indirect job opportunities (18 million direct jobs at the EU) and satisfies the people's needs for buildings and facilities (European Commission, 2016; Zhao et al., 2019). Moreover, this sector is one of the main consumers of resources: about 50% of the total use of raw materials, and 36% of the global final energy use (IEA, 2019; Pérez-Lombard et al., 2008). As this sector accounts for 39% of the energy and process-related emissions and the agents of acid rain, the continuation of these greenhouse gas emissions at the same rate will certainly lead to a problematic situation (Allouhi et al., 2015; IEA, 2019). Therefore, any effort concerning global climate change and cleaner production should include this industry as a major player (Geng et al., 2017; Wu et al., 2014).

In addition to these environmental impacts, the construction and demolition projects are also responsible for about a third of the total waste generated in the EU, with a significant share being landfilled which creates serious environmental problems during the entire lifecycle of buildings, especially during the operation and end-of-life stages (Ghaffar et al., 2020). Moreover, it is predicted that with the current population growth rate, the middle class will increase from 2 billion to over 4 billion people by 2030 (Kharas, 2017). Therefore, there is a need to build more urban capacity than has been built in the past 4,000 years to secure progress, contemporary and future well-being (Eberhardt et al., 2019). Another important issue is the price-increase of raw materials which pushes the building industry for using efficient resource alternative materials, for example by reusing and recycling (Eberhardt et al., 2019; Kylili and Fokaides, 2017). In this context, it can be concluded that there are an urgent need and pressure in the construction industry to shift from the current paradigm into a more sustainable one with a focus on adopting the circular economy approach to ensure a more sustainable building sector (Munaro et al., 2020; Núñez-Cacho et al., 2018; Panteli et al., 2018).

The concept of the Circular Economy (CE) , evolved from industrial ecology (Jacobsen, 2008), tries to bring under one name a collection of pre-existing ideas from various scientific fields with shared qualities and characteristics, *e.g.,* industrial ecosystems and industrial symbioses, the 3Rs principle (reduce, reuse and recycle), cleaner production including manufacturing systems' circular materials flows, product-service systems, eco-efficiency, cradle-to-cradle design, green growth, biomimicry, natural capitalism, resilience of social-ecological systems, the concept of zero emissions and others (Eberhardt et al., 2020; Ellen MacArthur Foundation, 2016; Ghisellini et al., 2016; Korhonen et al., 2018). The CE paradigm is proposed to change the current production and consumption pattern of "take-make-dispose" that is threatening the sustainability of human life on earth and is approaching the planetary boundaries (Rockström et al., 2009). Steps in this direction require closing the loops by reusing wastes and resources as well as slowing material loops by developing long-lasting, reusable products (Ajayabi et al., 2019; Bocken et al., 2016; Leising et al., 2018). The development and implications of CE are still progressing (Hossain et al., 2020), and there is no single definition of CE because of its interdisciplinary nature (Hart et al., 2019; Yuan et al., 2006). According to the literature review on CE in the building industry by Benachio et al. (Benachio et al., 2020), the most cited sources of CE definition are established by the Ellen MacArthur Foundation (EMF), as "restorative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles" (Ellen MacArthur Foundation, 2015a), and in the next places are the definitions proposed by Lacy and Rutqvist (Lacy and Rutqvist, 2016), Pomponi and Moncaster (Pomponi et al., 2017), Geissdoerfer et al. (Geissdoerfer et al., 2017), and Leising et al. (Leising et al., 2018), respectively. Despite this lack of a generally accepted definition of CE, there is wide agreement among scholars and practitioners that CE enhances the life cycle of components, materials and products through reuse, repair, recycling, remanufacture, and refurbishing (Zacho et al., 2018). In this paper, we embrace a definition of CE proposed by Kirchherr et al. (Kirchherr et al., 2017): "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks), and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers".

The basic CE concepts of reduction, reuse, and recyclability of materials and components have been already widely implemented successfully from electrical equipment and furniture to textilles, but its application in the building sector has a shorter history and to a lesser extent (Ellen MacArthur Foundation, 2013; Ghisellini et al., 2016; Pomponi et al., 2017), basically limited to waste prevention and material management (mainly focused on recycling) (Di Biccari et al., 2019). The construction sector has been known as one of the three sectors with a high potential to implement CE strategies (Ellen MacArthur Foundation et al., 2017), particularly through the adoption of eco-friendly products and technologies (Smol et al., 2015). The adopting of CE principle in the construction industry promotes the using of sustainable materials, maximizing material recovery, and avoiding unnecessary waste generation and waste disposed to landfill (Akanbi et al., 2018; Ghisellini et al., 2018; Herczeg et al., 2018). It is expected that by applying CE principles in the European built environment, it is possible to save €350 billion through resource and energy savings by 2030 (Ellen MacArthur Foundation, 2015b). However, this sector is characterized by strong project-based institutionalized practices and market mechanisms, which in many aspects do not facilitate the inclusion of CE principles (Eberhardt et al., 2019). For building projects, the accomplishment of the project needs inputs from a high number of stakeholders within a complex supply chain, where each chain-echelon contributes to environmental impacts and cost of the building production (Eberhardt et al., 2019; Nasir et al., 2017; Winkler, 2011). In this context, it is clear that governments must play their key roles by dictating relevant guidelines and policy interventions to support CE transition in the construction industry (Hossain et al., 2020).

In the literature, there are review papers and bibliometric research dealing exclusively with CE such as (Benachio et al., 2020; Deus et al., 2017; Gregorio et al., 2018; Homrich et al., 2018; Mas-Tur et al., 2019; McDowall et al., 2017; Nobre and Tavares, 2017; Türkeli et al., 2018), and the relation of CE with various other concepts such as built environment (Gallego-Schmid et al., 2020; Hart et al., 2019; Munaro et al., 2020; Ruiz-Real et al., 2018), industrial symbiosis (Lopes and Farinha, 2019), industrial ecology (Saavedra et al., 2018), green and bio-economy (D'Amato et al., 2017), demolition waste sector (López Ruiz et al., 2020), and sustainability (Geissdoerfer et al., 2017). However, to date, to the best of our knowledge, there is no work published assessing systematically and quantitatively the scientific evolution of literature referring to the theory and practice of CE in the building and construction industry from a bibliometric perspective. To contribute to fulfilling this limitation, this paper aims to detect the characteristics of worldwide literature of the CE in the field of interest through statistical analyzing the scientific works published in Web of Science (WoS) and Scopus databases from 2005 to 2020. Moreover, in the present work, the records are collected from both Web of Science (WoS) and Scopus databases that result in having a more extensive global perspective of bibliometric data (Rodríguez-Soler et al., 2020), as well as eliminating any dependency of the results on the database (Mongeon and Paul-Hus, 2016). Hence, another novelty of this work is to detect the characteristics of a large volume of literature published in the field of interest at the two of the most influential databases.

This study provides a summary of the status quo of the global research on CE implementation in the building industry, including the scientific publication growth, the most influential authors, institutions, countries, and journals as well as the degree of existing academic collaboration between researchers, institutions, and countries. Moreover, science mapping, including the word-clustering analysis, frequency, and co-occurrence analysis of keywords were conducted to explore the intellectual structure of a field and to seek the emerging and hot research lines and the historical developments of the topic. The findings of this article could prove useful for the academic community in identifying the gaps and potential opportunities in the current knowledge and suggesting the pathway for future research. The knowledge generated by the present study, for example, the data regarding collaborations, may also provide a handy tool for investigations or policies that aim to approach the topic with the support of specialized groups (Rodríguez-Soler et al., 2020).

II.2 Methodology

There are several review methods for analyzing the existing literature, such as critical review, literature review, meta-analysis, systematic search, and review (Grant and Booth, 2009). Bibliometrics, as a systematic quantitative literature review, follows a transparent detailed systematic method and more importantly the reproducible process of review to collect and systematize information (Pollack and Adler, 2015), while as of its quantitative nature, it is objective-oriented and includes statistical analysis of bibliometric data (Grant and Booth, 2009). This method can be used particularly for trans-disciplinary research to identify the geographic, scalar, theoretical, and methodological gaps in the literature (Pickering and Byrne, 2014).

Scholars assess the impact of units (*e.g.*, researchers, institutions, countries, publications and sources) in three main metrics of productivity (assess how productive the units are), impact (measure the impact of units on other units), and integration of productivity and impact using several bibliometric indicators, such as publication count, citation count, the cites per paper and citation thresholds (Merigó and Yang, 2017), the h-index (Alonso et al., 2009; Hirsch, 2005), the g-index (Egghe, 2008), the m-quotient (Hirsch, 2010). These methods complement each other rather than being alternatives to one another (Zupic and Čater, 2015). Still, so far, the most popular indicators are the number of publications, citation count, and h-index (defined as the number of publications of an author/journal (say h) that has received at least h times citation) (Michael Hall, 2011). In this study, in addition to these three indicators, the average number of citations per document, the m-quotient, and g-index parameters are reported. The m-quotient, the result of dividing the h-index number by the scientific age of a scientist, eliminates the dependency of the h-index on the duration of each scientist’s career (Choudhri et al., 2015; Hirsch, 2010). The g-index, which can be seen as averaged h-index, overcomes the shortcoming of the h-index in accounting for the performance of the author's top articles (Choudhri et al., 2015).

In this study, co-word, co-citation, and co-authorship analyses were adopted. A brief description of each is presented below:

- Citation analysis: in a scientific article, the authors cite the related literature to support their arguments (Pilkington and Meredith, 2009). This citation indicates the relevancy of the citing and the cited document, and thus, citation analysis can help in identifying the main authors, literature, journals, source countries or institutions (Goodwin and Garfield, 1980).

- Co-citation analysis: it shows the frequency in which two documents are cited together simultaneously by another document (Kessler, 1963). This method, therefore, works as an indicator of how much two works share related subjects. Co-citation analysis can map the intellectual structure of a research field (Pilkington and Meredith, 2009). It is possible to identify the core themes of a research field by analyzing the links in a cluster of articles, mapping the links, and establishing the importance and proximity of topics (Chai and Xiao, 2012; Ji et al., 2018).

- Co-authorship analysis: it examines the authors and their affiliations, to discover academic collaborations, collaborative behavior, and the schools of thought (Liu et al., 2005). Data about collaborations could be useful for investigations and policies aiming to approach the topic with the support of specialized groups (Donthu et al., 2020). Moreover, this method has been used to investigate the development of a field (Liu and Xia, 2015), to identify the subdisciplines of the interdisciplinary field of a field, and to investigate trends in collaboration and productivity between subdisciplines (Glynatsi and Knight, 2021; Youngblood and Lahti, 2018).

In the present study, we adopted a similar approach as the method proposed in Aria and Cuccurullo (Aria and Cuccurullo, 2017), and Zupic and Čater (Zupic and Čater, 2015), where five stages of (i) conceptualization of research, (ii) collection of bibliometric data, (iii) analysis of collected data, (iv) visualization and (v) interpretation have been followed. In the first step, the research questions and the proper bibliometric methods are defined (Aria and Cuccurullo, 2017). As partially shown in Figure II.1, in data collection, the search query, the database that contains the bibliometric data, the document filtering criteria, and exporting data from the selected database are carried out. Then the required preprocessing measures, including data cleaning and screening, are followed. One or more bibliometric or statistical tools can be utilized to conduct the data analysis. Later, in the data visualization step, the scholar should choose the visualization method and the appropriate mapping software. Finally, the scholars analyze and describe the findings (Aria and Cuccurullo, 2017).

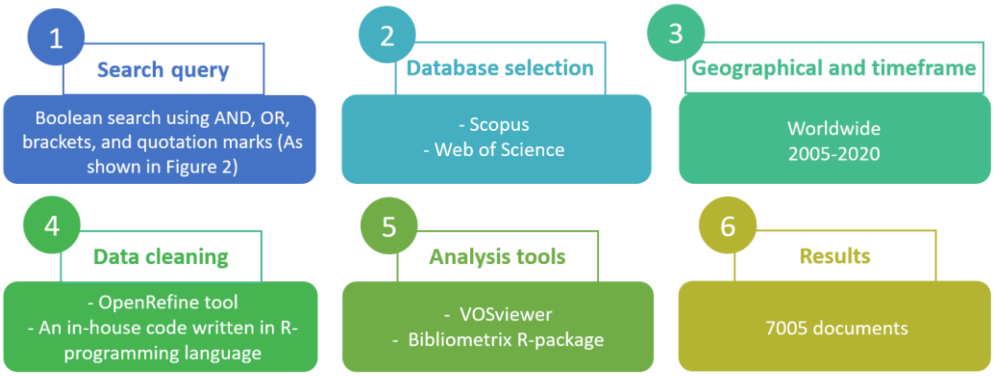

Figure II.1: The methodological framework of the bibliometric analysis.

II.2.1 Search query

In the bibliometric analysis, the identification of search keywords is one of the most important stages as it has major impacts on the results of the study. In most of the cases, scholars consider the search query by (i) using the generic literal concepts (*e.g.*, “circular economy” (Deus et al., 2017; Merli et al., 2018)); (ii) using wildcards to represent different combinations of characters in construction of a query (*e.g.*, “circular econom*” (Nobre and Tavares, 2017)); (iii) using the expert-driven semantically-related terms, to identify an extended collection of keywords (Linnenluecke et al., 2020). We use a combination of all three above-mentioned choices.

A preliminary publications retrieval was performed using the search query TS = “circular econom*” AND (“building*” OR “construction*”), in the “Topic” field of WoS Core Collection, for journal articles (the Boolean operators “AND” is used to link the two fields and “OR” is employed to combine the two fields). In accordance with Nobre and Tavares (Nobre and Tavares, 2017), we found that many articles containing the terms semantically different, but with the same meaning, were missed since the search query did not include the corresponding required terms to record them (*e.g.*, the term “circulatory economy” or “circular supply chain”). Moreover, the publication related to the CE does not necessarily use this expression to describe the underlying phenomenon in their body (Blomsma and Brennan, 2017; Hart et al., 2019). Thus, an extensive literature review was conducted to find different definitions and classifications to complete the collection of keywords.

Based on (i) the literature review conducted, specifically those reporting various definitions of CE by Kirchherr et al. (Kirchherr et al., 2017), and CE in the construction industry (Ellen MacArthur Foundation, 2015a; Geissdoerfer et al., 2017; Lacy and Rutqvist, 2016; Leising et al., 2018; Pomponi et al., 2017), (ii) the list of keywords proposed by Nobre and Tavares (Nobre and Tavares, 2017), (iii) the keywords collection obtained from our preliminary exercise on the publications retrieval (as detailed in the previous paragraph), the authors proposed to use a formulated search query containing three main parts (see Figure II.2). The first part (TSA), includes the terms and concepts semantically related to the circular economy; the second part (TSB), encompasses a semantic set of keywords related to the building and construction; and the third (TSC), part consists of commonly used terms for the CE implemented buildings. The list of terms (TS), can be consulted in Appendix II.6.1.

$$TS = \left(\overbrace{\left(TS_1 \textbf{ OR } \left(\left(TS_2 \textbf{ OR } TS_3 \right) \textbf{ AND } TS_4 \right) \right)}^{\text{TS}_A} \textbf{ AND } \overbrace{\left(TS_5 \right)}^{\text{TS}_B} \right) \textbf{OR} \overbrace{\left(TS_6 \right)}^{\text{TS}_C}$$

$$TS_1 = \text{Circular Economy-like Terms (see Appendix 1)}$$

$$TS_2 = \text{List of Terms (see Appendix 1)}$$

$$TS_3 = \text{"Reduc*"} \textbf{ AND } \text{"Reus*"} \textbf{ AND } \text{"Recycl*"}$$

$$TS_4 = \text{"Sustainable"} \textbf{ OR } \text{"Sustainability"}$$

$$TS_5 = \text{"Building*"} \textbf{ AND } \text{"Construction*"}$$

$$TS_6 = \text{"Building Circularity"} \textbf{ OR } \text{"Circular Construction*"} \textbf{ OR } \text{"Circular Building*"}$$

Figure II.2: Search query used in both Scopus and Web of Science.

To define the logic query of the first part (TSA), the combination of keywords proposed by Nobre and Tavares (Nobre and Tavares, 2017), and Hossain et al. (Hossain et al., 2020) was used with modifications according to the conducted literature review. The together use of basic principles of the CE so-called 3R’s (reduce, reuse, recycle) in the logic query should be highlighted because when these terms are used separately, some out of the scope results are retrieved. The terms “sustainable” and “sustainability” were added according to our embraced definition of CE (Kirchherr et al., 2017; Nobre and Tavares, 2017).

Regarding the second part (TSB), the wildcards of the semantic set of keywords related to the building sector, “building*” and “construction*”, were used. Using these terms, leads to the inclusion of the most relevant studies, especially as the query would atomically include works with any noun phrasal combination of the aforementioned terms, *e.g.*, residential building, building materials, building information modeling (BIM), etc.

The third part (TSC), contains the three common expressions referring to the buildings that circular economy principles have been implemented on them, the so-called circular building: “*A building that is designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles*” (Pomponi et al., 2017).

There could still be some relevant articles missing from this study due to employing the search query proposed. However, after a number of trials to use various combinations of the keywords and by checking descriptive and co-word analysis of the datasets, we observed that the proposed search string provides a proper sample to capture the general research directions and different considerations of the field.

II.2.2 Database selection

The Web of Science (WoS) was the only tool for conduting bibliometric analysis until the creation of Scopus and Google Scholar in 2004 (Harzing and van der Wal, 2008; Harzing and Alakangas, 2016). However, the lack of quality control and low reliability of bibliometric results in Google Scholar raises questions about its suitability as a bibliometric tool (Aghaei Chadegani et al., 2013; Aguillo, 2012). Thus, WoS and Scopus, as the two most influential databases, remain today as the main sources for citation data (Aghaei Chadegani et al., 2013; Cabeza et al., 2020). A structural comparison of these databases can be found in Martín-Martín et al. (Martín-martín et al., 2019) and Echchakoui (Echchakoui, 2020).

In this study, the records are collected from both WoS and Scopus and then merged. Considering such a large dataset improves the analysis from: (i) having a more global perspective of bibliometric analysis (Rodríguez-Soler et al., 2020) (ii) eliminating any dependency of the results on the database used (Mongeon and Paul-Hus, 2016) (iii) following the good practice to “*supplement results retrieved from a citation database with additional publications to reach the desired level of completeness for the study at hand.*” (Ertz and Leblanc-Proulx, 2018; Zhao and Strotmann, 2015).

In the present study, the document type was restricted to scientific articles, proceeding papers, and reviews for the case of WoS Core Collection; and articles, reviews, conference paper, and conference reviews for the case of Scopus. The search query was employed in the "Topic" field of WoS Core Collection, and "title, abstract, keywords" field of the Scopus database. The timespan was set to 2005-2020.

II.2.3 Data cleaning

After gathering the records from both databases, the results from not relevant categories (*i.e.*, agriculture, biology, pharmacology, medicine, etc.) were removed. In addition, an extensive effort was done to check the relevancy of the results through skimming the records' title, abstract, resulting in the exclusion of some documents, *e.g.*, those related to infrastructures such as roads, bridges, tunnels, railways, airports, etc. The WoS and Scopus use different data frame to index documents bibliographic information, and therefore, a normalization of the field was performed. Moreover, un-related words (*e.g.*, generic terms, organizations names, and regional words) were excluded from the results. Finally, repetitive words are written in different ways (*e.g.*, singular and plural forms, abbreviations) were standardized and merged, for example, "Circular economy", "Circulating Economy", "Circularity", "CE", merged to "Circular economy". The above-mentioned data refining and preprocessing tasks were performed using OpenRefine tool.

Using an in-house code written in R-programming language (Team, 2018), the duplicate records were removed during preprocessing. The algorithm of duplication removal is based on the DOI, and the document's normalized term based on the title, first author last name, the first letter of the first author's first name, and the publication year (Ruiz-Rosero et al., 2019; van Eck and Waltman, 2017). As a result of the retrieval and refining procedure, 7005 documents were collected from the databases.

II.2.4 Research tools

The Bibliometrix R-package (Aria and Cuccurullo, 2017), an open-source tool written in R-language, was used to perform basic bibliometric citation analysis, comprehensive science mapping analysis as well as analyzing different architectures of a bibliographic collection through conceptual, intellectual, and social structures (Aria and Cuccurullo, 2017). Besides, VOSviewer (van Eck and Waltman, 2017) is used to map and visualize the networks, and to identify the structure of the study field.

II.3 Results and discussions

II.3.1 Global statistics

From the 7005 documents collected from the two databases, 55.9 % records were journal articles (3913), 14.6 % (1025) proceeding papers, and 23.4 % (1639) conference papers, and 6.1 % (428) reviews. Detailed information on the dataset is provided in Table II-1. In this table, the reported statistics for the sources, keyword plus, author’s keywords, and average citation per document are with taking all various types of documents into account. Publications were retrieved from 2355 scientific journals/repositories with an average of 2.7 authors per publication, and with a great majority (85%) multi-authored.

Table II.1. General information about the dataset collection of circular economy in buildings (2000-2019).

Description	**Results**
Type of documents	
Journal Articles	3913
Conference papers	1639
Proceedings papers	1025
Review papers	428
Sources (Journals, etc.)	2355
Keywords plus	17008
Author's keywords	12643
Average citations per documents	11.17
Collaboration index	3.06
Annual growth rate	21%

Figure II-3 indicates that there has been moderate growth in the production of literature from 2005 (64 documents) to 2008 (142 documents). However, the number of articles had been increasing significantly since 2008, reaching 1112 records in 2020 with an average annual growth rate of 18.5%. Since the creation of EMF in 2010, the initiatives and researches on the circular economy have become more intense, which contributes and confirms the high interest in the subject in the last five years.

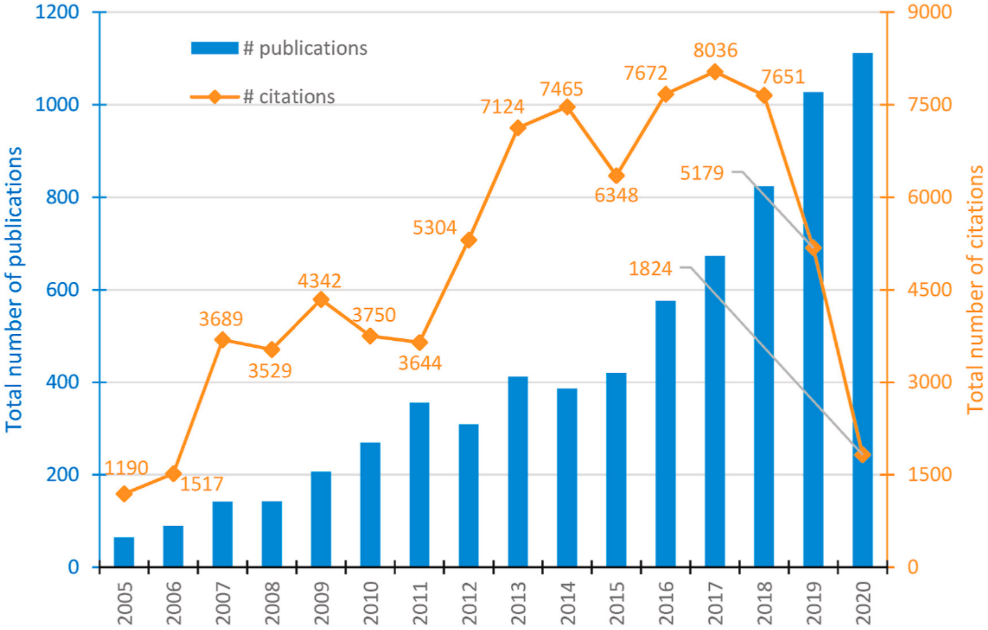

Figure II.3: Evolution of the number of publications and the total number of citations of circular economy in buildings (2005-2020).

Concerning the evolution of the number of citations, it is similar to the growth in the number of publications (Figure II-3). This evolution is generally increasing, with a growth rate of 11% (the highest growth rate in the number of citations was recorded in 2007) although several ups and downs can be seen. As illustrated in Figure II-3, the total citation number reached a peak of 8036 in 2017, then decreased gradually arguably due to the time required to get influence from the accumulation of new publications. It can be inferred that the topic has not arrived at its maturity stage yet and, likely, will continue to attract considerably more research. As a result of the number of publications and their citations over the period under analysis have been considered as a measure of scientific productivity, influence, and interest in the subject.

II.3.2 Country/area statistics

In the past 15 years (2005-2020), 122 countries or regions publish on the topic analyzed. Table II.2 lists the top 15 countries concerning the total number of publications, total citation, average citation per document, and h-index. Note that in this study, "UK" is a member of the European Union (EU-28) and it includes England, Scotland, Wales, and Northern Ireland, while "China" refers to mainland China, Hong Kong, Macao, and Taiwan.

Table II.2. Top 15 publishing countries in the circular economy in buildings (2005-2020).

Country	TP	TC	SCP	MCP	TC/TP	Local h-index
China	1234	10206	877	357	8.27	54
USA	741	14522	361	380	19.60	58
United Kingdom	615	15316	291	324	24.90	58
Italy	502	6368	344	158	12.69	39
Australia	292	5535	106	186	18.96	36
Spain	283	4015	159	124	14.19	32
Germany	251	3628	109	142	14.45	27
Netherlands	187	4089	80	107	21.87	32
India	186	2586	121	65	13.90	27
Canada	172	4877	83	89	28.35	32
Malaysia	161	1893	84	77	11.76	23
Brazil	146	1637	87	59	11.21	20
Portugal	141	2385	85	56	16.91	23
Sweden	133	2591	55	78	19.48	27
France	122	1938	40	82	15.89	23

TP = Total number of publications, TC = Total number of citations, SCP = Single country publications, MCP = Multiple country publications, Local h-index = h-index calculated from the dataset

Of the top 15 countries, eight were from Europe, three from Asia, two from North America, one from Oceania (Australia), and one from South America (Brazil), with any country from Africa. China contributes with 17.6% of the total of the publications, followed by the USA (10.6%). These top 15 countries are the leading players of this emerging topic, accounting for more than 70 % of the number of the publication. Worthy to note that the proportion of the articles that involve international collaboration is relatively high (> 27%), indicating that the topic is favorable for international cooperation.

As shown in Table II.2, China has contributed most to the body of research. This country, as the first country in the world to adopt a legislation for the development of the CE (De Pascale et al., 2021), has been making progress in implementing and developing CE concepts for decades, both in academia and in politics (Zhou et al., 2014). This prominence is linked to the related top-down laws, policies and regulations (J. Zhu et al., 2019), such as China's Circular Economy policies, Sustainable Development Goals (SDGs), Chinese indicator sets for the 13th Five Year Plan (2015–2020), the Green Development Indicator System, and the Ecological Civilization Construction Assessment Target System (Wang et al., 2020). Furthermore, high number of publications from European countries reflects the growing sustainability awareness building up in the continent, which is mainly due to the adopting the CE policy by the European Union (EU), *e.g.*, the circular economy package "*Towards a circular economy: a zero waste programme for Europe*" (European Commission, 2015) and "*Closing the Loop – An EU Action Plan for the Circular Economy*", and its inclination towards sustainability (Domenech and Bahn-Walkowiak, 2019). It seems that the CE-related policies and regulations have been influential in contribution of other top countries into the CE body of knowledge. In the USA, the dominant bottom-up political approaches have been adopted aiming to enhance circularity mainly through eco-industrial parks initiatives at a regional scale, mainly through eco-industrial parks initiatives at a regional scale (*e.g.*, in Baltimore, Maryland; in Brownsville, Texas; and in the Cape Charles Sustainable Technologies Industrial Park in the town of Cape Charles) (Heeres et al., 2004; Winans et al., 2017).

According to the average citations per paper, Canada, United Kingdom, Netherlands, the USA, and Sweden are the top five countries with prominent academic influence. These countries are also among the top nine countries concerning the local h-index, reinforcing their leading role in the research field. Although China held a leading position in the publication quantity, it is not well-ranked in the indicators related to the influence, which indicates that the quality of their publications varies considerably.

Figure II.4 presents the evolution of the number of documents published for the top 10 productive countries, showing in all cases an increasing trend. China has been the most productive country for all the periods, with two intense growth periods, starting in 2008 and 2015, respectively. Another important finding is the take-up trend for the CE related publications with contributions by EU countries in 2015. That could be partially explained by the European Commission (EC) strategy on CE, outlined in 2014 and a revised CE package in 2015 (European Commission, 2015).

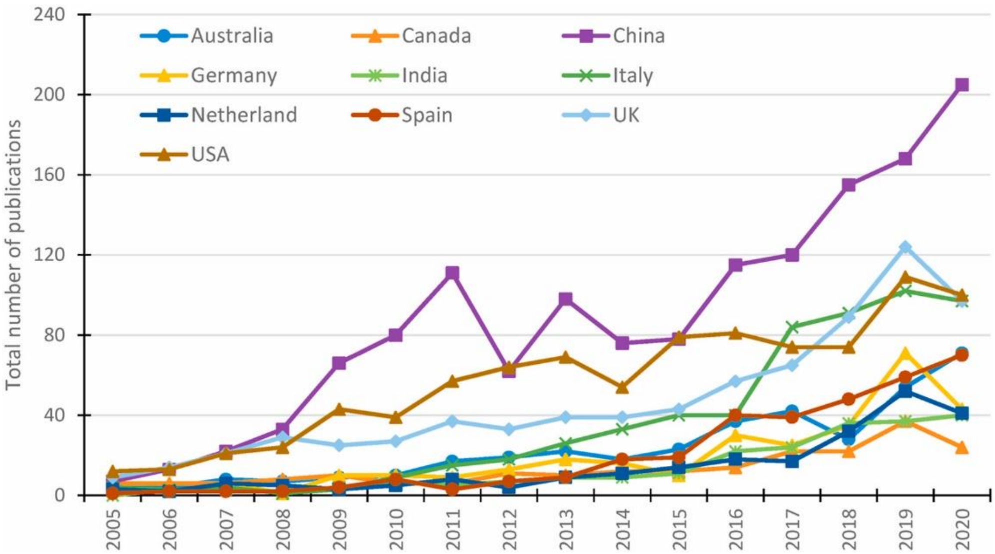

Figure II.4: Trends of publications of the main 10 productive countries in the circular economy in buildings (2005-2020).

Figure II.5 shows the academic interaction between countries through the joint publications based on the authors' affiliation, regardless of the author's order in the publication. In this figure, the node size and the thickness of the links are proportional to the number of published documents and the volume of publications the authors have published together, respectively. To facilitate the analysis, the map only considers countries that have collaborated in at least 25 documents. China, United Kingdom, United States, Australia, Netherlands, Germany, Italy, and Spain perform better than the average in international collaboration. The main interactions are between the European Union (EU) and the USA, followed by collaborations of the USA and China, the EU and China, and the Australia and China. From this collaboration networks, it can be concluded that the scientific research field of CE in buildings is highly international although the real cases and applications are local. While there are some exceptions, close collaborations between geographically proximate countries can be seen. In addition, except China, the developing and undeveloped countries have few cooperation with developed countries, implying that more cooperation between those countries with the developed countries should be encouraged to address environmental and resources issues at the global level.

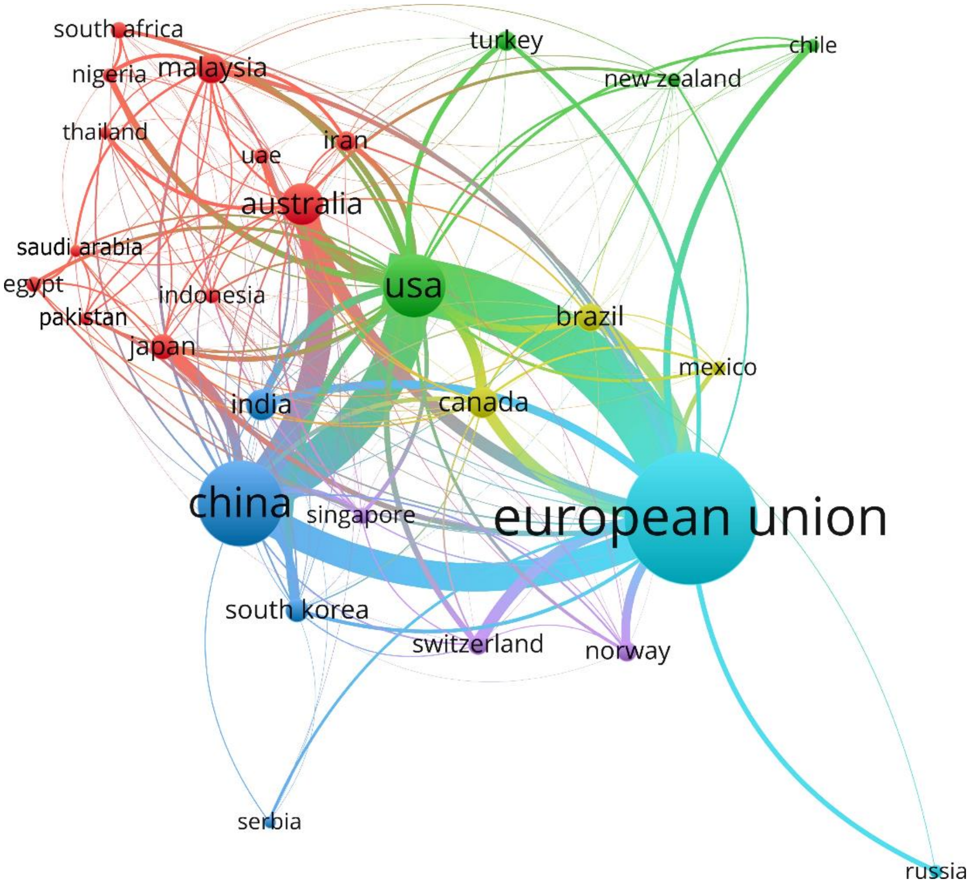

Figure II.5: Co-authorship interaction between countries in the circular economy in buildings (2005-2020).

Figure II.6 shows the interaction between EU countries. As expected, the five main publishing countries highly interact between themselves, share authorship with all the other countries, and form four clusters: (1) (1) the biggest (in blue) led by Italy, comprises Spain, Portugal, and Greece; (2) led by the UK, includes France, Belgium, Ireland and Luxembourg (in green); (3) led by Germany, includes the Netherlands, Austria, and Czech Republic (in red); and (4) led by Sweden, includes Denmark, Finland and Lithuania (in yellow).

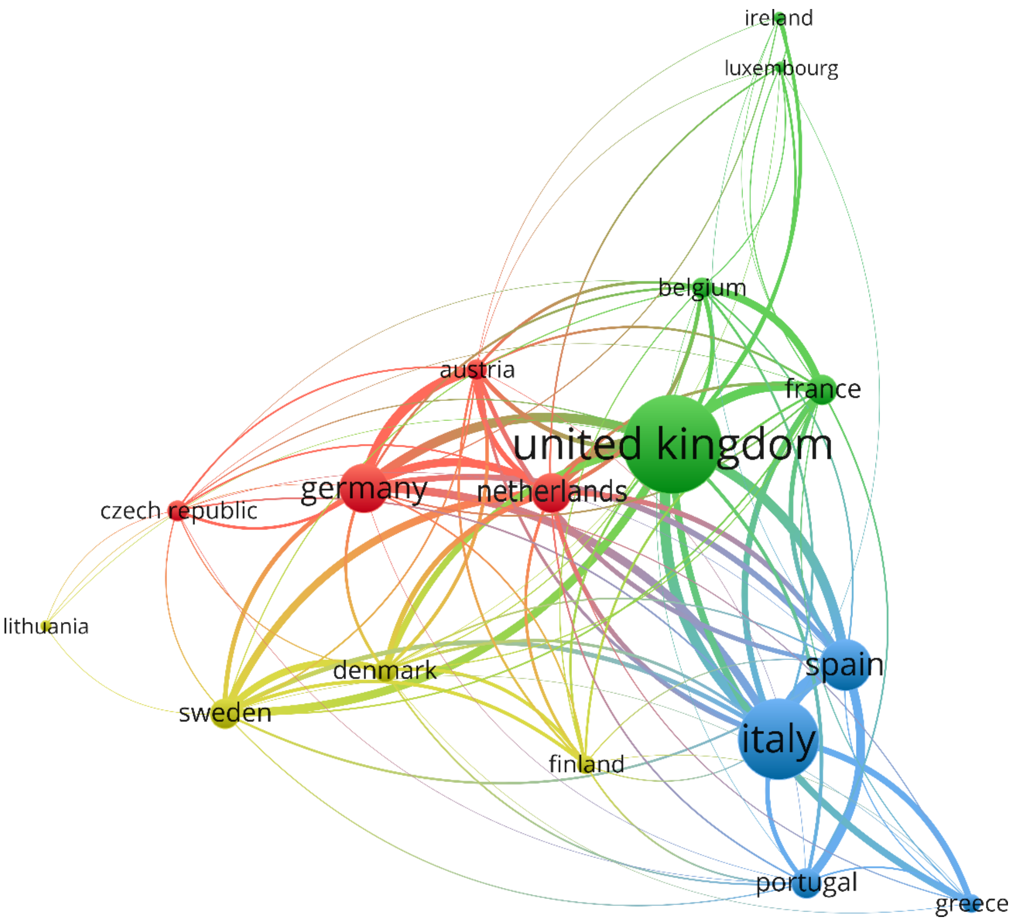

Figure II.6: Co-authorship interaction of EU countries in the circular economy in buildings (2005-2020).

II.3.3 Institution statistics

Many organizations from academia, government, and industry have an active role in the field analyzed. The top 15 productive organizations based on the number of publications are reported in Table A.1 in Appendix II.6.2. 12% of the articles were published by authors affiliated with these organizations. Among the 15 most productive research institutions, three are from China, two from Italy, two from Malaysia, and one from the Netherlands, UK, Norway, Iran, Sweden, Portugal, Spain, and Denmark. The Delft University of Technology has the largest number. Moreover, the geographical distribution of the top 15 most productive institutions is relatively limited, showing that the topic more attracted researches' attention among the developed countries and China.

Figure II.7 shows that the collaboration network between the leading research institutions, with a minimum threshold to appear in the graph of 25 documents published to facilitate the analysis. 39 institutions were identified, forming seven clusters, where each cluster mainly includes institutions from the same country or region. Two reasons could explain this observation: first, it is easier and common that researchers tend to work on topics particularly popular in that region; and second, the co-authorship, implying that two authors present a similar citation profile.

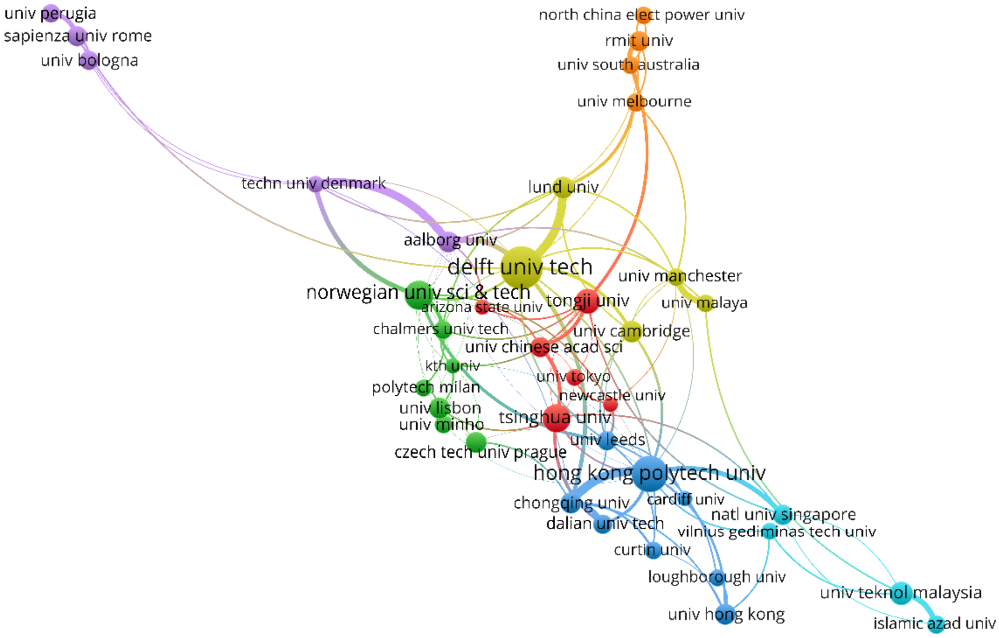

Figure II.7: Collaboration network of institutions in the circular economy in buildings (2005-2020).

II.3.4 Journals statistics

Publications in the field of CE in buildings are retrieved from a wide range of journals and different knowledge areas: 2355 journals and conferences. These journals are distributed in different knowledge areas such as environmental science, science and technology, energy, materials science, social science, and economics. This implies that CE theme has widely attracted the attention of many researchers in various fields as a relevant system to promote other areas environmentally and economically. Among the top 15 sources (see Table II.3), some of them are from a specific edition of the conferences: IOP Conference Series: Earth and Environmental Science; WIT Transactions on Ecology and the Environment; and International Multidisciplinary Scientific Geoconference Surveying Geology and Mining Ecology Management (SGEM). The top 15 productive ones publish 27% of the total publications (TP). In particular, the Journal of Cleaner Production (IF=7.246) was the most productive, with 409 publications (5.8%), followed by Sustainability (IF=2.576) with 347 articles (5%) and IOP Conference Series: Earth and Environmental Science with 283 records (4%). The Impact Factors (IFs) of the journals were collected from the 2019 Journal Citation Reports (JCR).

Table II.3. Top 15 source journals of the study in the circular economy in buildings (2005-2020).

Sources	**TP**	**TC**	**TC/TP**	**Local h-index**	**IF (2019)**	**IF (5 years)**	**Best quartile**
Journal of Cleaner Production	409	10508	25.6	48	7.246	7.491	Q1
Sustainability	347	2119	6.1	20	2.576	2.798	Q2
IOP conference series: Earth and Environmental Science	283	196	0.7	5	---	---	---
Energy and Buildings	115	4170	36.3	34	4.867	5.055	Q1
Resources Conservation and Recycling	106	2353	22.2	31	8.086	7.589	Q1
Renewable and Sustainable Energy Reviews	95	3988	42.0	34	12.11	12.348	Q1
Sustainable Cities and Society	82	1043	12.7	18	5.268	5.143	Q1
Construction and Building Materials	69	1827	26.5	20	4.419	5.036	Q1
WIT Transactions on Ecology and the Environment	57	54	0.9	4	---	---	---
Building and Environment	54	1556	28.8	22	4.971	5.459	Q1
International Multidisciplinary Scientific Geoconference Surveying Geology and Mining Ecology Management	53	32	0.6	3	---	---	---
Building Research and Information	51	1199	23.5	19	3.887	4.036	Q1

Energies	51	311	6.1	9	2.702	2.822	Q1
Waste Management	50	1313	26.3	20	5.448	5.997	Q1
Journal of Industrial Ecology	45	2310	51.3	22	6.539	5.883	Q1

TP = Total number of publications, TC = Total number of citations, TC/TP = Total citations per document, Local h-index = h-index calculated from dataset, IF (2018) = Impact Factor (2018 Journal Citation Reports®), Best quartile = Journals in the 25% top journals of a category are Q1.

The ranking of the source according to the h-index and number of citations are almost equal. In contrast, the conferences have low h-index and total citations per article (TC/TP), indicating their low impact in the community. The top three publisher according to TC/TP (Journal of Industrial Ecology, Renewable and Sustainable Energy Reviews, and Energy and Buildings), are ranked 15th, 6th, and 4th considering the number of articles, indicating a high quality of the publications of these journals.

II.3.5 Author statistics

To find the most relevant authors, some bibliometric indicators, such as the quantity of the author's publication, the number of citations received and h-index are used. After debugging the repetition of authors' names, Table II.5 in Appendix II.6.3 ranks the top 15 contributing authors based on the number of publications. Among them, four came from China, three came from Denmark, two came from Canada, and from Australia, South Africa, Portugal, Sweden, UK, and Spain (one author each).

The most productive author is Yong Geng from Shanghai Jiao Tong University (China), who authored 19 articles. He is also the second most influential author, cited 976 times (*i.e.*, 51 times each), and he has the highest local h-index (16). With respect to the number of publications, Chi Sun Poon with 17 records (13 local h-index) from The Hong Kong Polytechnic University, China and Vivian WY Tam with 16 records (7 local h-index), from the Western Sydney University, Australia, respectively. As shown in Table II.5 in Appendix II.6.3, Morten Birkved from the University of Southern Denmark, and Md Uzzal Hossain from the Hong Kong Polytechnic University, are the top-ranked authors with regard to the m-quotient parameter, meaning that they are emerging authors and their publishing productivity was continuing to increase over time and was developed to correct for the duration of author's career. Furthermore, Yong Geng and Chi Sun Poon have the highest g-index, highlighting a high citation count received by their top publications. A remarkable case is that of Nancy Bocken, who with 12 articles co-authored, with an average of

160 per paper. This is mainly due to three highly cited papers, one of them is one of the first review papers published in the domain, while the rests are original research.

The researchers should be aware of the existing collaborations in a research field to prevent from isolation and improve productivity (Hosseini et al., 2018). Figure II.8 illustrates the collaboration network of the key authors. The minimum number of authors' documents has been established on four, and authors without connections are not presented to facilitate the interpretation of the network map. The most influential authors from each cluster can be identified in most of the groups: Cluster 1, in red, is led by Yong Geng; cluster 2, in green, is led by Bijia Huang; cluster 3, in dark blue, is led by. Md. Uzzal Hossain; cluster 4, in yellow, is led by Chi Sun Poon; cluster 5 in light blue, is led by Jack CP Cheng; cluster 6, in orange, is led by Qinghua Zhu; and cluster 7, in purple, is led by Mingming Hu.

According to the affiliation of main authors in Figure II.8, it evident that the geographical centralization is in EU, Asia, and Australia, and therefore, it is required to conduct more research activities in other continents such as Africa, South America, and North America. Moreover, any research carried out across continents can additionally support cross-cultural awareness (Osobajo et al., 2020).

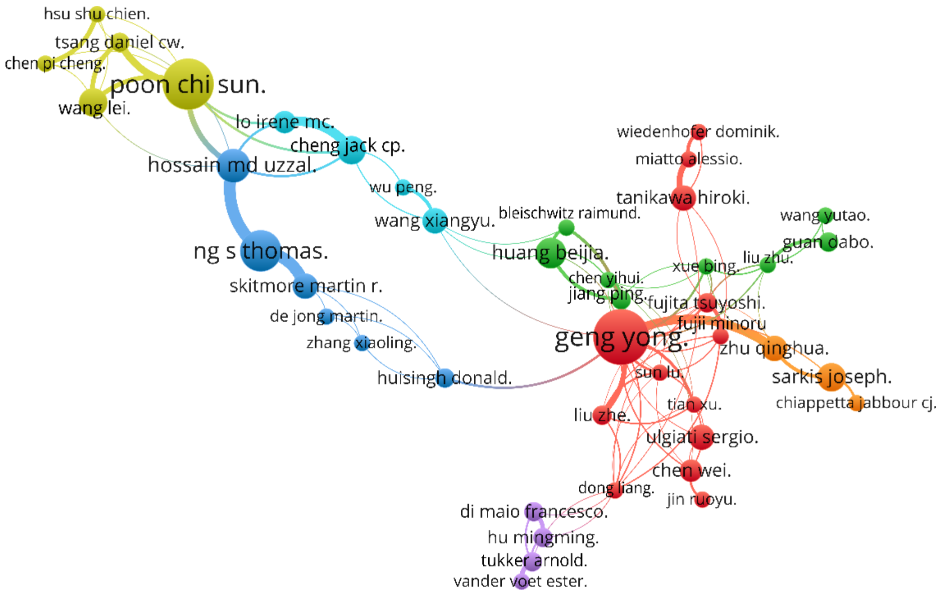

Figure II.8: Collaboration network of authors in the circular economy in buildings (2005-2020).

II.3.6 Research hotspots and evolution

The analysis of keywords in a research field provides an opportunity to discover some underlying information that sometimes is not self-evident. In this study, author keywords, rather than all keywords, were used to obtain a reproducible and readable analysis (Darko et al., 2019).

Meaningless words such as “research”, “problem”, “survey”, and so on, were removed. The keywords co-occurrence network was produced using VOSviewer software are shown in Figure II.9. The node size represents the frequency, and the relative position of terms in the map reflects their relative association. This bibliometric map is created for the minimum number of keyword occurrences of 37 and contains 69 nodes and 5681 links, grouped into five clusters: (i) energy and energy efficiency in buildings; (ii) recycling, waste management and alternative construction materials; (iii) sustainable development; (iv) circular economy in urban regions; and (v) green buildings and green supply chain within the construction industry. The list of all terms above the threshold is shown in the appendix (Table II.6 in Appendix II.6.4). As can be seen, the map also identifies subtopics of the circular economy, such as recycling, reuse, waste management, energy, and energy efficiency. It also incorporates other concepts that are cross-fertilized with CE, such as industrial symbiosis, industrial ecology, sustainability, and sustainable development.

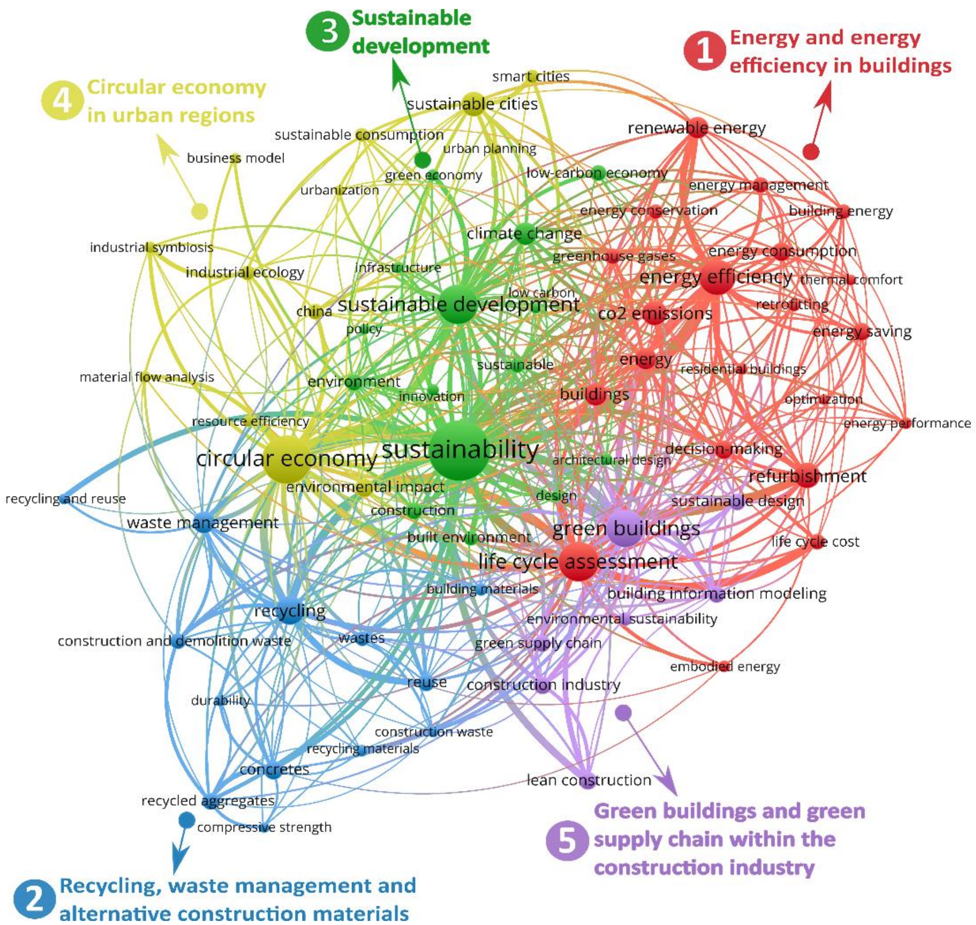

Figure II.9: Map based on co-occurrence on the authors keywords in the circular economy in buildings (2005-2020).

Cluster #1, in red in Figure II.9, is the most significant cluster with 21 keywords (see Table II.6 in Appendix II.6.4). The main concerns of this cluster are energy and energy efficiency in the buildings and their corresponding environmental questions, as can be concluded from the terms “energy”, “energy efficiency”, “renewable energy”, “energy consumption”, “energy management”, “buildings”, “building energy”, “energy saving”, “energy performance”, “energy conservation”, “renewable energy”, “embodied energy”, and regarding environmental impacts from “greenhouse gases”, “CO_2 emission”, and “life cycle assessment”.

Focusing on the use of energy in the building is of high importance since the buildings (residential, commercial, and public) are responsible for consuming approximately 60% of global energy (Soares et al., 2017b). Energy is the main input during the whole life of buildings as it plays a key role in their functioning during their use. The environmental impacts as associated with energy use correspond to 10% of global

GHG emissions (Soares et al., 2017b). Improving the energy efficiency is probably the most relevant strategy to increase the life cycle of buildings, resulting in improved living conditions (*e.g.*, occupants' wellness by dealing thermal comfort), lower energy costs for occupants (Cabeza and Chàfer, 2020; Dascalaki et al., 2016), and reduction of environmental impacts caused by building construction and operation (*e.g.*, CO_2 emissions) (Nagy et al., 2015). Holding a building LCA provides a suitable tool to evaluate options for CE solutions, helping decision-makers to minimize the environmental impact, carbon emission, energy and cost during the whole life cycle of the building (Haupt and Zschokke, 2017; Khasreen et al., 2009; Mhatre et al., 2020).

The appearance of the terms "refurbishment", and "retrofitting" may suggest that performing energy retrofitting of the existing buildings, as well as building refurbishment and renovation can help to meet the concerns of the cluster.

Cluster #2, in blue in Figure II.9, has 13 nodes. The key terms of this cluster and their frequency of occurrence are presented in Table II.6. This cluster concerns mainly on recycling, waste management, and alternative construction materials in the building industry, as can be inferred from "recycling", "waste management", and other terms "recycled aggregates", "recycling materials", "recycling and reuse", "wastes", "construction waste", "construction and demolition waste", and "building materials".

Many academic studies, stakeholders organizations, as well as government legislation in recycling and waste reduction, argue the possibility of a substantial reduction in environmental impacts of building and construction materials through producing durable products and the greater use of reused/recycled materials/systems instead of natural resources during the production phase (Lu et al., 2018; Moh and Abd Manaf, 2017). This is more and more relevant given the increment in the off-site fabrication of building systems, and the application of advanced technologies in production plants. For instance, it is estimated that the production of cement accounts for 5-7% of the CO_2 generated by human activities and, therefore, the substitution of cement with fly ash or other pozzolanic materials in concrete production reduces its carbon footprint (Van Den Heede and De Belie, 2012). According to Núñez et al. (Nuñez-Cacho et al., 2018), waste management is one essential of the scales for measuring the CE in the construction sector that can be quantified by assessing the extent to which reducing waste generation, improving the recycling rate of solid waste, reducing the production of hazardous waste, efficient waste management, taking measures to prevent, recycle and eliminate waste, using a bill of solid waste for the manufacturing process.

Cluster #3, in green in Figure II.9, has 15 key terms (Table II.6 in Appendix II.6.4). The main objective of the articles within this cluster is sustainability while giving the solution to mitigate the environmental impacts. The CE model has been considered as a means for achieving sustainability, and it is perceived as sustainable, which can be inferred from "environment", "climate change", "green economy", "low-carbon economy", and "low carbon" (Heinrichs, 2013; Piscicelli et al., 2015). A sustainable building, in principle, should adopt a triple bottom line approach that addresses the economic, social, and environmental aspects of the entire building life cycle (Piscicelli et al., 2015). Achieving high-performance, low-environmental impact sustainable buildings can be followed from many aspects, including sustainable materials, sustainable operations, sustainable services, and sustainable consumption to integrate concepts of sustainability in any part of the lifecycle of a building. Here, the importance of two contested topics of technology and innovation for approaching sustainable development should be emphasized. To link economic growth with the state of the art of technology, innovation plays a central role as it can propose solutions to expand the limits of economic growth while considering that the availability of resources is finite (Franceschini et al., 2016; Hekkert et al., 2007).

Cluster #4, in yellow in Figure II.9, is formed by 15 key terms (Table II.6 in Appendix II.6.4). Papers within this cluster focus in CE applied to city areas and urban regions, as can be inferred from "circular economy", "industrial symbiosis", "material flow analysis", "sustainable cities", "smart cities", "urban planning", "urbanization", and "transportation". The high frequency of "China" implies that this country is intensely concerned about the application of circular economy concepts in building and urban development.

"Industrial symbiosis (IS)" is a subset of the academic term "industrial ecology (IE)" which again is a subset of the "circular economy" umbrella (Danielsson, 2017). IS is a key concept in moving towards sustainable development as it is linked to resource depletion, waste management, and pollution (Baldassarre et al., 2019). IE studies industrial systems and aims to identify and implement strategies that reduce their environmental impacts. One of the main focuses of the industrial ecology perspective is on quantitative evaluation of positive environmental impacts of IS using Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) (Massard et al., 2014).

Regarding city and urban development, to promote a CE of the construction sector, building design and technologies should be focused to reach the maximum amount of reduction, reuse, and recycling of material, practical strategies for energy cascading and symbiotic exchange of resources among different firms, industrial sectors, cities and regions (Fernández, 2007).

Cluster #5, in purple in Figure II.9, is the smallest, contains seven nodes (Table II.6 in Appendix II.6.4). The main objective of this cluster is the green buildings and green supply chain applied to the building industry, as can be concluded from the "green buildings", "green supply chain", "construction industry", "lean construction", "sustainable design", and "environmental sustainability".

Green buildings are designed and constructed following ecological principles (Kibert, 2012) and have minimal influence on the natural environment and human health (Yudelson, 2008), usually consume considerably fewer resources than regular buildings, and promote occupants' productivity, comfort, and satisfaction by providing quality thermal comfort (Darko and Chan, 2016; Worden et al., 2020). The concept of lean construction shares the same goal as green buildings, and it emphasizes on the importance of reducing wastes, optimization of flows, and eliminating unproductive and unfruitful processes to approach sustainability objectives (Ahuja, 2013; Solaimani and Sedighi, 2020).

As suggested by Sarkis et al. (Sarkis et al., 2011), basically green supply chain is about the integration of environmental considerations into the supply chain, including the material flows reduction and the minimization of inadvertent negative consequences of the production and consumption processes (Badi and Murtagh, 2019). According to Balasubramanian (Balasubramanian, 2014), green supply chain management in construction is based on three dimensions: environmental, economic, and operational performance. Addressing the processes involved in construction from an operational perspective, the green supply chain management includes "green purchasing, green manufacturing, green distribution (marketing) and reverse logistics" (Adawiyah et al., 2015; Badi and Murtagh, 2019).

Figure II.10 shows the research trends based on the keywords analyzed, including the top five most-used author's keyword per year. A minimum threshold frequency of five has been applied. As a general finding, and in agreement with Figure II.3 and Figure II.4, the perspectives of the topic are huge and it has a high potential for more and deeper research works.

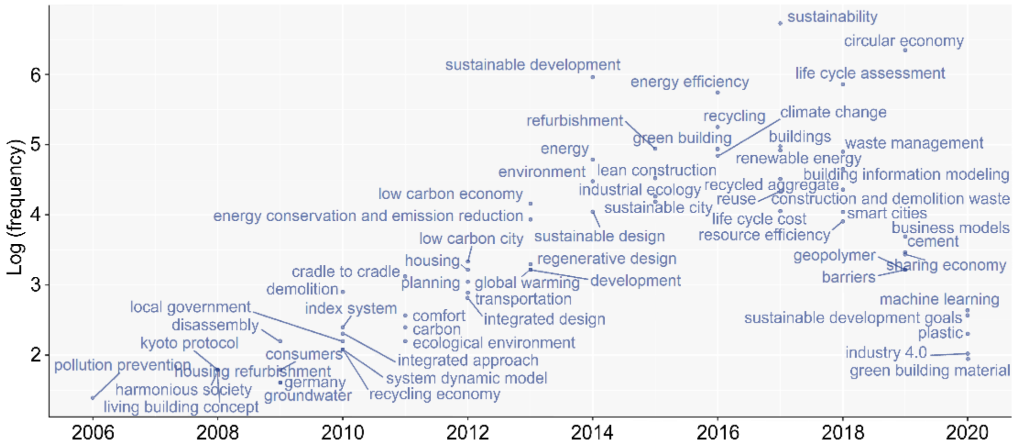

Figure II.10: Map based on authors keywords for trending topics in the circular economy in buildings (2005-2020).

In the beginning, from 2006 to 2013, the key areas of research were mainly related to CE adoption measures, policies, and frameworks at different levels of countries, regions, etc., as well as the importance of the circular economy from the purely environmental aspects (Hossain et al., 2020). During 2013-2018, the researchers have focused on the challenges of CE-enabled design as an early-stage measure to promote circulatory, *e.g.*, through design for disassembly and deconstruction using design tools (*e.g.*, BIM) (Mhatre et al., 2020). In the same period, *i.e.*, 2013-2018, addressing the concerns of sustainability and sustainable development as well as energy and energy efficiency within the context of the building industry have been other research areas that have attracted a lot of researchers. Since 2016, there has been some research on introducing potential methodologies for CE evaluation, such as using the LCA framework for evaluating the quantifiable benefits in terms of environmental impacts and associated costs, and materials flow analysis (MFA) for assessing the flow of materials during the entire life cycle (Hossain et al., 2020). However, there is still a lack of clear mythology and a comprehensive set of indicators to evaluate the CE adoption in sustainable building construction. Recently, 2017-2020, the researchers have focused mainly on (i) material selection, aiming to choose or substitute the construction materials with more circular materials, (ii) development of circular business models, and (iii) the relation of CE with new technologies. These three research areas are detailed below as the research hotspots.

As shown in Figure II.10 and Cluster #2 (in blue) of Figure II.9, the current leading edge of the literature is the development and the use of alternative construction materials in the building and construction industry (Corinaldesi and Moriconi, 2009; Det Udomsap and Hallinger, 2020). The increasing use of green building materials, bio-materials, various types of aggregates in cement, concrete and asphalt, geopolymers, fly ash, solid wastes, plastic and foam, and concrete recycled from demolished buildings can be interpreted in this direction (Benachio et al., 2020; López Ruiz et al., 2020; Mair and Stern, 2017; Pearlmutter et al., 2020). The production and processing of these materials should lead to lower environmental impacts and decrease the use of harmful chemicals (Pearlmutter et al., 2020). Thus, their use can make a significant contribution in the transition to a circular economy.

Another hot topic is the development of circular business models within the building and construction industry (Benachio et al., 2020; Nußholz et al., 2019), as emphasized with the recent use of the related terms to “business models” in Figure II-10. The current business models in the field are still based on the linear use of resources (BAMB, 2017), and therefore, there is a big need for researching on CE from a systems perspective within the field, including the investigation of using new business models in enabling materials to retain high residual values (Benachio et al., 2020; Høibye and Sand, 2018).

The other research hotspot is about the link between CE and the Fourth Industrial Revolution (Industry 4.0) in the context of the construction industry. Industry 4.0 is a combination of Cyber-physical systems, Internet of Things, Big data, and Cloud Computing, which has made possible the human-machine interconnection utilizing the information generated from different smart devices (Rajput and Singh, 2019). Industry 4.0 is nowadays considered as a key innovative technology in the transformation from linear to the circular economy in the manufacturing industry (Rajput and Singh, 2019). Industry 4.0 can reduce the emission and resource from the industrial systems by optimizing the sustainable solutions (Tseng et al., 2018), and its integration with CE can contribute towards achieving the sustainable development goals (Dantas et al., 2021).

Another featured topic addressed recently is smart cities and its relation to CE and industrial symbiosis. The smart city modelled around the CE principles brings together technology, government, and society within an urban context, promoting sustainable development, and with a little impact on the environment nature (Bibri and Krogstie, 2017; Borghi et al., 2014; Yigitcanlar et al., 2019). As can be concluded from Figure II.10 and the Custer 4 (in yellow) in Figure II.9, and also highlighted by Borghi et al. (Borghi et al., 2014), the future research in smart cities should be directed towards industrial symbiosis, through the development and implementation of tools for regenerative systems and symbiotic business links.

Figure II.10 also shows that the concepts of “waste management”, “life cycle cost”, “recycling”, “reuse”, “recycled aggregates”, ”building information modeling”, the use of “renewable energies”, and improving “energy efficiency” and “resource efficiency" have been among the top authors' keywords in the last five years (2016-2020). These findings along with the keyword co-occurrence network of Figure II.9 emphasize the fact that waste management is well intertwined with CE (Esa et al., 2017) This is because of closed-loop nature of CE which implicates recycling and reuse as well as the shift from raw materials and fossil fuels to renewable energies, resulting to the improvement of resource and energy efficiency, wherein recycling serves as a generalized strategy to reach the goals of CE (Haas et al., 2015).

II.4 Conclusions

In the present study, different bibliometric methods were used to analyze 7005 publications of the circular economy within the building and construction sector for 2005-2020. In this regard, the records extracted from WoS and Scopus were merge and were analyzed consequently using Bibliometrix R-package and VOSviewer.

The number of publications has continuously increased with an average annual growth rate of 21%. During the first years, the publication growth was lower, however, since 2014 it has encountered a significant increase. This recent acceleration indicates that CE in the construction sector is a hot area that is receiving more and more attention. Results showed that China is the country with more publications (18% of total) but it has a low number of citations per documents, indicating that the impact varies considerably. In terms of the number of publications, the USA (741) and United Kingdom (615) are ranked second and third, respectively. The Delft University of Technology is found to be the most productive institution followed by Hong Kong Polytechnic University. The majority of the top 15 institutions showed a cooperative relationship with other institutions. Among the authors, Yong Geng (19 publications, local h-index = 16), Chi Sun Poon (17 publications, local h-index = 17), and Vivian WY Tam (16 publications, local h-index = 7) are the most prolific authors. Besides, from the collaboration networks, it concluded that the scientific research field of CE in buildings is highly international although the real cases and applications are local. Therefore, international co-authorships, co-funding, and policy co-programming are relevant for policy options and agendas. In terms of the major sources of publications, the Journal of Cleaner Production (5.8%), Journal of Sustainability (5%), Journal of Energy and Buildings (1.6%) were the three most influential.

Co-occurrence map and chronological co-occurrence analysis showed that "sustainability", "sustainable development", "life cycle assessment", "green buildings", "energy efficiency", and "recycling" had the most frequency, while "waste management", "life cycle cost", "resource efficiency", "reuse", "recycled aggregates", "renewable energy", and "building information modeling" burst recently (after 2017). In addition, the analysis showed six keyword-clusters, which in order of size and significance, are: (i) energy and energy efficiency in buildings; (ii) recycling, waste management and alternative construction materials; (iii) sustainable development; (iv) circular economy in urban regions; (v) green buildings green supply chain within the construction industry. Moreover, this paper identified that (i) the development and use of alternative construction materials; (ii) the development of circular business models; (iii) smart cities, Industry 4.0 and their relations with CE, are the current research hotspots that can be considered as future research directions. We believe that further investigation of these interdisciplinary research topics would increase our understanding of the more effective implementation of the CE concepts in the sector, which proves helpful in promoting sustainable construction and addressing the sector's environmental concerns.

As with every research, this study possesses some limitations, mainly related to the intrinsic nature of bibliometric approach. First of all, keywords were chosen based on previous literature and several trials to ensure scientific significance and avoided pollution in the dataset. However, there may be related works that are not covered by the proposed search, yet more keywords may increase the noise in the sample and the risk of including unrelated articles. However, there may be related works that are not covered by the proposed search, yet more keywords may increase the noise in the sample and the risk of including unrelated articles. Second, this study used both WoS and Scopus. The global perspective may be improved with the inclusion of other databases. Additionally, much effort in driving CE has been made by not-for-profit organizations, supra-national and world organizations and institutions (*e.g.*, the Ellen MacArthur Foundation, European Commission, and United Nations Environment Programme), and has been published as grey literature studies. Even though the applied methodology in this paper is not capable of those reports, it is recommended to include them if a deeper content-related state of the art is of interest. The finding of this study showed an unfair geographical balance of the studies carried out among CE-actors (governments, institutions). Hence, it is encouraged to replicate this study for each continent, or two or more specific countries (especially from developed and in developing countries).

II.5 Acknowledgments

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II.6 Appendix

The supplementary materials for the article "Circular economy in the building and construction sector: A scientific evolution" are presented in this section. The Appendix is organized as follows:

II.6.1 Search query used in WoS and Scopus database

Search query used in WoS and Scopus database:
(TS= ((
("Circular econom*" OR "Circular business model" OR "Circular competence indicator" OR "Circular corporation" OR "Circular ecology" OR "Circular industr*" OR "Circular management" OR "Circular product*" OR "Circular supply chain" OR "Circular technology innovation" OR "Circular transition framework" OR "Circular value chain*" OR "Circulatory econom*")
OR
((("3R" OR "5R" OR "6R" OR "Reutilisation of product*" OR "Reduc* material*" OR "Reduc* water" OR "Reduc* energy" OR "Reduc* emission*" OR "Reduc* greenhouse gas*" OR "Reduc* waste" OR "Recycl* water" OR "Recycl* wastewater" OR "Recycl* material*" OR "Recycl* resource*" OR "Recycl* waste*" OR "Recycl* component*" OR "Recycl* element*" OR "Reus* water" OR "Reus* material*" OR "Reus* waste" OR " Reus* element*" OR "Reus* component*" OR "Design* for reassemb*" OR "Design* for disassemb*" OR "Design* for deconstruct*" OR "Design* for demolition" OR "Design* for adapt*" OR "Material* circularity indicator*" OR "Design* for flexib*" OR "Adaptive design*" OR "Bioeconom*" OR "Biomimicry" OR "Carbon capture and storage" OR "Carbon capture and utilization" OR "Carbon dioxide recovery" OR "Carbon emission reduction" OR "Carbon footprint reduction" OR "Closed loop" OR "CO2 emissions reduction" OR "Collaborative consumption" OR "Collaborative econom*" OR "Collaborative model" OR "Collaborative technolog*" OR "Complex circular ecosystem" OR "Cradle to cradle" OR "Development model in circular" OR "Eco cycle industry" OR "Emission cutting" OR "Emission reduct*" OR "End of life" OR "End of waste" OR "Environmental oriented supply chain cooperation" OR "Environmental supply chain cooperation" OR "Environmentally responsible manufacturing" OR "Extended producer responsibility" OR "Green econom*" OR "Green manufactur*" OR "Green remanufactur*" OR "Green supply chain" OR "Industrial symbiosis" OR "Intra county cyclic econom*" OR "Low carbon city

strategies" OR "Low carbon development" OR "Low carbon econom*" OR "Low carbon enterprise" OR "Low carbon future cit*" OR "Low carbon governance" OR "Low carbon hotel" OR "Low carbon innovative system" OR "Low carbon office" OR "Low carbon policy" OR "Low carbon scenario" OR "Low carbon technolog*" OR "Low carbon transition" OR "Optimal model circular" OR "Refurbishment" OR "Regenerative design" OR "Regenerative econom*" OR "Remanufacturing" OR "Resource recirculation" OR "Resource recovery" OR "Restorative econom*" OR "Sharing cit*" OR "Sharing econom*" OR "Sharing societ*" OR "Sharing value system" OR "Sustainable business model" OR "Sustainable cit*" OR "Sustainable consumption" OR "Sustainable industrial development" OR "Sustainable logistics" OR "Sustainable materials management" OR "Sustainable resource use" OR "Sustainable supply chain network" OR "Sustainable waste management" OR "Waste prevention" OR "Waste recovery" OR "Waste reduction" OR "Waste to energy" OR "Waste to materials" OR "Waste to resource" OR "Waste to value" OR "Zero emissions" OR "Zero waste" OR "Lean construction*")

OR

("Reduc*" AND "Reus*" AND "Recycl*"))

AND

("Sustainability" OR "Sustainable")))

AND

("Building*" OR "Construction*")))

OR

("Building circularity" OR "Circular construction*" OR "Circular building*"))

II.6.2 The top 15 most productive institutions

Table II.4 The top 15 most productive institutions in the circular economy in buildings (2005-2020)

Affiliations	Number of publications	Country
Delft University of Technology	116	Netherlands
Hong Kong Polytechnic University	89	China
Tsinghua University	77	China
Norwegian University of Science and Technology	74	Norway
Tongji University	69	China
University of Technology Malaysia	64	Malaysia
University of Cambridge	56	United Kingdom

University of Lisbon	55	Portugal
University of Bologna	50	Italy
Lund University	49	Sweden
Islamic Azad University	49	Iran
Sapienza University of Rome	48	Italy
Polytechnic University of Madrid	47	Spain
Aalborg University	45	Denmark
University of Malaya	45	Malaysia

II.6.3 The top 15 most productive authors

Table II.5 Top 15 most productive authors in the circular economy in buildings (2005-2020)

Author	**Affiliation**	Country	TP	TC	TC/TP	Local h-index	Local g-index	Local m-quotient
Geng Yong	Shanghai Jiao Tong University	China	19	976	51.4	16	19	1.1
Poon Chi Sun	The Hong Kong Polytechnic University	China	17	551	32.4	13	17	0.9
Tam Vivian WY	Western Sydney University	Australia	16	261	16.3	7	16	0.5
Birgisdottir Harpa	Aalborg University	Denmark	15	55	3.7	5	7	0.8
Aigbavboa Clinton O	University of Johannesburg	South Africa	14	15	1.1	2	3	0.4
de Brito Jorge	University of Lisbon	Portugal	13	454	34.9	8	13	0.5
Ng S Thomas	University of Hong Kong	China	13	145	11.2	7	12	0.7

Birkved Morten	University of Southern Denmark	Denmark	13	96	7.4	6	9	1.2
Bocken Nancy	Lund University	Sweden	12	1921	160.1	9	12	1
Oyedele Lukumon O	University of West of England (UWE)	United Kingdom	12	262	21.8	7	12	0.7
Haas Carl	University of Waterloo	Canada	11	81	7.4	5	9	1
Sanchez Benjamin	University of Waterloo	Canada	11	72	6.5	4	8	1
Hossain Md Uzzal	The Hong Kong Polytechnic University	China	10	244	24.4	8	10	1.3
Garcia Navarro Justo	Universidad Politécnica de Madrid	Spain	10	107	10.7	5	10	0.6
Nygaard Rasmussen Freja	Aalborg University	Denmark	10	50	5.0	4	7	0.7

TP = Total number of publications, TC = Total number of citations, TC/TP = Total citations per document, Local h-index = h-index calculated from dataset, Local g-index = g-index calculated from dataset, Local m-quotient = m-quotient calculated from dataset

II.6.4 List of author’s keyword occurrence and their frequency

Table II.6 List of author’s keyword occurrence and their frequency in the circular economy in buildings (2005-2020)

Cluster 1	building energy (70); buildings (145); CO2 emission (177); decision-making (105); embodied energy (47); energy (132); energy conservation (65); energy consumption (107); energy efficiency (330); energy management (73); energy performance (43); energy saving (98); greenhouse gases (79); life cycle assessment (391); life cycle cost (74); optimization (41); refurbishment (180); renewable energy (140); residential buildings (43); retrofitting (56); thermal comfort (40)

Cluster 2	building materials (53); compressive strength (39); concretes (102); construction and demolition waste (78); construction waste (33); durability (49); recycled aggregates (84); recycling (224); recycling and reuse (37); recycling materials (49); reuse (88); waste management (132); wastes (70)
Cluster 3	architectural design (48); built environment (65); climate change (151); construction (83); design (40); environment (88); green economy (46); infrastructure (38); innovation (43); low carbon (40); low-carbon economy (75); policy (41); sustainability (837); sustainable (67); sustainable development (388)
Cluster 4	business model (39); China (75); circular economy (569); environmental impact (107); industrial ecology (71); industrial symbiosis (44); material flow analysis (44); resource efficiency (49); smart cities (61); sustainable cities (170); sustainable consumption (59); urban planning (48); urbanization (38)
Cluster 5	building information modeling (89); construction industry (95); environmental sustainability (57); green buildings (367); green supply chain (83); lean construction (92); sustainable design (90)

II.7 References

Adawiyah, W.R., Pramuka, B.A., Najmudin, Jati, D.P., 2015. Green supply chain management and its impact on construction sector Small and Medium Enterprises (SMEs) performance: A case of Indonesia. Int. Bus. Manag. https://doi.org/10.3923/ibm.2015.1018.1024

Aghaei Chadegani, A., Salehi, H., Md Yunus, M.M., Farhadi, H., Fooladi, M., Farhadi, M., Ale Ebrahim, N., 2013. A comparison between two main academic literature collections: Web of science and scopus databases. Asian Soc. Sci. 9, 18–26. https://doi.org/10.5539/ass.v9n5p18

Aguillo, I.F., 2012. Is Google Scholar useful for bibliometrics? A webometric analysis. Scientometrics. https://doi.org/10.1007/s11192-011-0582-8

Ahuja, R., 2013. Sustainable construction: Is lean green?, in: ICSDEC 2012: Developing the Frontier of Sustainable Design, Engineering, and Construction - Proceedings of the 2012 International Conference on Sustainable Design and Construction. American Society of Civil Engineers, pp. 903–911. https://doi.org/10.1061/9780784412688.108

Ajayabi, A., Chen, H.M., Zhou, K., Hopkinson, P., Wang, Y., Lam, D., 2019. REBUILD: Regenerative Buildings and Construction systems for a Circular Economy, in: IOP Conference Series: Earth and Environmental Science. Institute of Physics Publishing. https://doi.org/10.1088/1755-1315/225/1/012015

Akanbi, L.A., Oyedele, L.O., Akinade, O.O., Ajayi, A.O., Davila Delgado, M., Bilal, M., Bello, S.A., 2018. Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2017.10.026

Allouhi, A., El Fouih, Y., Kousksou, T., Jamil, A., Zeraouli, Y., Mourad, Y., 2015. Energy consumption and efficiency in buildings: Current status and future trends. J. Clean. Prod. 109, 118–130. https://doi.org/10.1016/j.jclepro.2015.05.139

Alonso, S., Cabrerizo, F.J., Herrera-Viedma, E., Herrera, F., 2009. h-Index: A review focused in its variants, computation and standardization for different scientific fields. J. Informetr. https://doi.org/10.1016/j.joi.2009.04.001

Aria, M., Cuccurullo, C., 2017. bibliometrix: An R-tool for comprehensive science mapping analysis. J. Informetr. https://doi.org/10.1016/j.joi.2017.08.007

Badi, S., Murtagh, N., 2019. Green supply chain management in construction: A systematic literature review and future research agenda. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2019.03.132

Balasubramanian, S., 2014. A structural analysis of green supply chain management enablers in the UAE construction sector. Int. J. Logist. Syst. Manag. https://doi.org/10.1504/IJLSM.2014.064655

Baldassarre, B., Schepers, M., Bocken, N., Cuppen, E., Korevaar, G., Calabretta, G., 2019. Industrial Symbiosis: towards a design process for eco-industrial clusters by integrating Circular Economy and Industrial Ecology perspectives. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2019.01.091

BAMB, 2017. Buildings as Material Banks and the need for innovative Business Models. BAMB. 1–47.

Benachio, G.L.F., Freitas, M. do C.D., Tavares, S.F., 2020. Circular economy in the construction industry: A systematic literature review. J. Clean. Prod. 260, 121046. https://doi.org/10.1016/j.jclepro.2020.121046

Bibri, S.E., Krogstie, J., 2017. Smart sustainable cities of the future: An extensive interdisciplinary literature review. Sustain. Cities Soc. https://doi.org/10.1016/j.scs.2017.02.016

Blomsma, F., Brennan, G., 2017. The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. J. Ind. Ecol. 21, 603–614. https://doi.org/10.1111/jiec.12603

Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. https://doi.org/10.1080/21681015.2016.1172124

Borghi, A. Del, Gallo, M., Strazza, C., Castagna, M., 2014. Waste management in Smart Cities : the application of circular economy in Genoa. Impresa Progett. 0 Electron. J. Manag.

Cabeza, L.F., Chàfer, M., 2020. Technological options and strategies towards zero energy buildings contributing to climate change mitigation: a systematic review. Energy Build. 219, 110009 (1–46). https://doi.org/10.1016/j.enbuild.2020.110009

Cabeza, L.F., Chàfer, M., Mata, É., 2020. Comparative Analysis of Web of Science and Scopus on the Energy Efficiency and Climate Impact of Buildings. Energies 13, 409.

Chai, K.H., Xiao, X., 2012. Understanding design research: A bibliometric analysis of Design Studies (1996-2010). Des. Stud. https://doi.org/10.1016/j.destud.2011.06.004

Choudhri, A.F., Siddiqui, A., Khan, N.R., Cohen, H.L., 2015. Understanding Bibliometric Parameters and Analysis. RadioGraphics 35, 736–746. https://doi.org/10.1148/rg.2015140036

Corinaldesi, V., Moriconi, G., 2009. Influence of mineral additions on the performance of 100% recycled aggregate concrete. Constr. Build. Mater. https://doi.org/10.1016/j.conbuildmat.2009.02.004

D'Amato, D., Droste, N., Allen, B., Kettunen, M., Lähtinen, K., Korhonen, J., Leskinen, P., Matthies, B.D., Toppinen, A., 2017. Green, circular, bio economy: A comparative analysis of sustainability avenues. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.09.053

Danielsson, S., 2017. Industrial Symbiosis in a Circular Economy.

Dantas, T.E.T., de-Souza, E.D., Destro, I.R., Hammes, G., Rodriguez, C.M.T., Soares, S.R., 2021. How the combination of Circular Economy and Industry 4.0 can contribute towards achieving the Sustainable Development Goals. Sustain. Prod. Consum. https://doi.org/10.1016/j.spc.2020.10.005

Darko, A., Chan, A.P.C., 2016. Critical analysis of green building research trend in construction journals. Habitat Int. https://doi.org/10.1016/j.habitatint.2016.07.001

Darko, A., Chan, A.P.C., Huo, X., Owusu-Manu, D.G., 2019. A scientometric analysis and visualization of global green building research. Build. Environ. https://doi.org/10.1016/j.buildenv.2018.12.059

Dascalaki, E.G., Balaras, C.A., Kontoyiannidis, S., Droutsa, K.G., 2016. Modeling energy refurbishment scenarios for the Hellenic residential building stock towards the 2020 & 2030 targets. Energy Build. https://doi.org/10.1016/j.enbuild.2016.06.003

De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., Ioppolo, G., 2021. A systematic review for measuring circular economy: The 61 indicators. J. Clean. Prod. 281. https://doi.org/10.1016/j.jclepro.2020.124942

Det Udomsap, A., Hallinger, P., 2020. A bibliometric review of research on sustainable construction, 1994–2018. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2020.120073

Deus, R.M., Savietto, J.P., Battistelle, R.A.G., Ometto, A.R., 2017. Trends in publications on the circular economy. Espacios.

Di Biccari, C., Abualdenien, J., Borrmann, A., Corallo, A., 2019. A BIM-Based Framework to Visually Evaluate Circularity and Life Cycle Cost of buildings., in: IOP Conference Series: Earth and Environmental Science. https://doi.org/10.1088/1755-1315/290/1/012043

Domenech, T., Bahn-Walkowiak, B., 2019. Transition Towards a Resource Efficient Circular Economy in Europe: Policy Lessons From the EU and the Member States. Ecol. Econ. 155, 7–19. https://doi.org/10.1016/j.ecolecon.2017.11.001

Donthu, N., Kumar, S., Pandey, N., 2020. A retrospective evaluation of Marketing Intelligence and Planning: 1983–2019. Mark. Intell. Plan. 39, 48–73. https://doi.org/10.1108/MIP-02-2020-0066

Eberhardt, L.C.M., Birgisdottir, H., Birkved, M., 2019. Potential of Circular Economy in Sustainable Buildings. IOP Conf. Ser. Mater. Sci. Eng. 471. https://doi.org/10.1088/1757-899X/471/9/092051

Eberhardt, L.C.M., Birkved, M., Birgisdottir, H., 2020. Building design and construction strategies for a circular economy. Archit. Eng. Des. Manag. 1–21. https://doi.org/10.1080/17452007.2020.1781588

Echchakoui, S., 2020. Why and how to merge Scopus and Web of Science during bibliometric analysis: the case of sales force literature from 1912 to 2019. J. Mark. Anal. https://doi.org/10.1057/s41270-020-00081-9

Egghe, L., 2008. Mathematical theory of the h- and g-index in case of fractional counting of authorship. J. Am. Soc. Inf. Sci. Technol. 59, 1608–1616. https://doi.org/10.1002/asi.20845

Ellen MacArthur Foundation, 2016. Circular Economy Schools Of Thought. URL https://www.ellenmacarthurfoundation.org/circular-economy/concept/schools-of-thought (accessed 2.28.21).

Ellen MacArthur Foundation, 2015a. Towards a Circular Economy: Business Rationale for an Accelerated Transition. Ellen MacArthur Found. URL https://www.ellenmacarthurfoundation.org/publications/towards-a-circular-economybusiness-rationale-for-an-accelerated-transition (accessed 2.20.20).

Ellen MacArthur Foundation, 2015b. Growth within: a circular economy vision for a competitive europe. Ellen MacArthur Found.

Ellen MacArthur Foundation, 2013. Towards the Circular Economy: Opportunities for the consumer goods sector, Ellen MacArthur Foundation. https://doi.org/10.1162/108819806775545321

Ellen MacArthur Foundation, SISTEMIQ, SUN Institute, 2017. Achieving “Growth Within” A €320-Billion Circular Economy Investment Opportunity Available to Europe up to 2025. Ellen MacArthur Found.

Ertz, M., Leblanc-Proulx, S., 2018. Sustainability in the collaborative economy: A bibliometric analysis reveals emerging interest. J. Clean. Prod. 196, 1073–1085. https://doi.org/10.1016/j.jclepro.2018.06.095

Esa, M.R., Halog, A., Rigamonti, L., 2017. Developing strategies for managing construction and demolition wastes in Malaysia based on the concept of circular economy. J. Mater. Cycles Waste Manag. https://doi.org/10.1007/s10163-016-0516-x

European Commission, 2016. The European Construction Sector. Eur. Union 16.

European Commission, 2015. Closing the loop - An EU action plan for the Circular Economy. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels, 2.12.2015. COM(2015) 614 final. Com 2.

Fernández, J.E., 2007. Resource consumption of new urban construction in China. J. Ind. Ecol. https://doi.org/10.1162/jie.2007.1199

Franceschini, S., Faria, L.G.D., Jurowetzki, R., 2016. Unveiling scientific communities about sustainability and innovation. A bibliometric journey around sustainable terms. J. Clean. Prod. 127, 72–83. https://doi.org/10.1016/j.jclepro.2016.03.142

Gallego-Schmid, A., Chen, H.M., Sharmina, M., Mendoza, J.M.F., 2020. Links between circular economy and climate change mitigation in the built environment. J. Clean. Prod. 260, 121115. https://doi.org/10.1016/j.jclepro.2020.121115

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – A new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Geng, S., Wang, Y., Zuo, J., Zhou, Z., Du, H., Mao, G., 2017. Building life cycle assessment research: A review by bibliometric analysis. Renew. Sustain. Energy Rev. 76, 176–184. https://doi.org/10.1016/j.rser.2017.03.068

Ghaffar, S.H., Burman, M., Braimah, N., 2020. Pathways to circular construction: An integrated management of construction and demolition waste for resource recovery. J. Clean. Prod. 244, 118710. https://doi.org/10.1016/j.jclepro.2019.118710

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Ghisellini, P., Ripa, M., Ulgiati, S., 2018. Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.11.207

Glynatsi, N.E., Knight, V.A., 2021. A bibliometric study of research topics, collaboration, and centrality in the iterated prisoner's dilemma. Humanit. Soc. Sci. Commun. 8, 1–12. https://doi.org/10.1057/s41599-021-00718-9

Goodwin, J., Garfield, E., 1980. Citation Indexing-Its Theory and Application in Science, Technology, and Humanities. Technol. Cult. https://doi.org/10.2307/3104125

Grant, M.J., Booth, A., 2009. A typology of reviews: an analysis of 14 review types and associated methodologies. Heal. Inf. Libr. J. 26, 91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x

Gregorio, V.F., Pié, L., Terceño, A., 2018. A systematic literature review of bio, green and circular economy trends in publications in the field of economics and business management. Sustain. https://doi.org/10.3390/su10114232

Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European Union and the world in 2005. J. Ind. Ecol. 19, 765–777.

Hart, J., Adams, K., Giesekam, J., Tingley, D.D., Pomponi, F., 2019. Barriers and drivers in a circular economy: The case of the built environment, in: Procedia CIRP. https://doi.org/10.1016/j.procir.2018.12.015

Harzing, A., van der Wal, R., 2008. Google Scholar as a new source for citation analysis. Ethics Sci. Environ. Polit. 8, 61–73. https://doi.org/10.3354/esep00076

Harzing, A.W., Alakangas, S., 2016. Google Scholar, Scopus and the Web of Science: a longitudinal and cross-disciplinary comparison. Scientometrics 106, 787–804. https://doi.org/10.1007/s11192-015-1798-9

Haupt, M., Zschokke, M., 2017. How can LCA support the circular economy?—63rd discussion forum on life cycle assessment, Zurich, Switzerland, November 30, 2016. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-017-1267-1

Heeres, R.R., Vermeulen, W.J.V., De Walle, F.B., 2004. Eco-industrial park initiatives in the USA and the Netherlands: First lessons. J. Clean. Prod. 12, 985–995. https://doi.org/10.1016/j.jclepro.2004.02.014

Heinrichs, H., 2013. Sharing economy: A potential new pathway to sustainability. GAIA. https://doi.org/10.14512/gaia.22.4.5

Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: A new approach for analysing technological change. Technol. Forecast. Soc. Change. https://doi.org/10.1016/j.techfore.2006.03.002

Herczeg, G., Akkerman, R., Hauschild, M.Z., 2018. Supply chain collaboration in industrial symbiosis networks. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.10.046

Hirsch, J.E., 2010. An index to quantify an individual’s scientific research output that takes into account the effect of multiple coauthorship. Scientometrics. https://doi.org/10.1007/s11192-010-0193-9

Hirsch, J.E., 2005. An index to quantify an individual’s scientific research output. Proc. Natl. Acad. Sci. U. S. A. 102, 16569–16572. https://doi.org/10.1073/pnas.0507655102

Høibye, L., Sand, H., 2018. Circular Economy in the Nordic Construction Sector : Identification and assessment of potential policy instruments that can accelerate a transition toward a circular economy, TemaNord. Nordic Council of Ministers, Copenhagen. https://doi.org/10.6027/TN2018-517

Homrich, A.S., Galvão, G., Abadia, L.G., Carvalho, M.M., 2018. The circular economy umbrella: Trends and gaps on integrating pathways. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.11.064

Hossain, M.U., Ng, S.T., Antwi-Afari, P., Amor, B., 2020. Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2020.109948

Hosseini, M.R., Martek, I., Zavadskas, E.K., Aibinu, A.A., Arashpour, M., Chileshe, N., 2018. Critical evaluation of off-site construction research: A Scientometric analysis. Autom. Constr. https://doi.org/10.1016/j.autcon.2017.12.002

IEA, 2019. 2019 Global Status Report for Buildings and Construction, UN Enviroment programme. https://doi.org/https://doi.org/10.1038/s41370-017-0014-9

Jacobsen, N.B., 2008. Industrial Symbiosis in Kalundborg, Denmark: A Quantitative Assessment of Economic and Environmental Aspects. J. Ind. Ecol. 10, 239–255. https://doi.org/10.1162/108819806775545411

Ji, L., Liu, C., Huang, L., Huang, G., 2018. The evolution of Resources Conservation and Recycling over the past 30 years: A bibliometric overview. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2018.03.005

Kessler, M.M., 1963. Bibliographic coupling between scientific papers. Am. Doc. https://doi.org/10.1002/asi.5090140103

Kharas, H., 2017. The unprecedented expansion of the global middle class an update, Global Economy & Development. WORKING PAPER 100. FEBRUARY 2017.

Khasreen, M.M., Banfill, P.F.G., Menzies, G.F., 2009. Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. Sustain. 2009, Vol. 1, Pages 674-701 1, 674–701. https://doi.org/10.3390/SU1030674

Kibert, C.J. (Ed.), 2012. Sustaination: Green Building Design and Delivery. John Wiley and Sons, Hoboken, NJ.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2017.09.005

Korhonen, J., Honkasalo, A., Seppälä, J., 2018. Circular Economy: The Concept and its Limitations. Ecol. Econ. 143, 37–46. https://doi.org/10.1016/j.ecolecon.2017.06.041

Kylili, A., Fokaides, P.A., 2017. Policy trends for the sustainability assessment of construction materials: A review. Sustain. Cities Soc. https://doi.org/10.1016/j.scs.2017.08.013

Lacy, P., Rutqvist, J., 2016. Waste to wealth: The circular economy advantage, Waste to Wealth: The Circular Economy Advantage. https://doi.org/10.1057/9781137530707

Leising, E., Quist, J., Bocken, N., 2018. Circular Economy in the building sector: Three cases and a collaboration tool. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.12.010

Linnenluecke, M.K., Marrone, M., Singh, A.K., 2020. Conducting systematic literature reviews and bibliometric analyses. Aust. J. Manag. https://doi.org/10.1177/0312896219877678

Liu, P., Xia, H., 2015. Structure and evolution of co-authorship network in an interdisciplinary research field. Scientometrics 103, 101–134. https://doi.org/10.1007/s11192-014-1525-y

Liu, X., Bollen, J., Nelson, M.L., Van De Sompel, H., 2005. Co-authorship networks in the digital library research community. Inf. Process. Manag. https://doi.org/10.1016/j.ipm.2005.03.012

Lopes, J., Farinha, L., 2019. Industrial symbiosis in a circular economy: Towards firms' sustainable competitive advantage. Int. J. Mechatronics Appl. Mech. https://doi.org/10.17683/ijomam.issue5.27

López Ruiz, L.A., Roca Ramón, X., Gassó Domingo, S., 2020. The circular economy in the construction and demolition waste sector – A review and an integrative model approach. J. Clean. Prod. 248. https://doi.org/10.1016/j.jclepro.2019.119238

Lu, W., Chen, X., Peng, Y., Liu, X., 2018. The effects of green building on construction waste minimization: Triangulating 'big data' with 'thick data.' Waste Manag. https://doi.org/10.1016/j.wasman.2018.07.030

Mair, C., Stern, T., 2017. Cascading Utilization of Wood: a Matter of Circular Economy? Curr. For. Reports 3, 281–295. https://doi.org/10.1007/s40725-017-0067-y

Martín-martín, A., Orduna-malea, E., López-cózar, E.D., Martín-martín, A., 2019. Google Scholar, Web of Science, and Scopus: a systematic comparison of citations in 252 subject categories. (arXiv:1808.05053v1 [cs.DL]). J. Informetr.

Mas-Tur, A., Guijarro, M., Carrilero, A., 2019. The influence of the circular economy: Exploring the knowledge base. Sustain. https://doi.org/10.3390/su11164367

Massard, G., Jacquat, O., Zürcher, D., 2014. International survey on eco-innovation parks. Learning from experiences on the spatial dimension of eco-innovation. Environ. Stud. https://doi.org/UW-1402-E

McDowall, W., Geng, Y., Huang, B., Barteková, E., Bleischwitz, R., Türkeli, S., Kemp, R., Doménech, T., 2017. Circular Economy Policies in China and Europe. J. Ind. Ecol. https://doi.org/10.1111/jiec.12597

Merigó, J.M., Yang, J.B., 2017. A bibliometric analysis of operations research and management science. Omega (United Kingdom) 73, 37–48. https://doi.org/10.1016/j.omega.2016.12.004

Merli, R., Preziosi, M., Acampora, A., 2018. How do scholars approach the circular economy? A systematic literature review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.12.112

Mhatre, P., Gedam, V., Unnikrishnan, S., Verma, S., 2020. Circular Economy in Built Environment – Literature Review and Theory Development. J. Build. Eng. https://doi.org/10.1016/j.jobe.2020.101995

Michael Hall, C., 2011. Publish and perish? Bibliometric analysis, journal ranking and the assessment of research quality in tourism. Tour. Manag. 32, 16–27. https://doi.org/10.1016/j.tourman.2010.07.001

Moh, Y.C., Abd Manaf, L., 2017. Solid waste management transformation and future challenges of source separation and recycling practice in Malaysia. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2016.09.012

Mongeon, P., Paul-Hus, A., 2016. The journal coverage of Web of Science and Scopus: a comparative analysis. Scientometrics. https://doi.org/10.1007/s11192-015-1765-5

Munaro, M.R., Tavares, S.F., Bragança, L., 2020. Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment. J. Clean. Prod. 260. https://doi.org/10.1016/j.jclepro.2020.121134

Nagy, Z., Yong, F.Y., Frei, M., Schlueter, A., 2015. Occupant centered lighting control for comfort and energy efficient building operation. Energy Build. https://doi.org/10.1016/j.enbuild.2015.02.053

Nasir, M.H.A., Genovese, A., Acquaye, A.A., Koh, S.C.L., Yamoah, F., 2017. Comparing linear and circular supply chains: A case study from the construction industry. Int. J. Prod. Econ. https://doi.org/10.1016/j.ijpe.2016.06.008

Nobre, G.C., Tavares, E., 2017. Scientific literature analysis on big data and internet of things applications on circular economy: a bibliometric study. Scientometrics 111, 463–492. https://doi.org/10.1007/s11192-017-2281-6

Nuñez-Cacho, P., Górecki, J., Molina-Moreno, V., Corpas-Iglesias, F.A., 2018. What gets measured, gets done: Development of a Circular Economy measurement scale for building industry. Sustain. 10. https://doi.org/10.3390/su10072340

Núñez-Cacho, P., Górecki, J., Molina, V., Corpas-Iglesias, F.A., 2018. New Measures of Circular Economy Thinking In Construction Companies. J. EU Res. Bus. https://doi.org/10.5171/2018.909360

Nußholz, J.L.K., Nygaard Rasmussen, F., Milios, L., 2019. Circular building materials: Carbon saving potential and the role of business model innovation and public policy. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2018.10.036

Osobajo, O.A., Oke, A., Omotayo, T., Obi, L.I., 2020. A systematic review of circular economy research in the construction industry. Smart Sustain. Built Environ. https://doi.org/10.1108/SASBE-04-2020-0034

Panteli, C., Kylili, A., Stasiuliene, L., Seduikyte, L., Fokaides, P.A., 2018. A framework for building overhang design using Building Information Modeling and Life Cycle Assessment. J. Build. Eng. https://doi.org/10.1016/j.jobe.2018.07.022

Pearlmutter, D., Theochari, D., Nehls, T., Pinho, P., Piro, P., Korolova, A., Papaefthimiou, S., Mateo, M.C.G., Calheiros, C., Zluwa, I., Pitha, U., Schosseler, P., Florentin, Y., Ouannou, S., Gal, E., Aicher, A., Arnold, K., Igondová, E., Pucher, B., 2020. Enhancing the circular economy with nature-based solutions in the built urban environment: green building materials, systems and sites. Blue-Green Syst. 2, 46–72. https://doi.org/10.2166/bgs.2019.928

Pérez-Lombard, L., Ortiz, J., Pout, C., 2008. A review on buildings energy consumption information. Energy Build. https://doi.org/10.1016/j.enbuild.2007.03.007

Pickering, C., Byrne, J., 2014. The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers. High. Educ. Res. Dev. 33, 534–548. https://doi.org/10.1080/07294360.2013.841651

Pilkington, A., Meredith, J., 2009. The evolution of the intellectual structure of operations management-1980-2006: A citation/co-citation analysis. J. Oper. Manag. https://doi.org/10.1016/j.jom.2008.08.001

Piscicelli, L., Cooper, T., Fisher, T., 2015. The role of values in collaborative consumption: Insights from a product-service system for lending and borrowing in the UK. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2014.07.032

Pollack, J., Adler, D., 2015. Emergent trends and passing fads in project management research: A scientometric analysis of changes in the field. Int. J. Proj. Manag. 33, 236–248. https://doi.org/10.1016/j.ijproman.2014.04.011

Pomponi, F., Moncaster, A., Pomponi, F., Moncaster, A., 2017. Circular economy for the built environment: A research framework. J. Clean. Prod. 143, 710–718. https://doi.org/10.1016/J.JCLEPRO.2016.12.055

Rajput, S., Singh, S.P., 2019. Connecting circular economy and industry 4.0. Int. J. Inf. Manage. https://doi.org/10.1016/j.ijinfomgt.2019.03.002

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J., 2009. Planetary boundaries: Exploring the safe operating space for humanity. Ecol. Soc. https://doi.org/10.5751/ES-03180-140232

Rodríguez-Soler, R., Uribe-Toril, J., De Pablo Valenciano, J., 2020. Worldwide trends in the scientific production on rural depopulation, a bibliometric analysis using bibliometrix R-tool. Land use policy 97, 104787. https://doi.org/10.1016/j.landusepol.2020.104787

Ruiz-Real, J.L., Uribe-Toril, J., Valenciano, J.D.P., Gázquez-Abad, J.C., 2018. Worldwide research on circular economy and environment: A bibliometric analysis. Int. J. Environ. Res. Public Health 15. https://doi.org/10.3390/ijerph15122699

Ruiz-Rosero, J., Ramirez-Gonzalez, G., Viveros-Delgado, J., 2019. Software survey: ScientoPy, a scientometric tool for topics trend analysis in scientific publications. Scientometrics. https://doi.org/10.1007/s11192-019-03213-w

Saavedra, Y.M.B., Iritani, D.R., Pavan, A.L.R., Ometto, A.R., 2018. Theoretical contribution of industrial ecology to circular economy. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.09.260

Sarkis, J., Zhu, Q., Lai, K.H., 2011. An organizational theoretic review of green supply chain management literature. Int. J. Prod. Econ. https://doi.org/10.1016/j.ijpe.2010.11.010

Smol, M., Kulczycka, J., Henclik, A., Gorazda, K., Wzorek, Z., 2015. The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2015.02.051

Soares, N., Santos, P., Gervásio, H., Costa, J.J., Simões da Silva, L., 2017. Energy efficiency and thermal performance of lightweight steel-framed (LSF) construction: A review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2017.04.066

Solaimani, S., Sedighi, M., 2020. Toward a holistic view on lean sustainable construction: A literature review. J. Clean. Prod. 248, 119213. https://doi.org/10.1016/j.jclepro.2019.119213

Team, R.C., 2018. R: A Language and Environment for Statistical Computing. R Found. Stat. Comput. Vienna, Austria.

Tseng, M.L., Tan, R.R., Chiu, A.S.F., Chien, C.F., Kuo, T.C., 2018. Circular economy meets industry 4.0: Can big data drive industrial symbiosis? Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2017.12.028

Türkeli, S., Kemp, R., Huang, B., Bleischwitz, R., McDowall, W., 2018. Circular economy scientific knowledge in the European Union and China: A bibliometric, network and survey analysis (2006–2016). J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2018.06.118

Van Den Heede, P., De Belie, N., 2012. Environmental impact and life cycle assessment (LCA) of traditional and “green” concretes: Literature review and theoretical calculations. Cem. Concr. Compos. https://doi.org/10.1016/j.cemconcomp.2012.01.004

van Eck, N.J., Waltman, L., 2017. Citation-based clustering of publications using CitNetExplorer and VOSviewer. Scientometrics. https://doi.org/10.1007/s11192-017-2300-7

Wang, H., Schandl, H., Wang, X., Ma, F., Yue, Q., Wang, G., Wang, Y., Wei, Y., Zhang, Z., Zheng, R., 2020. Measuring progress of China’s circular economy.

Resour. Conserv. Recycl. 163, 105070. https://doi.org/10.1016/j.resconrec.2020.105070

Winans, K., Kendall, A., Deng, H., 2017. The history and current applications of the circular economy concept. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2016.09.123

Winkler, H., 2011. Closed-loop production systems-A sustainable supply chain approach. CIRP J. Manuf. Sci. Technol. https://doi.org/10.1016/j.cirpj.2011.05.001

Worden, K., Hazer, M., Pyke, C., Trowbridge, M., 2020. Using LEED green rating systems to promote population health. Build. Environ. https://doi.org/10.1016/j.buildenv.2019.106550

Wu, P., Xia, B., Zhao, X., 2014. The importance of use and end-of-life phases to the life cycle greenhouse gas (GHG) emissions of concrete - A review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2014.04.070

Yigitcanlar, T., Kamruzzaman, M., Foth, M., Sabatini-Marques, J., da Costa, E., Ioppolo, G., 2019. Can cities become smart without being sustainable? A systematic review of the literature. Sustain. Cities Soc. https://doi.org/10.1016/j.scs.2018.11.033

Youngblood, M., Lahti, D., 2018. A bibliometric analysis of the interdisciplinary field of cultural evolution. Palgrave Commun. 4, 1–9. https://doi.org/10.1057/s41599-018-0175-8

Yuan, Z., Bi, J., Moriguichi, Y., 2006. The circular economy: A new development strategy in China. J. Ind. Ecol. https://doi.org/10.1162/108819806775545321

Yudelson, J., 2008. The green-building revolution. HPAC Heating, Piping, AirConditioning Eng.

Zacho, K.O., Mosgaard, M., Riisgaard, H., 2018. Capturing uncaptured values & #x2014; A Danish case study on municipal preparation for reuse and recycling of waste. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2018.04.031

Zhao, D., Strotmann, A., 2015. Analysis and Visualization of Citation Networks. Synth. Lect. Inf. Concepts, Retrieval, Serv. https://doi.org/10.2200/s00624ed1v01y201501icr039

Zhao, X., Zuo, J., Wu, G., Huang, C., 2019. A bibliometric review of green building research 2000–2016. Archit. Sci. Rev. 62, 74–88. https://doi.org/10.1080/00038628.2018.1485548

Zhou, K., Bonet Fernandez, D., Wan, C., Denis, A., Juillard, G., Zhou, K., Bonet Fernandez, D., Wan, C., Denis, A., Juillard, G., 2014. A Study on Circular Economy Implementation in China.

Zhu, J., Fan, C., Shi, H., Shi, L., 2019. Efforts for a Circular Economy in China: A Comprehensive Review of Policies. J. Ind. Ecol. 23, 110–118. https://doi.org/10.1111/jiec.12754

Zuo, J., Zhao, Z.Y., 2014. Green building research-current status and future agenda: A review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.10.021

Zupic, I., Čater, T., 2015. Bibliometric Methods in Management and Organization. Organ. Res. Methods 18, 429–472. https://doi.org/10.1177/1094428114562629

Chapter III

Low-energy buildings in combination with grid decarbonization

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III. Low-energy buildings in combination with grid decarbonization

Low-Energy Buildings in Combination with Grid Decarbonization, Life Cycle Assessment of Passive House Buildings in Northern Ireland

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III.1 Introduction

In recent years, the world has been facing major environmental challenges such as global warming, ozone depletion, and the destruction of natural habitats, mainly arising from human activities. Therefore, there is an urgent need for worldwide commitments to prevent and reduce these consequences (Luisa F. Cabeza et al., 2014; Causone et al., 2019). Among different sectors, the building sector is a significant consumer of energy and natural resources, and it potentially damages the environment (Motuziene et al., 2016). For instance, in Europe, the impact on the buildings' life cycle is around 50% of all energy use, 33% of all water use, 50% of all raw material extraction, and 40% of all greenhouse gas emissions (European Commission, 2019). According to the UN Sustainable Development Goals (SDGs), the construction sector has unique opportunities for addressing local and global environmental objectives (United Nations, 2015b). From this perspective, any effort towards increasing sustainability and cleaner construction must include this sector as a critical element in decreasing the total energy usage and greenhouse gases.

Concerning the desire to reduce building energy use and greenhouse gases, the operational stage of a building is critically important as it typically contributes to 60–90% of the total building environmental impacts (Gustavsson and Joelsson, 2010; Hossain and Marsik, 2019; Ortiz-Rodríguez et al., 2010; Rodrigues and Freire, 2017; Tokbolat et al., 2019). Several strategies may help to achieve a significant reduction of energy use in the building operation phase: (i) minimizing the need for energy inputs (*e.g.*, increasing levels of insulation, glazing with better thermal performance, and using airtightness); (ii) adopting buildings with energy-efficient and low-carbon technologies (*e.g.*, electrical heat pumps); (iii) decarbonize of the electricity mix production and use on-site electricity production (*e.g.*, photovoltaics, wind, hydro, and biomass); and (iv) variation of occupant behaviors (*e.g.*, thermal management, and typology of the family) (EASAC, 2021; Monahan and Powell, 2011; Zhou et al., 2016). Several studies have been conducted to address these strategies, for example, using different insulation materials for the building envelope (Wang et al., 2009; Zhu et al., 2009b, 2009a); choosing more efficient heating, ventilation, and air-conditioning (HVAC) equipment (Chica et al., 2011; Litjens et al., 2018; Moynihan and Triantafillu, 2012); using building automation and control system (BACS) (D'Agostino and Parker, 2018; Waide, 2019); encouraging energy-saving measures within occupant behaviors (Lee et al., 2013; Martani et al., 2012; Richardson et al., 2008; Roetzel et al., 2014); and applying renewable energy technologies (Louwen et al., 2016; Magrini et al., 2020; Thygesen and Karlsson, 2013; Visa et al., 2014).

With regard to solar energy technologies, the benefits of implementing innovative practices of Building Integrated Photovoltaic (BIPV), Building Integrated Photovoltaic-Thermal (BIPVT) systems, and passive solar building technologies should be highlighted. Essentially BIPV/BIPVT systems are the integration of the PV module into the building structure so that the conventional building materials are replaced by PV cells. These systems not only can act as a standard exterior building envelope but also provide the opportunity for on-site electricity production (and thermal energy via an absorption process in the case of BIPVT). This would pave the way for net-zero energy constructions, whose potential in terms of energy consumption and reduction of global warming is commonly recognized (Zhang et al., 2018). In addition, using BIPV/BIPVT can significantly improve the building aesthetic, natural lighting, and thermal comfort (Debbarma et al., 2017a). The main advantage of using BIPV/BIPVT systems over non-integrated PV systems is that they carry out multi-functions, for example, by providing thermal insulation, noise prevention, being weatherproof, as well as offsetting the system initial costs (Zhang et al., 2018). In passive solar building technologies, the windows, walls, and floors are made in a way to collect, store, reflect, and distribute solar energy in the building without using mechanical and electrical devices (unlike active solar techniques, *e.g.*, PV). These techniques not only convert sunlight into heat (in water, air, and thermal mass), but they cause air-movement for the purpose of ventilation, with a small share of using other energy sources (Kumar, 2014). An example of a passive solar heating system is the Trombe wall that is a massive wall located behind glass; it absorbs solar energy and releases it towards the building interior at night. The hot air between the wall and the window can be introduced into interior spaces by incorporating heat-distributing vents at the top of the wall (Jaber and Ajib, 2011).

Northern Ireland, the region studied in this work, follows the UK’s commitment to Paris Climate Agreement (Paris Agreement, 2015) to reach net-zero greenhouse gas (GHG) emissions by 2050. The Northern Ireland region has a number of challenges, including high levels of fuel poverty, lack of natural resources, high dependence on imported fossil fuels, and building regulations which are the lowest in the UK. According to the 2016 House Condition Survey (HCS, 2016), 99% of dwellings in Northern Ireland had central heating, where 68% of them are oil-fired, 24% with central gas heating, and 8% including solid fuel, electric, and fuel systems. However, the potential for the deployment of low-energy buildings is considerable. Previous studies have shown that the net additional cost of a three-bedroomed passive house can be as low as £5,088 (Colclough and McWilliams, 2019). Moreover, passive houses combined with electric heat pumps can simultaneously reduce the operational energy demand, remove the dependence on imported fossil fuels, improve comfort levels, and realize multiple financial benefits (Colclough et al., 2020). In particular, the construction of new buildings based on passive house standards is in line with the demand of UN energy efficiency standard as well as the findings of the UK Climate Change Committee (CCC) for new buildings to be built with a space heating demand of 15 to 20 kWh/m2/year (CCC, 2019a).

As shown previously in (Colclough et al., 2020; Colclough and McWilliams, 2019), the use of three-bedroomed passive houses can provide economic, logistic, and energy benefits, along with improvement in inhabitant comfort level. Moreover, a vast majority of existing Life Cycle Assessment (LCA) practices do not consider the influence of future decarbonization in the electricity mix on LCA results, and frequently, the practitioners use current energy mixes for future scenarios (De Wolf et al., 2017). To the best of the authors' knowledge, there is no work published to address the environmental performance of semi-detached passive house dwellings in which Northern Ireland's electricity decarbonization is evaluated. Therefore, this study looks at how this approach can contribute to meeting the UK's environmental commitments by considering not only the operational carbon emissions of the case study passive house dwelling with integrated heat pump, but also in particular, the impact of the decarbonizing grid on the typology which shows such potentials. For doing so, the relevance of considering future electricity mix according to the Tomorrow's Energy Scenarios Northern Ireland (2020) (SONI, 2020) on the environmental impact of case studies is evaluated. Furthermore, to improve the understanding of decision-makers on the buildings' environmental performance, the LCA results of the present study will be further compared to an existing UK's benchmark regime for the buildings.

The paper is organized as follows: a general outline of the environmental assessment methodology and tools is explained in Section III.2. It also describes the future electricity mix scenarios considered. Section III.3 describes the case studies, and Section III.4 reports the LCA results and discusses the effects of decarbonization in the case studies. The conclusion and insights for future research are provided in Section III.5.

III.2 Materials and methods

In this section, the framework employed to model and analyze the effect of decarbonization is described. The first step of this analysis is to collect the data, and to perform a traditional LCA on the four single-family houses. Besides, the energy scenarios are defined to model the current and future electricity mix's decarbonization pathways, and the life cycle inventory datasets are modeled using the defined electricity mixes. In the next step, the impact of decarbonization of the electricity generation is integrated into the LCA of the case studies. Finally, the environmental impact (embodied carbon) and the operational energy of the dwellings are compared to the existing national benchmark to assess the contribution of the building sector in achieving the UK's environmental targets.

III.2.1 Environmental impact assessment

The Life Cycle Assessment (LCA) is a broadly accepted tool to carry out the environmental impact assessment associated with a process/product through its whole life cycle. This study follows the standardized ISO norms 14040 and 14044 (ISO 14040, 2006; ISO 14044, 2006), in which the framework of an LCA includes four steps: (1) Goal and scope definition: outlines the envisioned application, the motivations for conducting a study, define the methodological framework to satisfy the intended goals, outlines the boundary of the system, and defines the functional unit; (2) Life cycle inventory (LCI): compiles and quantifies inputs (*e.g.*, materials, and energy) and outputs (*e.g.*, emissions to air, water, and soil) that cross the system boundary; (3) Life cycle impact assessment (LCIA): uses environmental impact indicators to predict the extent and importance of the impacts to human health and the environment; (4) Interpretation phase: depicts the results and derives conclusions (ISO 14044, 2006).

III.2.1.1 Goal and scope of the LCA

This study aims to evaluate the environmental impact of four different residential buildings located in Northern Ireland, including two low-energy buildings complying with functional requirements of SAP (2009) and SAP (2012) (BRE, 2014; DECC, 2009), and two dwellings meeting the requirements of Passivhaus standard. In particular, the environmental performance of the case studies is evaluated based on both construction materials and elements breakdowns, related to the production phase, in-use, and end-of-life phases, which highlight the co-benefits of low-energy/passive houses. Additionally, we study the influence of future electricity mix on the LCA results of the aforementioned case studies, see section III.2.2.

In the present study, the functional unit in the inventory analysis is one square meter gross internal area (GIA) of the building. The lifespan of 60 years was assumed for the operational stage, which is consistent with RICS as the buildings' lifetime in the UK (RICS, 2017).

III.2.1.2 System boundaries

The overall LCA of a building, using the cradle to grave approach, covers from raw material to demolition. According to the European standard EN 15978 standard (CEN, 2011), as shown in Figure III.1, the life cycle stages of a building are (i) product stage (A1–A3); (ii) construction stage (A4–A5); (iii) use stage (B1–B7); (iv) end-of-life stage (C1–C4); and (v) benefit and loads beyond building life cycle (D).

Life cycle of buildings																Supplement
Production			Construction		Use							End-of-life				Beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Row materials supply	Transport to manufacturer	Manufacturing	Transport to construction site	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/demolition	Transport	Waste processing	Disposal	Reuse/recycling
✓	✓	✓	✓	-	-	✓	-	✓	-	✓	-	-	✓	✓	✓	(✓)

Figure III.1: Life cycle stages of buildings (CEN, 2011), Note: [✓] indicates if processes in a life cycle stage are included, [-] indicates if the processes of a life cycle stage are omitted, and [(✓)] indicates that the processes of a life cycle stage are partially included.

According to EN 15978 standard, as shown in Figure III.1, the LCA study includes (i) materials production phase (modules A1–A3); (ii) transport to the building site (module A4); (iii) in-use phase, including ordinary maintenance, *i.e.*, the combination of maintenance and replacement (modules B2 and B4), and operational energy use (module B6), which covers all the processes occurring during the building service, such as heating, cooling, and energy usage by electrical appliances; (iv) end-of-life, including transport from construction site to waste processing/disposal, and processes for waste processing and disposal (modules C2–C4); and (v) beyond the system boundary, including resource recovery of building materials and components, and in particular the benefits deriving from the surplus of renewable energy exported to the grid (module D). The modules use (B1), repair (B3), refurbishment (B5), and operational water use (B7) were not considered due to the lack of data, and in the present LCA comparison would be assumed to be similar for all dwellings, so they were omitted from the LCA boundary. The construction (A5), and deconstruction (C1) modules were also excluded since these modules typically have a negligible impact (Morris et al., 2021; Sandin et al., 2014). The system boundaries included in this study contribute to the majority of building life cycle impacts (82–98%) (Rasmussen et al., 2019). The analysis covered the materials utilized in the structure and the building envelope, including the foundation, beams and columns, floor slabs, exterior, and interior walls, roofs, windows, surface materials, electrical and heating systems, and paints. However, fixtures, fittings, lighting, and plumbing were not included in this study.

One of the features of the wood-based buildings is the biogenic carbon contained in the bio-based materials. Biogenic carbon is the sequestration of carbon dioxide from the atmosphere during plant growth involving photosynthetic processes. When these materials ultimately decompose or are incinerated at the end-of-life stage, the sequestered carbon is re-emitted to the air (Hoxha et al., 2020). According to RICS (RICS, 2017), this study assumes that the timber originates from a sustainably managed forest (certified by FSC/PEFC or equivalent). Therefore, the two main approaches can be distinguished when assessing the impact of biogenic carbon: (i) according to the product environmental footprint (PEF) standard (European Commission, 2017), it can be omitted since any carbon sequestered initially will be released back into the atmosphere (the '0/0' approach); (ii) based on EN 15804 standard (CEN, 2013), it can be taken into account as a negative emission during materials production stage (A1-A3), and an equivalent positive emission at the end-of-life (C) stage (the '–1/+1' approach; –1 for CO_2 uptake; +1 for CO_2 emission) (Hoxha et al., 2020). The amount of sequestered carbon in wood products is calculated according to EN 16449 (EN 16449, 2014). It is worth noting that absorption of CO_2 by carbonation of the cement-based products is not accounted as the use phase (module B1) was out of the system boundary included.

III.2.1.3 Life cycle inventory (LCI)

The LCI of the primary data, including building drawings and the data about building products, electricity, fuel consumption for plants and equipment, and wastes, were provided by the construction company (Table III.5 and Table III.6 in Appendix III.8). These documentations contain a building information modeling (BIM) object (products' details and technical specifications), spillage, and maintenance instructions. Other required data, such as equipment, was gathered through questionnaires and interviews with experts. If the data was unavailable, it was retrieved from environmental product declarations (EPDs), the information from manufacturers, and scientific papers. Quantity information (*e.g.*, length, area, and volume) of different materials and components were exported from Revit/BIM (Autodesk, 2021). In this study, the cut-off criteria of the EN 15804 (CEN, 2012) were followed. According to this standard, the inputs with less than 1% contribution to the mass or primary energy demand may be neglected, while the cumulative total of these neglected inputs should not exceed 5%. However, this cut-off rule was not applied to hazardous materials and substances. The inventory data for pellet fuel production was taken from (Dias and Arroja, 2012), and data for pellet combustion were taken from (Quinteiro et al., 2019; Vicente et al., 2016). In addition, the physical properties of the heating oil were taken from the digest of UK energy statistics (DUKES) report (DUKES, 2020).

Domestic consumptions and ordinary maintenance have been calculated with the assumption of a lifespan of 60 years. The estimated service life (ESL) of different inputs is mainly based on information of the manufacturer from the EPDs, and the durability of fabric components taken from RISC default service life (RICS, 2017) (Table III.7 in Appendix III.8). The values given within the ESL are considered for each building component to calculate the materials and energy consumption. The consumption of wood pellet, oil, and electric energy needed for heating and cooling was assessed considering the local climate conditions, characteristics of the building shell, heating and cooling mode and the form of energy systems, and users' behaviors. The operational energy for various case studies was evaluated by thermal energy performance in the Passive House Planning Package (PHPP) (Passivhaus Institut, 2015).

For transportation (modules A4 and C2), a combination of average values specified by RICS was used (RICS, 2017). These default values consider the transportation from the manufacturing companies of materials and components to the UK project site, and from the building to the recycling plants and/or disposal sites (Table III.8 in Appendix III.8). The transportation data emissions were taken from the Ecoinvent database (Wernet et al., 2016).

Concerning the end-of-life stage, for all built-in products, a waste treatment scenario was implemented for different processing options (*i.e.*, recycling, landfill, and incineration), based on the data obtained from EPDs, and the RICS recommendation (RICS, 2017) (Table III.9 in Appendix III.8). The present work adopts the method proposed by the PEF4Buildings project assumptions (VITO et al., 2018) to quantify the avoided impacts related to recycling processes for various materials (Mirzaie et al., 2020). In particular, according to the PEFCR Guidance (European Commission, 2017), the default recycled content values on the EU market were used for inert materials, metals, plastics, and wood products.

III.2.1.4 Life cycle impact assessment (LCIA)

The LCI data was employed to calculate the environmental impact of the materials and products throughout their life cycles. According to EN 15978 (CEN, 2011), the most relevant data for environmental analysis is specific information from each product collected from EPDs defined in EN 15804 (CEN, 2012). However, due to lack of sufficient open access EPDs for all materials, in the case of those materials where no relevant data were available, use the generic data available at Ecoinvent v3.7.1 (Wernet et al., 2016) and the European Life Cycle Database (ELCD) v3.2 (ELCD, 2018) are proposed.

In this study, the two well-known LCIA methods of (i) Cumulative Energy Demand (CED) method (Frischknecht et al., 2015), and (ii) the CML-IA baseline V3.01 method (Guinee, 2002) were employed (Kiss et al., 2020). The CED is a commonly-used method to measure direct and indirect energy use throughout the entire life cycle of a product or a system (Rohrlich et al., 2000), and it serves as an indicator for choosing a more environmentally friendly alternative (Penny et al., 2013). CML is an impact assessment method to evaluate midpoint impact categories through focusing on quantitative modeling to early stages in the cause-effect chain to limit uncertainties (Guinee, 2002). This method is most widely used in building LCA studies from the environmental and political point of view (CEN, 2011; Dong et al., 2021; van Stijn et al., 2021). CML includes a set of 11 environmental, resource-depletion, and toxicology midpoint impact categories. In this study, CML was used to account for the major environmental concerns using the following impact categories: Global Warming Potential (GWP), Abiotic Depletion Potential for elements (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Oxidation Potential (POP), and Ozone Layer Depletion (OLD) (de Bruijn et al., 2002; Khasreen et al., 2009). The SimaPro v9.2 software (Pré Consultants, 2022) was used to estimate environmental impacts. Results for those items that come from the EPDs were modified and were added in LCA calculations.

III.2.2 Electricity mix scenario design

A parameter that has a significant hotspot impact on the LCA results is the electricity mix, as it is broadly assigned to the energy-consuming phase of many products. This is particularly true for buildings, as highlighted in multiple studies (Dahlstrøm et al., 2012; Mosteiro-Romero et al., 2014).

In this study, the LCA is implemented for the current, and three future electricity mix scenarios as defined in Tomorrow's Energy Scenarios Northern Ireland 2020 (TESNI 2020). As illustrated in Figure III.2, current Northern Ireland's electricity mix is still heavily dependent on fossil fuels, with an energy mix of 43% natural gas, coal 14%, oil 2%, wind 35%, solar, and others 6% (DUKES, 2019; NISRA and DfE, 2019). For the baseline analysis, the current electricity mix in 2018 is considered, and it is assumed to remain constant over the life cycle of the building. This type of modeling, *i.e.*, taking a static (current) electricity supply mix of a specific year in the product's life cycle, has been employed in many LCA studies (Itten et al., 2014; Kiss et al., 2020). However, since new renewable energy plants will be installed in the coming years, the substantial decarbonization of the electricity used is expected (European

Parliament, 2020). Therefore, the reliability of the environmental impact analysis may be significantly improved if the time-related changes in the electricity mix are considered (Ramon and Allacker, 2021; Su et al., 2017). Additionally, the uncertainties can be addressed by comparing potential scenarios in a sensitivity analysis.

TESNI 2020 reports the three future electricity mix scenarios, that exhibit potential energy pathways to achieve various degrees of decarbonization for Northern Ireland, respectively named: “Modest Progress”, “Addressing Climate Change”, and “Accelerated Ambition” (SONI, 2020). All these scenarios deliver Northern Ireland’s contribution to the UK target emission reduction of 80% by 2050 compared to 1990, based on the 2008 Climate Change Act (SONI, 2020).

The “Modest Progress”, corresponding to the “MP” scenario in this study, represents a situation in which decarbonization progress is made compared to the present day; however, it is slower than in the other scenarios. In this scenario, 60% of electricity is generated from renewables (60% RES-E) by 2030, and GHG reduction of more than 35% by 2030; little economic growth is expected over the next decade; new homes from 2025 and existing properties from 2035 must adopt the Future Homes Standard while a ban on new petrol and diesel cars will be proposed by 2040 (SONI, 2020).

In “Addressing Climate Change”, named as “ACC” scenario in the present study, a situation is assumed in which Northern Ireland achieves a low carbon future while 70% RES-E target for 2030 is met, and GHG reduction is more than 35% by 2030. The adoption of Future Homes Standard to new homes from 2025 and existing properties from 2035 is planned whilst new petrol and diesel cars will be banned by 2040. This scenario achieves UK net zero emissions reduction contribution for Northern Ireland by 2050, set out by the Committee on Climate Change (SONI, 2020).

The fastest decarbonization progress is achieved through “Accelerated Ambition”, corresponding to the scenario “AA” in this work. In this scenario, Northern Ireland reaches the very ambitious target of 80% RES-E by 2030 through continued development of onshore wind and a large increase in solar generation, including also a significant uptake by consumers through the use of rooftop PV. This scenario reaches the UK net zero emissions reduction contribution for Northern Ireland by 2040, 10 years sooner than ACC (SONI, 2020).

Information about future projections is available in the TESNI 2020 (SONI, 2020) for certain pivotal moments (*i.e.*, 2025, 2030, 2040, 2050). The electricity mixes used in this study for the current situation, and for the future scenarios (as reported in TESNI 2020 (SONI, 2020)) are presented in Figure III.2.

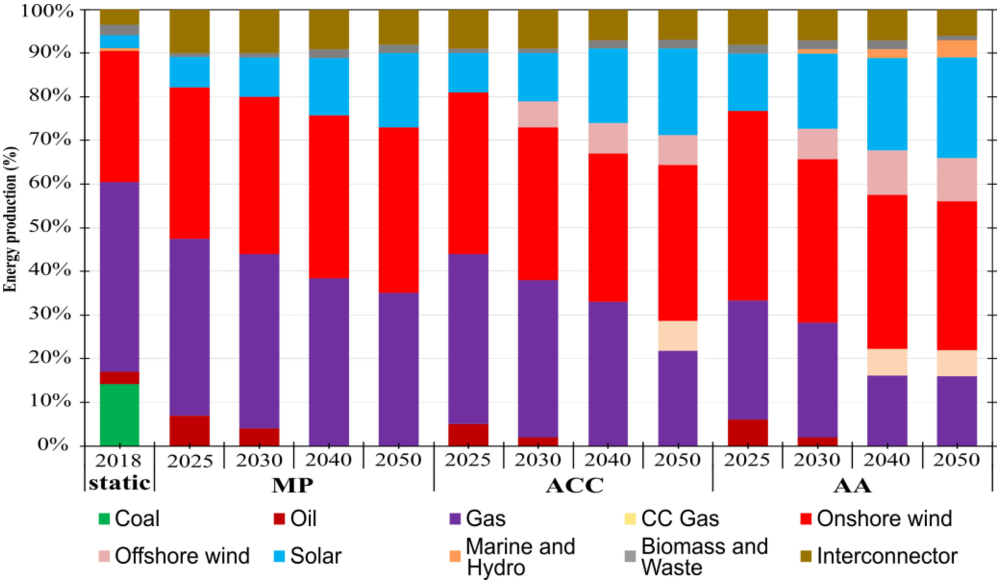

Figure III.2: Electrical energy production shares in Northern Ireland.

In this study, in order to calculate the yearly CO_2 emission factors of the current situation and future scenarios for a unit of the low-voltage electricity mix, the contribution of all generation technologies reported for the available moments are modeled with Ecoinvent 3.7.1 (Wernet et al., 2016) using Simapro (Table III.9 - Table III.13 in Appendix III.8) (*e.g.*, Ref. (Itten et al., 2014)). In this study, technological evolutions in the generation processes are beyond the scope of the current study and, therefore, not taken into account. The electricity imported and the losses due to the transmission and distribution are taken into account in the product system. The M2 model described in (Itten et al., 2014) was used to model the imported electricity. A gradual annual evolution of the electricity CO_2 factors is considered using a linear interpolation between the values obtained for the key moments. For the scenarios ACC and AA, it is considered that the value of the carbon emission factors remains stable at zero for the levels after 2050, while it decreases with a fixed slope to 2050 in the scenario MP. Figure III.3 shows the CO_2 emission factors in terms of kg/kWh electricity produced from different scenarios.

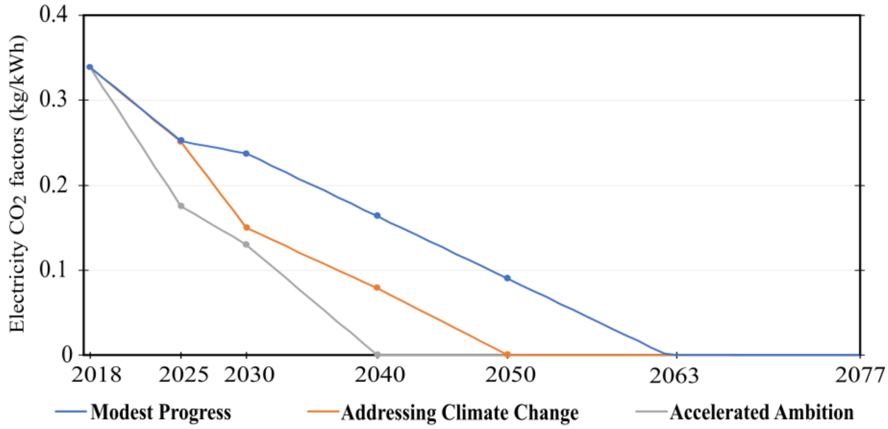

Figure III.3: Electricity CO_2 emission factors of the scenarios.

III.2.3 Benchmark

The benchmark used in this study for comparing the environmental performance of the analyzed case studies is the RIBA 2030 Climate Challenge. The RIBA 2030, developed by the Royal Institute of British Architects, proposes well-established voluntary target values for operational energy use, water use, and embodied carbon for domestic/residential and non-domestic buildings (RIBA, 2021). These performance targets set out a trajectory to realize the reductions necessary by 2030 in order to have a realistic prospect to achieve the net-zero carbon for the UK building stock by 2050 (RIBA, 2021). Based on these targets, an intermediate target by 2025 is established. These target values serve as the benchmark that does not necessarily need to be met, but they can be helpful in the building design process to identify where to act to improve the environmental performance of a building, and to understand if the building will contribute to achieving the UK environmental targets (RIBA, 2021). In this study, the operational energy and embodied carbon of the case studies were compared to the benchmark target values.

III.3 Application to the building case study

In this study, a reference house built based on the most common characteristics of typical semi-detached dwellings is considered. The building block has a two-story timber frame south-orientated (187.1 m^2 heated floor area) and is located in Northern Ireland. The house was designed in 2018, according to a project described by a local building company. The building envelope is constructed on a strip foundation of concrete, with a wooden frame insulated by mineral wool in the walls and roof. The ground-level floor is made from reinforced concrete cast over a layer of expanded polystyrene (EPS). Figure III.4 shows the 2D and 3D models of the reference house.

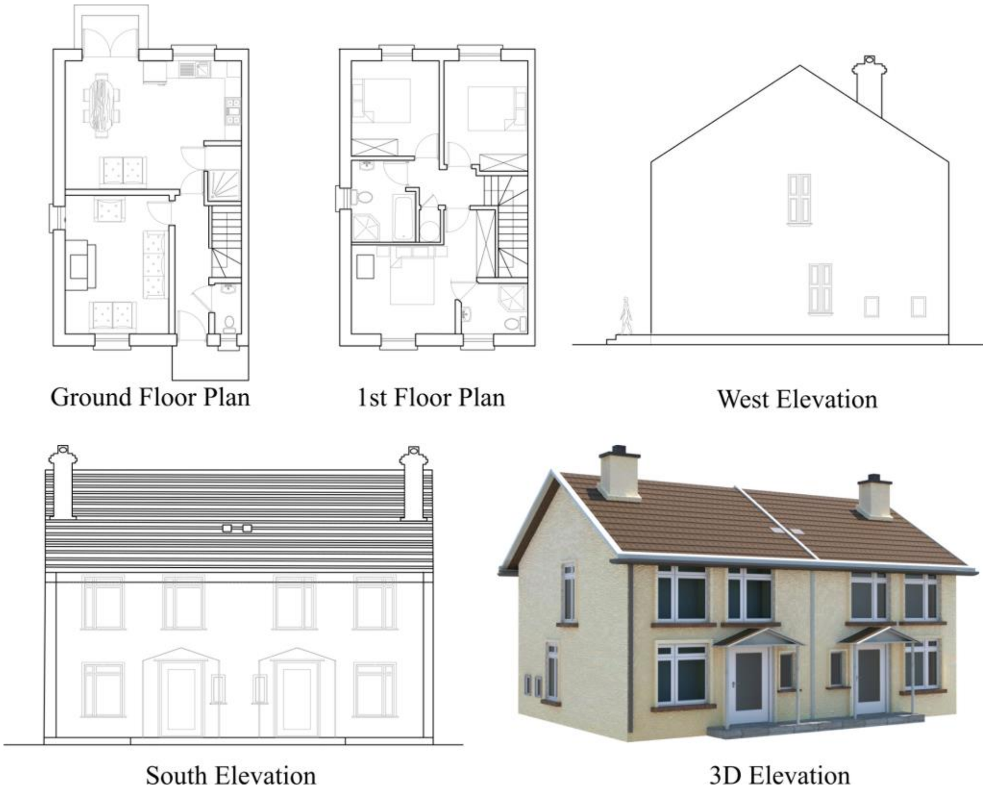

Figure III.4: 2D and 3D model of the reference house.

Four different actual types of semi-detached buildings built based on the reference house are considered in this study. Table III.1 and Table III.2 give an overview of the existing differences between case studies regarding their thermal properties, ventilation method, space heating systems, and installation of renewable technologies. Each of the different case studies uses a combination of different technologies to deliver energy.

In this work, the dwellings were modeled in Standard Assessment Procedure (SAP) 2009 and (2012) (BRE, 2014; DECC, 2009), and in Passive House Planning Package (PHPP). SAP was considered as it is the UK Government's National Calculation Methodology (NCM) (Moran et al., 2014). It is based on the BRE Domestic Energy Model (BREDEM), and it provides accurate and reliable assessments for calculating dwellings' energy performance to comply with UK building regulations (UK Government's National Calculation Methodology, 2021). SAP is a steady-state model for assessing how much annual energy (*e.g.*, space heating, domestic hot water, and electric lighting) a dwelling will consume when delivering a defined level of comfort and service provision (UK Government's National Calculation Methodology, 2021). PHHP incorporates the Passivhaus methodology for assessing the energy performance of a building, and it consists of systematically developed calculations by comparing dynamic simulations to validated measurements in completed Passive House projects (Moran et al., 2014).

Table III.1. Characteristics of the building envelope and ventilation systems for the case studies.

		Building case study			
		BS1	**BS2**	**PH1**	**PH2**
Energy-standard		Low energy	Low energy	Passive house	Passive house
U-Value (W/ (m^2 K))	External wall	0.20	0.20	0.148	0.148
	Roof	0.15	0.15	0.085	0.85
	Floor	0.258	0.175	0.209	0.209
	Window	1.80	1.80	0.75	0.75
Airtightness	(ac/h @ 50 Pa)	5	5	0.4	0.4
Ventilation		NV and MV	NV and MV	MVHR	MVHR (Compact P unit)
Mechanical ventilation system	HRE (%)	N/A	N/A	83	80

NV = Natural Ventilation (Purge ventilation via windows in the habitable room and open flue in the living room); MV = Mechanical Ventilation (Mechanical extract fan of 10 m^3/h in kitchen and bathrooms); MVHR = Mechanical Ventilation with Heat Recovery; HRE = Heat Recovery Efficiency; N/A = Not Available.

Table III.2. Characteristics of the heating systems and renewable technologies of each case study.

	Building case study			
	BS1	**BS2**	**PH1**	**PH2**
Heated Floor Area (m^2)	187.1	187.1	187.1	187.1
Primary heat generator	Heating oil boiler	Heating oil boiler	Heating oil boiler	HP compact P unit
[a]Secondary heat generator	Wood pellet stove	Wood pellet stove	N/A	Direct electrical (heating resistance)
Passive house compact unit	N/A	N/A	N/A	Compact P unit

with exhaust air heat pump				
Efficiency Heating System	Main: 93%, Sec: 84%	Main: 93%, Sec: 84%	Main: 93%	Main: SPF 300%, Sec: 70%
Renewable technology-multi-Si PV (m^2)	N/A	12	N/A	N/A

multi-Si PV = Multi-crystalline Silicon photovoltaics panels; SPF = Seasonal Performance Factor; N/A = Not Available.
a: Secondary heating systems account for 40% of space heating requirements.

The first case study (BS1) achieves compliance performance criteria that pass current minimum building regulations requirements on SAP (2009) (DECC, 2009). The second case study (BS2) focuses on using renewable technologies and using thicker insulation in the floor to meet the SAP (2012) regulation requirements (BRE, 2014). The BS1 and BS2 benefit from double glazing windows and doors, a wood pellet stove, and high efficiency condensing oil boiler supplied to the water tank for domestic hot water and space heating. The generated electricity by 2 kW photovoltaics is fully exported to the grid, and it is considered to be substituted for the low-voltage electricity from the Northern Ireland-country mix, which consequently brings environmental benefits to the system. Its configuration has been analyzed using a polycrystalline cell type. Based on the manufacturer specifications, the Terreal Solutions PV3-1S (82 Wp) modules with a 15.4% nominal efficiency have been considered. The installation performance was simulated using PVsyst (PVsyst SA, 2022), and the average annual electricity production was estimated to be 1,748 kWh/y. Solar PV technical specifications are listed in Table III.14 in Appendix III.8.

Case studies 3 and 4 (*i.e.,* PH1 and PH2) comply with the international Passive House standard and also the Irish buildings regulations. The case study PH1 benefits from its advanced building fabric design (*e.g.,* the application of triple glazing and advanced insulations), superior airtightness performance, in combination with mechanical ventilation with heat recovery (MVHR), and an efficient condensing oil boiler that is supplied to the water tank. The same design strategy as PH1 is used in PH2 but with a Heat Pump compact P unit instead of MVHR and oil boiler.

The materials inventory of the four case study types resulted in 252 processes, each characterized by the quantity of the materials, and their corresponding construction waste factors (Table III.5 in Appendix III.8). The building materials were grouped into ten main categories: concrete and cement product, timber, plastics, gravel and sands, glass, etc. Table III.3 reports the amounts used in the construction of the building.

Table III.3. Mass of different materials utilized in the reference building case studies (in ton).

Material	**Case study**			
	BS1	**BS2**	**PH1**	**PH2**
Ceramics	2.7	2.7	2.3	2.3
Concrete and cement product	66.9	66.9	63.8	63.8
Glass	0.7	0.8	1.1	1.1
Gravel and sand	23.2	23.2	23.2	23.2
Insulation	4.0	4.0	4.5	4.5
Paint	1.6	1.6	1.6	1.6
Plasterboard	8.3	8.3	8.7	8.7
Plastics	8.6	8.6	8.6	8.6
Steel and other metals	3.3	3.5	3.3	3.2
Timber	9.0	9.0	9.1	9.1

III.4 Results and discussion

III.4.1 Life cycle impact assessment

Table III.4 shows the overall LCA results balance (impacts + credits), including cumulative energy demand and six mid-point impact categories of the case studies. The BS1 (*i.e.,* low-energy building with wood pellet stove and oil boiler) is regarded as the base case. The relative performance of the remaining case studies is reported with respect to this base case study for a fixed building lifetime of 60 years. Table III.4 shows the passive house design reduces midpoint indicator of all impact categories with an average of 30% (and up to 50%) compared to the base case BS1, except the abiotic depletion potential category where the PH2 (*i.e.,* passive house with an electric heat pump compact unit) has relatively similar environmental impacts. Between the two PH case studies, the case of PH2 exhibits much better energy-saving and environmental benefits with an average of 18% compared to the passive house equipped with condensing oil boiler (*i.e.,* PH1).

Table III.4 also shows an advantage associated with passive house design, which is their more efficient energy systems. With regard to CED, the residential timber frame dwelling built in accordance with the passive house standard provides a consistent reduction of the energy demand (38– 53%) compared to the wood and oil-based heating system in low energy building standard of BS1. The better energy performance is due to upgrades to the insulation, windows/doors, airtightness, and heating systems (*e.g.*, boilers/HP).

The global warming potential (GWP) has a 30-43% lower environmental impact of PHs compared to BS1. This is mainly due to better efficient heating technology used in the PHs; these types of dwellings follow a similar pattern as the energy consumption of an energy source with minor fossil fuel contribution compared to the low-energy buildings. In both approaches of the −1/+1 and the 0/0, the biogenic carbon is assumed to be carbon neutral throughout the building life cycle; therefore, considering any of these approaches would lead to the same results. According to Table III.4, a similar consideration for the GWP indicator can be made for the ozone layer depletion (OLD) and photochemical oxidation potential (POP). Concerning the OLD, the environmental performance of PHs is distinct compared to BS1. This is basically because of fossil fuel burning (using pellet in stove heating system) in the latter case studies. An evaluation of the EP indicator results shows a 48-56% reduction of environmental impacts in PHs.

Table III.4. Impact assessment results balance for the case studies. Absolute emission per m^2 (GIA) for a 60-year lifetime is given for BS1 (low-energy building with oil boiler and wood stove), while corresponding relative values for comparison are given for the BS2 (low-energy building with oil boiler, wood stove, and MCPV), and PH1– PH2 (passive house with oil boiler, and heat pump, respectively).

Impact indicator	Unit	Absolute (unit/m^2 (GIA))	Difference (%)		
		Base case-BS1	BS2	PH1	PH2
GWP (‘0/0’ approach)	kg CO_2 eq	2431	−10	−30	−43
GWP (‘-1/+1’ approach)	kg CO_2 eq	2431	−10	−30	−43
AP	kg SO_2 eq	9.38	−8	−30	−40
ADP	kg Sb eq	0.0271	10	−7	0
OLD	mg CFC-11 eq	0.00052	−3	−35	−57
POP	kg NMVOC	0.52	−6	−38	−48
EP	kg N eq	2.51	−8	−48	−56
CED	GJ eq	64.0	−6	−38	−53

GWP = Global warming potential; AP = Acidification potential; ADP = Abiotic depletion potential; OLD = Ozone layer depletion; POP = Photochemical oxidation potential; EP = Eutrophication potential; CED = Cumulative energy demand.

Figure III.5 illustrates the environmental impact of each case study over the building life cycle, including GWP (from both '–1/+1' and '0/0' approaches), AP, ADP, OLD, POP, EP, and CED. With regard to the GWP, although the overall impact calculated with the approaches 0/0 and –1/+1 would be the same, they exhibit different impacts from their materials production and end-of-life stages. As shown in Figure III.5, with the 0/0 approach, the contribution of the materials production stage is 7-12% for case studies, while with the –1/+1 approach, it is 3-6%, which is basically due to the differences associated with the biogenic carbon uptake in the timber-based components. No benefit of sequestered biogenic carbon is considered with the 0/0 approach, while the –1/+1 approach includes biogenic carbon within the materials production stages; hence, the latter approach exhibits lower carbon emissions from the materials production stage. Figure III.5 shows that the impact from the EOL stage calculated with the –1/+1 approach is about 4% higher than the 0/0 approach. The reason behind this is that the timber-based components are assumed to be incinerated in the EOL stage, and the biogenic carbon is released accordingly.

The building operation, materials production, and maintenance stages are responsible for most environmental damages generated in most impact categories, while only a minor portion is generated during the end-of-life phase. The building operation dominates the overall indicator results in primary energy use (>70% on indicator CED), and all of the environmental categories (except abiotic depletion), whereas the ratio between building operation and other phases may vary strongly (*e.g.,* 45/55 % for PH1 in EP, reaching about 90/10 % for BS1 in indicator OLD). This dominating factor influencing the results is mainly caused by the fact that the requirement for operating energy used for household services in BS1 and BS2 is significantly higher than for passive houses.

As shown in Figure III.5, the second-largest contribution is followed by the materials production phase, basically due to the amount of materials used in the building elements during this stage, especially the cement in concrete-based components and silicone-based product on indicator GWP, ADP, and OLD. The high environmental indicator results for EP and AP are mainly due to construction products used for the building equipment, *e.g.,* the heating systems and electrical installations. The high value derives from metals, especially from copper products resulting from the use of primary copper. In contrast to that, the impacts in the category POP are influenced by other construction products, mainly plastic materials.

During the maintenance phase, the replacement of the equipment, the silicone-based product and painting in finishes, and PVC used on door and windows are the highest environmental impact contributors. The maintenance phase is the most significant contributor to the ADP indicator, essentially due to replacing the door and windows and steel production in new equipment.

As shown in Figure III.5, the possible environmental benefit coming with the application of renewable energies can be highlighted here: interestingly, the use of solar PV panels in BS2 results in a 7% reduction in the GWP, as is shown an offset for the displaced grid electricity. With technological advances and the cost reduction of PV materials, mass adoption of BIPV/BIPVT is expected that can lead to further reduction of energy consumption and global warming in net-zero energy constructions (Debbarma et al., 2017b). Additionally, while the operation phase dominates other phases with respect to primary energy use (*i.e.,* CED) and emissions in all case studies, the production and maintenance phases cannot be ignored, particularly for passive houses.

Figure III-5 also depicts that in most cases, the emissions from the end-of-life do not exceed 2% of the impacts from the use phase of existing buildings. In the recycling treatment phase, the benefits (negative values) and the loads beyond the system boundary are declared for the recycling potential of the materials. These recycling credits contribute by about 4% of the emissions balance from GWP, POP, AP, EP, and CED.

From Figure III.5, it can be concluded that as the dwellings become more energy-efficient, the environmental impacts stemming from the production, maintenance, and end-of-life of the building materials will represent a higher share of the buildings' total environmental burden and, consequently, the relevance of energy production decreases (Röck et al., 2020).

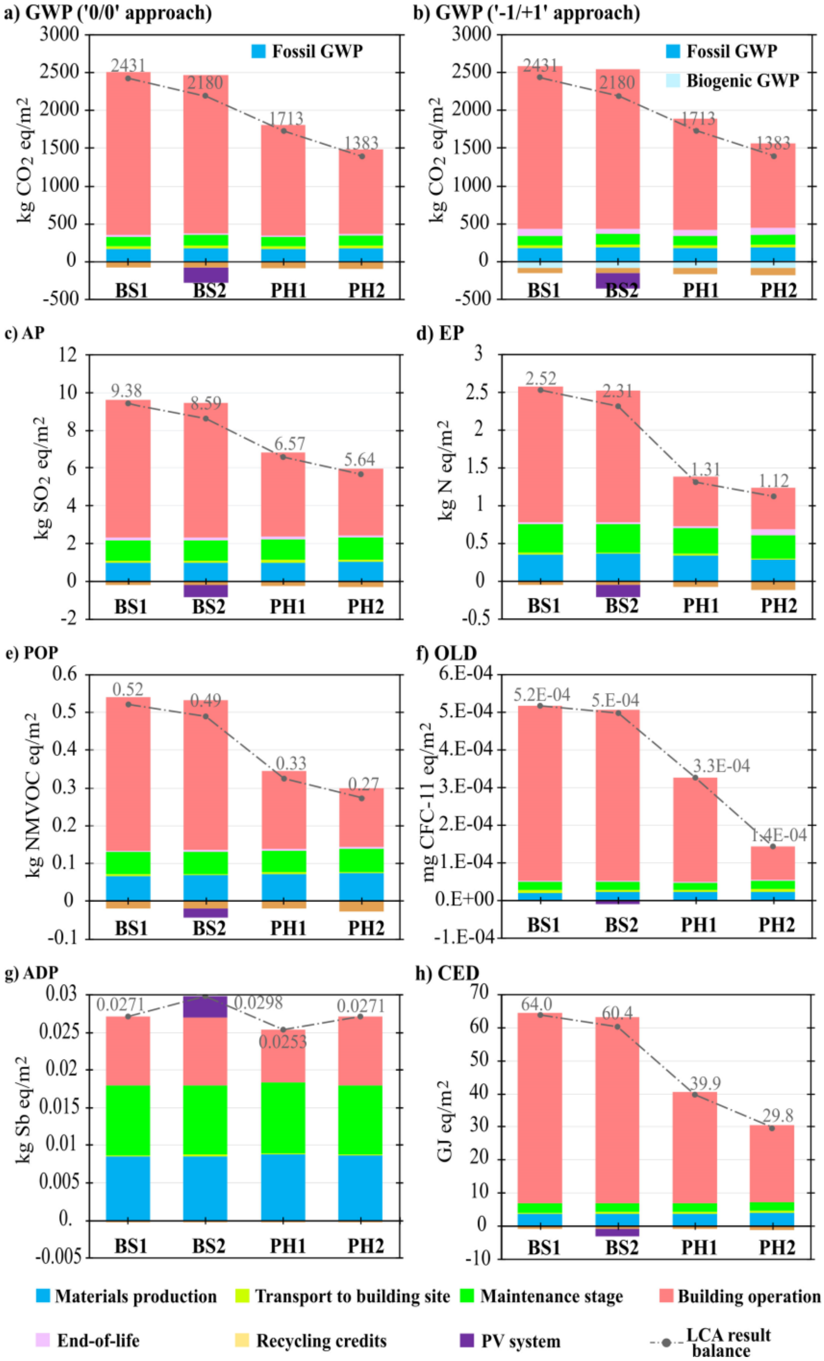

Figure III.5: Life-cycle environmental damage generated by each stage.

Figure III.6 shows the share of weight and GWP presented by various materials in each case study. As shown, concrete and cement products, insulation, and plastics contribute the most to the overall emission outputs of the constructions, while the highest portion of the construction's weight comes from the concrete and cement products (51%-53%), gravel and sand (18%-19%), and timber (7%). According to Figure III.6, there is a substantial contribution from the insulation (EPS, XPS, and mineral wool) and paint affecting the GHG (about 35% of the overall impact coming from the material level). Therefore, these materials should be considered among the main contributors to the environmental impact.

From Figure III.6 (panel a), timber has negative values in environmental impacts compared to other construction materials involved. As recovered wood is increasingly used for energy purposes in the UK (DEFRA, 2012), we assumed that wood is recovered and used as bioenergy. In addition, since concrete is used in a substantial quantity proportion in the construction, it becomes responsible for a large share of greenhouse gases.

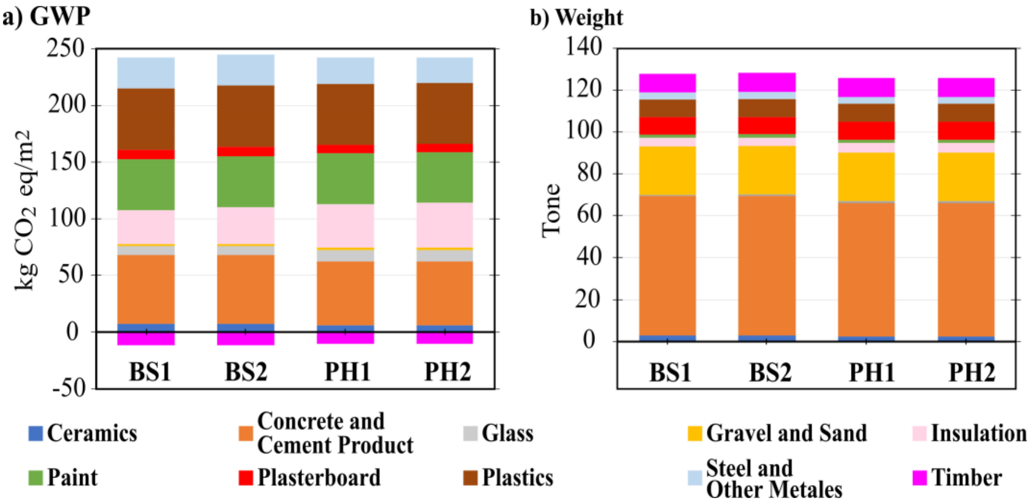

Figure III.6: The composition of house construction materials (a) in terms of greenhouse gas emission, and (b) in terms of weight.

Figure III.7 shows the breakdown of greenhouse gas emissions of each construction element for different scenarios. The finishes, mechanical works, and substructure are the top three elements with the highest GWP in all case studies. This is essentially due to silicon-based products and paints in finishes, insulation and steel in mechanical works, whereas concrete (which accounts for 50% of the total construction weight) in substructure shows relatively low GWP. The PV system significantly contributes to greenhouse gas emissions, as this dominant role is due to the significant amount of glass, steel, and aluminum in the production stage.

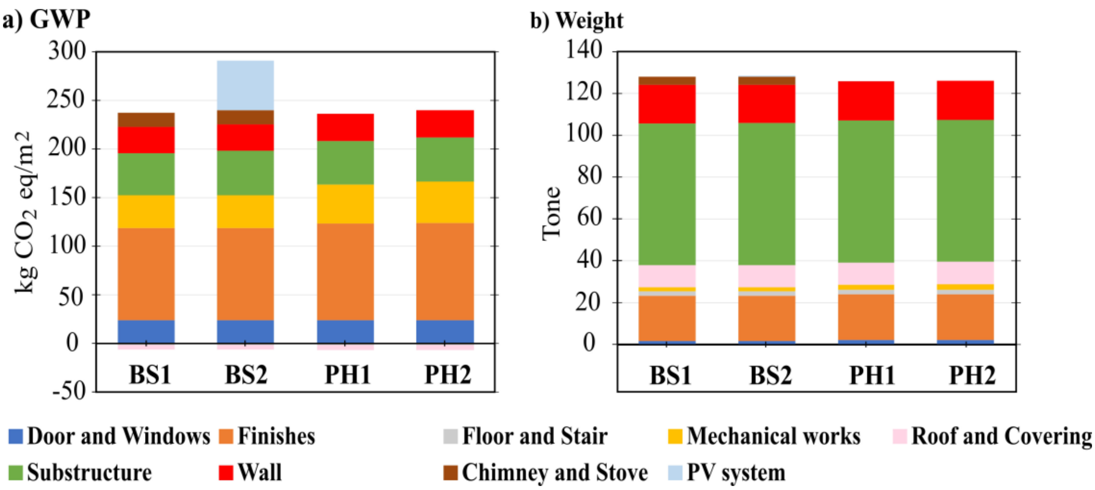

Figure III.7: The composition of house construction elements (a) in terms of greenhouse gas emission, and (b) in terms of weight.

Due to the specific nature of any LCA study (*i.e.*, the specific system under analysis, the specific assumptions, functional unit, system boundaries, quality of data, and allocation procedure), it is complicated to compare the results of this LCA analysis to other studies (Dixit et al., 2012; Dossche et al., 2017). Anyway, the results obtained for global warming potential, as the most utilized impact category, are in general agreement with those reporting the LCA results for passive houses (Dahlstrøm et al., 2012; Mahdavi and Doppelbauer, 2010; Proietti et al., 2013).

III.4.2 Effect of decarbonization of electricity production

After performing a traditional LCA in accordance with the baseline electricity mix, we analyzed the sensitivity to the decarbonization scenarios and their effects on LCA results.

Figure III.8 shows the life cycle GWP emissions over a 60-year building operation for the baseline (current energy mix of 2018) and three different electricity mix scenarios defined in TESNI (2020). Generally speaking, decarbonizing the electricity grid significantly impacts the hierarchy of case studies' life cycle GWP emissions and decreases the total environmental impact of the case studies by 70%.

The case study PH2 (*i.e.*, using the heat pump compact unit) shows the highest reduction in cumulative GWP emissions, representing 58%, 66%, and 70% reduction in the scenarios MP, ACC, and AA, respectively, in 2050, compared with current electricity mix scenario. This is due to the use of electricity as the only building energy source in this case, and therefore, a higher reduction in environmental impacts with an increase in the share of renewables. A similar consideration can be made for the low-energy case studies where a relatively low difference in GWP reduction is obtained (*e.g.*, 12% for the scenario MP, reaching about 22% for the scenario AA). This is due to the highest share of fossil fuels in its building operation among other case studies. Decarbonization of electricity is one of the key steps in order to meet the UK's target of 80% carbon reduction by 2050 (European Parliament, 2020), due to three reasons: (i) electricity generation is still one of the highest contributors to UK GHG emissions, 10% of the total national emissions in 2019 (CCC, 2020a), followed by (ii) it is expected that the electricity demand grows significantly in the future, as heating systems are electrified, and as climate change increases the demand for thermal comfort and HVAC systems (EASAC, 2021; SONI, 2020); and (iii) it is expected that the decarbonization of electricity becomes relatively more straightforward than of other sectors in the near future (Stamford and Azapagic, 2014). Therefore, it is necessary to "electrify" the building as much as possible to get the maximum benefits from the decarbonization scenario of electricity production.

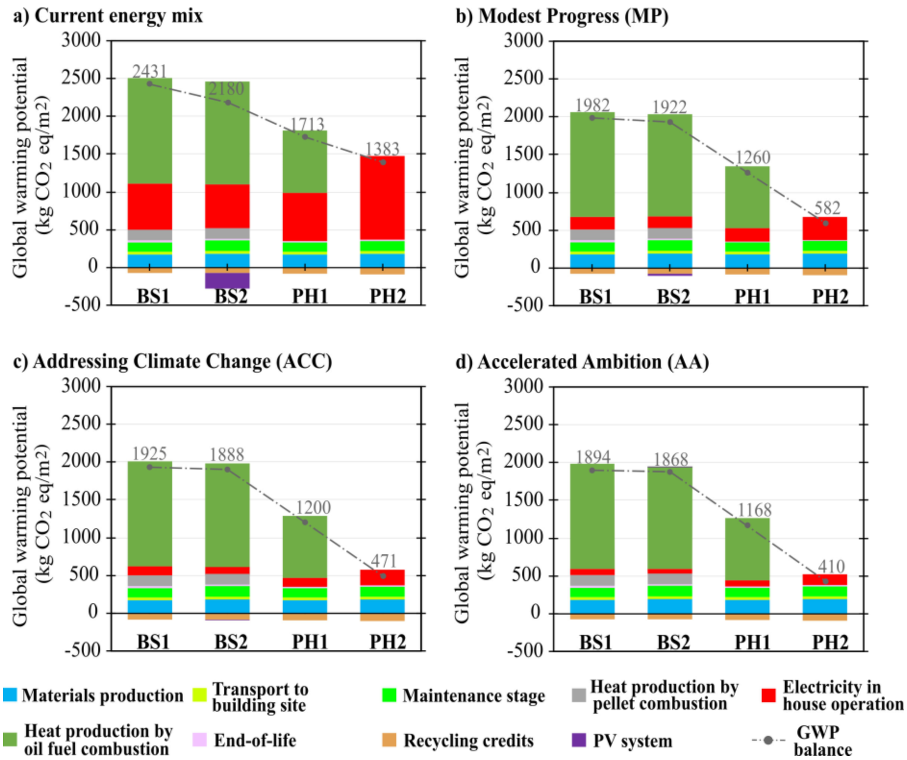

Figure III.8: Global warming potential associated with current energy mix and three future electricity mix scenarios for different case studies for the lifespan of 60 years.

This study assumes that production processes and emissions released by using the unit of energy generated from fossil-derived fuels energy carriers remain almost constant over time. As shown in Figure III.6, when electricity decarbonization is implemented, the ratio between the emission from the materials production stage to the emission from electricity-derived in the use-phase is increased significantly. For example, the ratio between building operation and other phases from the current situation and future electricity mix may vary considerably (*e.g.,* 86/14 % for BS1 in the current electricity mix, reaching about 23/77 % for PH2 in AA). This implies an increasing significance of materials production in the building's life cycle because of the decarbonization of electricity production. Therefore, close attention should be paid to the material market in any effort aiming to meet further environmental benefits.

Comparing panels a and b of Figure III.6, it can be concluded that for the case of PH2, 76% carbon emission reduction can be achieved even if modest progress is made in decarbonizing the electricity grid. Further emission reductions, up to 83%, can then be achieved as grid decarbonization becomes more prevalent.

III.4.3 Comparison to benchmark

Benchmark values from the RIBA 2030 Climate Challenge are used to assess the environmental performance and operational energy of the assessed buildings. At the time of this publication, the RIBA 2030 Climate Challenge provides metrics for embodied CO_2e benchmarking based on incremental goals for residential buildings as follows: for business as usual, it should be less than 1200 kg CO_2e/m^2 (GIA); for the year 2025, less than 800 kg CO_2e/m^2 (GIA); and for 2030, less than 625 kg CO_2e/m^2 (GIA) (RIBA, 2021). For the case of operational energy, this standard also set out the performance targets of 120 kWh/m^2 (GIA)/year, 60 kWh/m^2 (GIA)/year, and 35 kWh/m^2 (GIA)/year for business as usual, the years 2025, and 2030, respectively (RIBA, 2021).

Figure III.9 illustrates the target values of the RIBA 2030 Climate Challenge and the performance of all case studies. As shown in this figure, the case studies BS1, BS2, PH1, and PH2 emit 354 kg CO_2e/m^2, 430 kg CO_2e/m^2, 351 kg CO_2e/m^2, and 366 kg CO_2e/m^2, respectively, in which they meet not only the target values for the embodied carbon of the intermediate year 2025 (800 kg CO_2e/m^2) but also do for the targets of the year 2030 properly (625 kg CO_2e/m^2). However, with regard to the operational energy, not any of the case studies can achieve the required RIBA 2030 performance target for the year 2030. As it can be seen in Figure III-9, case study PH2 (*i.e.,* the passive house that uses a heat pump compact unit) is the only dwelling that can meet the RIBA 2030 target for operational energy by the year 2025. Therefore, as a general concluding remark, the performance of the buildings with respect to their operational energy should be improved. Here the importance of employing potential technologies such as BIPV/BIPVT systems and passive heating techniques (*e.g.*, Trombe wall) should be highlighted.

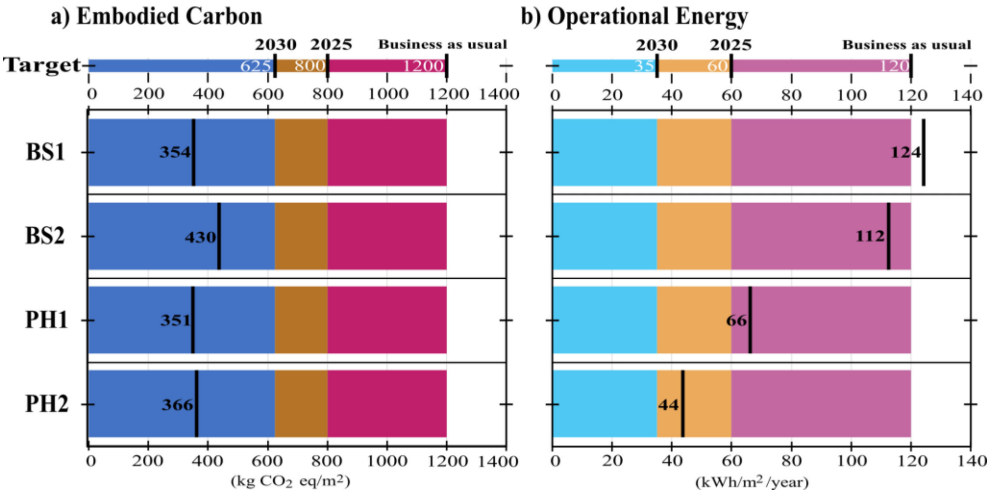

Figure III.9: Environmental and operational energy performance of the case studies and the performance targets of RIBA 2030 Climate Challenge (RIBA, 2021).

III.5 Conclusions

Previous studies have demonstrated a significant potential in Northern Ireland (NI) to combine low energy standards (*e.g.*, passive houses) with electrical heat pumps in order to achieve simultaneously reduction of operational energy and to substitute fossil fuels with renewable electricity (Colclough et al., 2020). The purpose of this life cycle approach is two-fold: to provide an estimation of the environmental impact of case study buildings designed to meet the current NI Building Regulations (as assessed by SAP 2009) and the Passivhaus standard in Northern Ireland; and to investigate the overall effect of the electricity decarbonization on the global warming potential (GWP) of the dwellings via an LCA.

The building's environmental performance was evaluated using seven environmental impact categories related to materials production, in use, and end-of-life phases. Within this study, three decarbonization scenarios, concerned with future electricity-mix scenarios according to Northern Ireland TESNI 2020, were defined, and their GWP was compared with the LCA results of the traditional static approach, *i.e.*, assuming the current electricity mix remains constant during the buildings life cycle of 60 years. All three future scenarios approach the target emission reduction of 80% for 2050 compared to 1990.

The results of the traditional LCA indicated that the building's operation phase contributed the most to the environmental impacts in all types of buildings. This is followed by the materials production phase, while the end-of-life stage shows negligible environmental impact. Additionally, in all environmental categories (except for abiotic depletion potential), the emission generated in the operation phase were dramatically higher than the corresponding amount in other building life phases. The findings also showed that implementing the passive-house standard may significantly decrease the environmental impacts with an average of 30% (and up to 50%) compared to low-energy buildings in all categories, except in abiotic depletion where low-energy buildings showed a better performance. At the material level, concrete is the main contributor to emissions across all environmental impact categories except in the adiabatic depletion category, where the insulation material is responsible for the highest environmental damages.

The findings showed that implementing any of the TESNI 2020 scenarios significantly reduced the GWP of any case study. The highest GWP reduction was corresponding to the passive house case study with the highest share of electricity demand and is as high as 58%, 66%, and 70% for the scenarios modest progress (MP), addressing climate change (ACC), and accelerated ambition (AA), respectively, when compared to the GWP reduction of the cases in traditional LCA.

Comparing the GWP of the static and the three future electricity decarbonization scenarios reveal that the highest emission reduction is related to the energy use in the "Accelerated Ambition" scenario. However, for the buildings with better thermal performance (*i.e.*, passive houses using the heat pump compact unit), the relative importance of the use phase will become smaller. In summary, it can be concluded that considering the future electricity mix over a building life cycle significantly influences the results. The results demonstrated that the passive house dwellings equipped with electric heat pump compact units represent 76% carbon emission reduction in case of modest decarbonization progress. The emission can be further reduced if the grid decarbonization becomes more prevalent (*e.g.*, up to 83% in AA). Analyzing the carbon emission of future electricity-mix scenarios showed an increase in the relative share of the production stage in the total building emission due to the decarbonization of electricity production. Therefore, close attention should be paid to the material market in any effort aiming to meet further environmental benefits.

Comparing the environmental performance of the case studies with the target values proposed in the RIBA 2030 Climate Challenge showed that all case studies perform well with respect to the embodied carbon, and they all meet the target levels set out for the intermediate year of 2025, and for 2030. However, concerning operational energy, not any of them can meet the levels proposed for 2030. Among the dwellings studied, only the case study PH2 (*i.e.*, the passive house that uses heat pump compact unit) which has represented the best performance, can meet the benchmark target value of operational energy for 2025. In this regard, the potential of employing innovative technologies, particularly BIPV/BIPVT systems and passive heating techniques (*e.g.,* Trombe wall) should be highlighted for both new and retrofit buildings, aiming to improve the building's operational energy performance.

III.6 Acknowledgments

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III.7 Nomenclature

AA	Accelerated Ambition [-]
ACC	Addressing Climate Change [-]
ADP	Abiotic Depletion Potential [kg Sb eq]
AP	Acidification Potential [kg SO_2 eq]
BIPV	Building-integrated photovoltaic [-]
BIPVT	Building-integrated photovoltaic with thermal [-]
BIM	Building Information Modelling [-]
BRE	Environmental Assessment Method
CED	Cumulative Energy Demand [GJ eq]
CML	Institute of Environmental Sciences (Faculty of Science University of Leiden, Netherlands) [-]
CO_2	Carbon dioxide [kg CO_2]
CO_2 eq	Carbon dioxide equivalent [kg CO_2 eq]
ELCD	European Life Cycle Database [-]
EoL	End-of-life [-]
EP	Eutrophication Potential [kg N eq]
EPD	Environmental Product Declaration [-]
FSC	Forest Stewardship Council [-]
ESL	Estimated Service Life [year]
FU	Functional Unit [-]
GHG	Greenhouse Gases [kg CO_2]
GIA	Gross Internal Area [m^2]
GSHP	Ground source heat pump [-]
GWP	Global Warming Potential [kg CO_2 eq]

HRE	Heat Recovery Efficiency [%]
HVAC	Heating, Ventilation and Air Conditioning [-]
ISO	International Organization for Standardization [-]
LCA	Life Cycle Assessment [-]
LCI	Life Cycle Inventory [-]
LCIA	Life Cycle Impact Assessment [-]
multi-Si PV	Multi-crystalline Silicon photovoltaics [-]
MP	Modest Progress [-]
MV	Mechanical ventilation [-]
MVHR	Mechanical ventilation with heat recovery [-]
NV	Natural Ventilation [-]
NZEB	Net or Nearly Zero Energy Building [-]
OLD	Ozone Layer Deplation [mg CFC-11 eq]
PH	Passive House [-]
PHPP	Passive house planning package [-]
PEFC	Programme for the Endorsement of Forest Certification [-]
POP	Photochemical Oxidation Potential [kg NMVOC eq]
PV	Photovoltaic [-]
RE	Renewable Energy [-]
RES-E	Electricity produced from renewable energy sources [-]
RIBA	Royal Institute of British Architects [-]
RICS	Royal Institute of Chartered Surveyors [-]
SAP	Standard Assessment Procedure [-]
SPF	Seasonal Performance Factor [%]
SDGs	Sustainable Development Goals [-]
TESNI	Tomorrow’s Energy Scenarios Northern Ireland [-]
U-value	Thermal Transmittance [W/(m^{2}K)]
UN	United Nation [-]

III.8 Appendix

The supplementary materials for the article “Low-Energy Buildings in Combination with Grid Decarbonization, Life Cycle Assessment of Passive House Buildings in Northern Ireland” are presented in this section. The Appendix is organized as follows:

III.8.1 Bill of materials for the case studies

Table III.5 reports the bill of materials used in each building case study and their corresponding construction waste factors.

Table III.5 Bill of materials for each of the case studies.

	Quantity (Ton)

Material name	**Density (kg/m3)**	**Construction waste factor** [1]	BS1	BS2	PH1	PH2
Aerated block	770	1.03	14.3	14.3	12.1	12.1
Aluminum	2700	1	0.3	0.3	0.3	0.5
Bitumen	1100	1.05	0.2	0.2	0.2	0.2
Cast iron	7200	1	0.1	0.1	0.0	0.0
Cement mortar	1800	1.05	6.3	6.3	6.3	6.3
Concrete (normal)	2200	1.03	27.4	27.4	27.4	27.4
Concrete roof tiles	44 (kg/m^2)	1	6.5	6.5	6.5	6.5
Copper	8960	1	0.6	0.6	0.6	0.6
EPS	30.5	1.03	0.1	0.1	0.1	0.1
Expanded clay	330	1.05	0.3	0.3	0.0	0.0
Fiberglass	48	1	0.0	0.0	0.0	0.0
Fly Ash Clay Brick	1800	1.02	1.9	1.9	1.9	1.9
Galvanized steel	7850	1.03	0.1	0.3	0.1	0.1
Glass wool	23	1.03	1.2	1.2	1.6	1.6
Glazing (double/triple glazing)	20/30 (kg/m^2) respectively	1	0.7	0.8	1.1	1.1
Gravel	1700	1	23.2	23.2	23.2	23.2
Gyproc board	9 (kg/m^2)	1.05	3.0	3.0	4.1	4.1
Gypsum board	941	1.05	3.0	3.0	1.8	1.8
Hardwood (oak)	740	1	0.1	0.1	0.1	0.1
MDF	800	1	0.1	0.1	0.1	0.1
OSB board	640	1	2.2	2.2	2.6	2.6
Paint (Alkyd)	1200	1.05	1.6	1.6	1.6	1.6
Phenolic resin	35	1.03	0.5	0.5	0.4	0.4
Mix plastics	1200	1.03	0.2	0.2	0.2	0.2
Plywood	620	1.03	0.4	0.4	0.4	0.4
Polyethylene (HDPE)-pipe	1.35 (kg/m)	1.03	0.3	0.3	0.3	0.3
Polyethylene (LDPE)	940	1.03	0.6	0.6	0.6	0.6
Polypropylene	920	1.03	0.5	0.5	0.5	0.5
Polyurethane	32	1.03	0.1	0.2	0.2	0.2

Precast concrete	2200	1	1.2	1.2	0.3	0.3
PVC frame	94.5 (kg/m^2)	1	0.4	0.4	0.5	0.5
Reinforcement	7850	1.03	1.2	1.2	1.2	1.2
Rockwool	45	1.03	0.4	0.4	0.5	0.5
Screed mortar	2100	1.03	11.2	11.2	11.2	11.2
Silicone seaming	1400	1.05	4.7	4.7	4.7	4.7
Softwood (Redwood, European)	510	1.03	8.4	8.4	8.4	8.4
Stainless steel	8000	1	0.0	0.0	0.0	0.0
Steel	7850	1	0.9	1.0	1.0	0.8
UPVC	1400	1	0.1	0.1	0.1	0.1
Vinyl Cork Flooring	9.2 (kg/m^2)	1.03	3.1	3.1	3.1	3.1
Wall tiles	13.5 (kg/m^2)	1	0.4	0.4	0.3	0.3
Wood chips	380	1	0.1	0.1	0.1	0.1
XPS (PolyFoam 300 kPa)	35	1.03	0.1	0.1	0.1	0.1

[1] The materials spill occurs at the construction site; the volume of this is highly dependent on the practice of the contractors. The values reported are provided by the construction company.

III.8.2 Processes used for the background data of building materials

This appendix presents the datasets used to model different materials/processes, as given in Table III.6. Most of the processes are employed from the recent data included in the Ecoinvent database v3.7.1 (Wernet et al., 2016), but others are employed according to EPDs, and the ELCD v3.2 (ELCD, 2018) databases.

Table III.6 Processes used for the background data of the materials.

Materials or process	**Source [1]**
ABS	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for
Adhesive mortar	Adhesive mortar {CH}| adhesive mortar production
Aerated block	Autoclaved aerated concrete block {CH}| autoclaved aerated concrete block production
Air filter	Air filter, decentralized unit, 180-250 m3/h {RER}| production

Alkyd paint	Alkyd paint, white, without water, in 60% solution state {RER}| alkyd paint production, white, water-based, product in 60% solution state
Aluminium	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production
Bitumen adhesive	Bitumen adhesive compound, cold {RER}| production
Bitumen seal	Bitumen seal {RER}| production
Brass	Brass {GLO}| market for
Cast iron	Cast iron {GLO}| market for
Cement mortar	Cement mortar {CH}| production
Chipboard	Folding boxboard/chipboard {GLO}| market for
Concrete (Normal)	Concrete, normal {CH}| market for
Concrete roof tiles	Concrete roof tile {CH}| concrete roof tile production
Control unit (decentralized)	Ventilation control and wiring, decentralized unit {RER}| production
Copper	Copper {GLO}| market for
Vinyl Cork Flooring	EPD Declaration number: EPD-AMO-20150058-IAA2-EN
Electronics	Electronics, for control units {RER}| production
EPS	EPD Declaration number: EPDIRE-19-14
Expanded clay	Expanded clay {RoW}| expanded clay production
Extrusion of pipes	Extrusion, plastic pipes {RER}| extrusion, plastic pipes
Extrusion of plastics	Extrusion, plastic film {RER}| production
Fiberglass	Glass fibre {RER}| glass fibre production
Fly ash cay brick	Flyash brick {RoW}| flyash brick production
Galvanized steel	Steel hot dip galvanized, including recycling, blast furnace route, production mix, at plant, 1kg, typical thickness between 0.3 - 3 mm. typical width between 600 - 2100 mm. GLO S
PVC (General)	Polyvinylchloride, suspension polymerised {RER}| polyvinylchloride production, suspension polymerisation
Glass wool	Glass wool mat {CH}| glass wool mat production
Glazing (double)	Glazing, double, U<1.1 W/m2K {GLO}| market for

Glazing (triple)	Glazing, triple, U<0.5 W/m2K {GLO}| market for glazing, triple, U<0.5 W/m2K
Gravel	Gravel, crushed {CH}| gravel production, crushed
Gyproc board	EPD Declaration number: S-P-00582
Gypsum plaster board	Gypsum plasterboard {CH}| gypsum plasterboard production
Hardwood (oak)	Sawnwood, board, hardwood, raw, dried (u=10%) {CH}| board, hardwood, raw, kiln drying to u=10%
Heat (oil)	Heat, central or small-scale, other than natural gas {Europe without Switzerland}| heat production, light fuel oil, at boiler 100kW condensing, non-modulating
Heat (wood pellet)	Heat, central or small-scale, other than natural gas {Europe without Switzerland}| heat production, wood pellet, at furnace 9kW, state-of-the-art 2014
Injection moulding	Injection moulding {RER}| processing
Lubricating oil	Lubricating oil {RER}| production
MDF	Medium density fibreboard {RER}| medium density fibre board production, uncoated
Metal working (copper)	Metal working, average for copper product manufacturing {RER}| processing
Metal working (metals)	Energy and auxilliary inputs, metal working machine {RER}| with process heat from natural gas
Oil fuel	Light fuel oil {Europe without Switzerland}| market for
OSB board	Oriented strand board {RER}| production
Phenolic resin	Phenolic resin//[RER] phenolic resin production
PV, monocrystalline	EPD Declaration number: TERR-00001-V01.01-FR
Plywood	Plywood, for indoor use {RER}| production
Polyethylene (fleece production)	Fleece, polyethylene//[RER] fleece production, polyethylene
Polyethylene	Fleece, polyethylene {RER}| production
Polyethylene (HDPE)	Combination of: Polyethylene, high density, granulate {GLO}| market for; Extrusion, plastic pipes {RER}| production; med 5% spill
Polyethylene (LDPE)	Combination of: Polyethylene, low density, granulate {GLO}| market for; Extrusion, plastic pipes {RER}| production; med 5% spill

Polypropylene	Combination of: Polypropylene, granulate {GLO}| market for; Extrusion, plastic pipes {RER}| production; med 5% spil
Polypropylene	Combination of: Polypropylene, granulate {GLO}| market for; Extrusion, plastic pipes {RER}| production; med 5% spil
Polyurethane	Polyurethane, rigid foam {RER}| production
Precast	Pre-cast concrete, min. reinf., prod. mix, concrete type C20/25, w/o consideration of casings RER S
PVC (frame)	Window frame, poly vinyl chloride, U=1.6 W/m2K {GLO}| market for
Refrigerant Gas	Refrigerant R134a {GLO}| market for
Reinforcement	Reinforcing steel//[Europe without Austria] reinforcing steel production
Rockwool (general)	Stone wool {CH}| stone wool production
Screed mortar	Concrete, 20MPa {RoW}| concrete production 20MPa
Sheet rolling, aluminium	Sheet rolling, aluminium {RER}| processing
Silencer	Silencer, steel, DN 315, 50 mm {GLO}| market for
Silicone-based seaming	EPD Declaration number: EPD-VDL-20190054-IBG1-DE
Softwood (inner door)	Door, inner, wood {RER}| production
Softwood (framing)	Sawnwood, board, softwood, raw, dried (u=10%) {CH}| board, softwood, raw, kiln drying to u=10%
Softwood (kit)	Pine wood, timber, production mix, at saw mill, 40% water content DE S
Stainless steel	Steel, chromium steel 18/8 {GLO}| market for
Stonewool	EPD Declaration number: 00131E rev1
Wall tiles	Ceramic tile {CH}| ceramic tile production
Wire-copper	Copper {RER}| production, primary
Wire coating	Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation
Wire drawing (Copper)	Wire drawing, copper {RER}| processing
Wood pellet	Wood pellet, measured as dry mass {RER}| market for wood pellet
XPS	EPD Declaration number: 000082

Zinc coat	Zinc coat, pieces {RER}| zinc coating, pieces
Road, EURO5, >32 Ton	Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5
Road, EURO5, 16-32 Ton	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5
Road, EURO5, 7.5-16 Ton	Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5
Road, EURO5, 3.5-7.5 Ton	Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5
Disposal of ABS	Waste rubber, unspecified {CH}| treatment of, municipal incineration
Disposal of adhesive mortar	Waste cement in concrete and mortar {CH}| treatment of, collection for final disposal
Recycling of aerated block	Waste concrete, not reinforced {CH}| treatment of, recycling
Disposal of aerated block	Waste concrete, not reinforced {CH}| treatment of, collection for final disposal
Disposal of air filter	Used air filter in exhaust air valve {CH}| treatment of used air filter, in exhaust air valve
Disposal of paint	Waste paint on wood {CH}| treatment of, collection for final disposal
Recycling of aluminium	Aluminium (waste treatment) {UK}| recycling of aluminium
Disposal of aluminium	Scrap aluminium {CH}| treatment of, municipal incineration
Disposal of waste bitumen	Waste bitumen {CH}| treatment of, sanitary landfill
Recycling of brass	Waste incineration of ferro metals, EU-27
Disposal of brass	Landfill of ferro metals EU-27
Recycling of cast iron	Steel and iron (waste treatment) {GLO}| recycling of steel and iron
Disposal of cement mortar	Waste cement in concrete and mortar {CH}| treatment of, collection for final disposal
Recycling of ceramics	Waste brick {CH}| treatment of, recycling
Disposal of ceramics	Waste brick {CH}| treatment of, collection for final disposal

Incineration of wood (treated)	Waste building wood, chrome preserved {CH}| treatment of, municipal incineration
Recycling of concrete	Waste concrete, not reinforced {CH}| treatment of, recycling
Disposal of concrete	Waste concrete, not reinforced {CH}| treatment of, collection for final disposal
Recycling of concrete roof tiles	Waste brick {CH}| treatment of, recycling
Disposal of concrete roof tiles	Waste brick {CH}| treatment of, collection for final disposal
Recycling of copper	Copper scrap, sorted, pressed {GLO}| market for
Disposal of copper	Scrap copper {CH}| treatment of, municipal incineration
Recycling of steel	Waste reinforcement steel {CH}| treatment of, recycling
Disposal of steel	Scrap steel {CH}| treatment of, municipal incineration
Electronic and electric waste	Waste electric and electronic equipment {GLO}| treatment of, shredding
Recycling of expanded clay	Waste brick {CH}| treatment of, recycling
Disposal of expanded clay	Waste brick {CH}| treatment of, collection for final disposal
Recycling of fiberglass	Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics
Disposal of fiberglass	Waste plastic, mixture {CH}| treatment of, sanitary landfill
Recycling of fly ash clay brick	Waste brick {CH}| treatment of, recycling
Disposal of fly ash clay brick	Waste brick {CH}| treatment of, collection for final disposal
Recycling of glass	Waste glass sheet {CH}| treatment of, sorting plant
Disposal of glass	Waste glass pane in burnable frame {CH}| treatment of, collection for final disposal

Disposal of gravel	Waste concrete gravel {CH}| treatment of, collection for final disposal
Recycling of gypsum board	Waste gypsum plasterboard {CH}| treatment of, recycling
Disposal of gypsum board	Waste gypsum plasterboard {CH}| treatment of, sorting plant
Incineration of MDF	Waste wood, untreated {CH}| treatment of, municipal incineration
Disposal of MDF	Waste fibreboard {CH}| treatment of, collection for final disposal
Incineration of OSB board	Waste incineration of wood products (OSB, particle board), EU-27
Landfill of OSB board	Landfill of wood products (OSB, particle board) EU-27
Disposal of phenolic resin	Waste plastic, mixture {CH}| treatment of, sanitary landfill
Incineration of wood (untreated)	Waste wood, untreated {CH}| treatment of, municipal incineration
Landfill of wood (untreated)	Landfill of untreated wood EU-27
Recycling of polyethylene	PE (waste treatment) {UK-adopted}| recycling of PE
Disposal of polyethylene	Waste polyethylene {CH}| treatment of, municipal incineration
Recycling of PP element	PP (waste treatment) {UK-adopted}| recycling of PP
Disposal of PP element	Waste polypropylene product {CH}| treatment of, collection for final disposal
Recycling of PU element	Waste polyurethane {CH}| treatment of, municipal incineration
Disposal of PU element	Waste polyurethane {CH}| treatment of, municipal incineration
Recycling of precast concrete	Waste concrete, not reinforced {CH}| treatment of, recycling

Disposal of precast concrete	Waste concrete, not reinforced {CH}| treatment of, collection for final disposal
Recycling of PVC element	PVC (waste treatment) {UK-adopted}| recycling of PVC
Disposal of PVC element	Waste polyvinylchloride {CH}| treatment of, sanitary landfill
Recycling of reinforced steel	Waste reinforcement steel {CH}| treatment of, recycling
Disposal of reinforced steel	Waste reinforcement steel {CH}| treatment of, collection for final disposal
Disposal of rockwool	Waste mineral wool {CH}| treatment of, collection for final disposal
Disposal of screed mortar	Waste cement in concrete and mortar {CH}| treatment of, collection for final disposal
Recycling of gypsum board	Waste gypsum plasterboard {CH}| treatment of, recycling
Disposal of gypsum board	Waste gypsum plasterboard {CH}| treatment of, sorting plant
Disposal of glass wool	Waste mineral wool {CH}| treatment of, collection for final disposal
Recycling of fly ash cay brick	Waste brick {CH}| treatment of, recycling
Disposal of fly Ash clay brick	Waste brick {CH}| treatment of, collection for final disposal
Recycling of wire coating	Waste wire plastic {CH}| treatment of, municipal incineration
Disposal of wire coating	Waste plastic, mixture {CH}| treatment of, sanitary landfill

[1] CH: Switzerland; RER: Representing Europe; RoW: Rest of the World; GLO: Global.

III.8.3 Lifespan of the different components

For the components lacking EPDs, the RISC default lifespan provided in Table III.7 should be used.

Table III.7 Lifespan of the different components according to the RICS guidance (RICS, 2017).

Building part	**Building elements/components**	**Expected lifespan (years)**
Roof	Roof coverings	30
Superstructure	Internal partitioning and dry lining	30
Finishes	Render	30
	Paint	10
	Floor finishes	30
	Raised Access Floor (RAF)/Finish layers	10
	Ceiling Substrate	20
	Ceiling Paint	10
Services/MEP	Heat source *e.g.*, boilers, …	20
	Space heating and air treatment	20
	Ductwork	20
	Electrical installations	30
Facade	Opaque modular cladding *e.g.*, rain screens, timber panels	30
	Glazed cladding/Curtain walling	35
	Windows and external doors	30

III.8.4 Transportation scenarios for the materials

The default scenarios for the UK projects specified by RICS (RICS, 2017) for transport to the building site (module A4), and scenarios for waste processing (C2) are given in Table III.8.

Table III.8 Transportation scenarios for the main materials based on RICS (RICS, 2017)

Materials	**A4 (km by road)**	**C2 (km by road) [1]**
Concrete, Gravel and sand, and Reinforcing steel	50	50
Concrete Block, Ceramics, Insulation, Plasterboard, Timber, Glass, and Plastics	300	50
Paint, PV system, Heating and Ventilation system	1500	50

[1] Transportation for both waste sorting and processing site

III.8.5 End-of-life scenarios for the different case studies

The end-of-life scenarios for the study are considered based on information collected from EPDs, and RICS recommendations are presented in Table III.9 (RICS, 2017). According to the RICS proportions, 90% of each material was assumed to be recycled, while the remaining 10% was lost during the recycling. For Timber waste, 25% is considered to be landfilled and 75% incinerated with energy recovery. The mineral wool and natural wastes are assumed to be fully landfilled.

Table III.9 End-of-life scenarios are based on RICS recommendation (RICS, 2017)

<table>
<tr><th rowspan="2">Materials and products used in the case studies</th><th colspan="3">RICS proportions</th></tr>
<tr><th>Landfill</th><th>Recycling</th><th>Incineration</th></tr>
<tr><td>Plywood, Wood Chipboard, Hardboard, Softwood</td><td>25%</td><td>0%</td><td>75%</td></tr>
<tr><td>Reinforcing Steel, Stainless Steel, Steel, Galvanised Steel</td><td>4%</td><td>96%</td><td>0%</td></tr>
<tr><td>Copper</td><td>35%</td><td>65%</td><td>0%</td></tr>
<tr><td>Aluminium</td><td>4%</td><td>96%</td><td>0%</td></tr>
<tr><td>Cement Mortar, Plaster Coat, Ceramic Tiles, Brick, Concrete Block, Plaster Boards</td><td rowspan="4">10%</td><td rowspan="4">90%</td><td rowspan="4">0%</td></tr>
<tr><td>Polystyrene, Polyurethane, XPS</td></tr>
<tr><td>PE, PP, LDPE Pipes, PS</td></tr>
<tr><td>PVC</td></tr>
</table>

III.8.6 Electricity production technologies and the corresponding processes used for the background data for the electricity mix scenarios

Table III.10 Electricity production technologies and the corresponding processes used for the background data for the electricity mix scenarios

Generation technology	Ecoinvent unit process used for modeling in this study (Wernet et al., 2016)
Coal	{GB}| electricity production, hard coal
Oil	{GB}| electricity production, oil
Natural gas (NGCC)	{GB}| electricity production, natural gas, combined cycle power plant
Natural gas CCS [1]	See note 1
Onshore Wind	{GB}| electricity production, wind, 1-3MW turbine, onshore
Offshore Wind	{GB}| electricity production, wind, 1-3MW turbine, offshore
Solar photovoltaics [2]	{GB}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si
	{GB}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted
Hydroelectric	{GB}| electricity production, hydro, run-of-river
Marine Tidal [3]	See note 3
Biomass	{GB}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014
Energy from waste	{GB}| electricity, from municipal waste incineration to generic market for electricity
Interconnector [4]	See note 4

[1] According to TESNI 2020 (SONI, 2020), carbon capture and storage (CCS) is deployed on the existing and new natural gas combined cycles (NGCCs), and it is assumed to capture 90% of CO_2 emissions from fuel combustion. Therefore, the NGCC process is adapted with the CCS model. The inventories for the CCS model are provided in Table III.11 and Table III.12.
[2] According to TESNI 2020 (SONI, 2020), an even split between photovoltaic rooftops installations and large-scale PV (ground arrays) is considered.
[3] The inventory information for this case is provided in Table III.13.
[4] The TESNI 2020 (SONI, 2020) imports are modeled with the "Electricity, high voltage {GB}| import from IE".

Table III.11 Inventory data for carbon capture and storage (CCS) technology, complementing natural gas combined cycle (NGCC) power plants; all data sourced from (Raugei et al., 2020).

Materials or process	**Unit**	**Quantity**
Activated Carbon	kg	3.2E10−5
Concrete	kg	2.1E10−7
Electricity	kWh	4.7E10−2
Monoethanolamine (MEA)	kg	1.8E10−4
Polyethylene, high density (HDPE)	kg	7.1E10−7
Sodium hydroxide (NaOH)	kg	5.5E10−5
Steel (low alloyed)	kg	7.7E10−5

Table III.12 Inventory data of use-phase emissions per kWh of electricity generated by the NGCC + CCS system, all data sourced from (Raugei et al., 2020).

Materials or process	**Unit**	**Quantity**
Carbon dioxide (CO_2)	g	47
Nitrogen oxides (NOx)	g	1.7E10−1
Sulphur dioxide (SO_2)	g	3.8E10−3
Particulate matter (PM)	g	2.2E10−3
Formaldehyde (HCHO)	g	1.1E10−1
Acetaldehyde (CH3-CHO)	g	7.0E10−2
Ammonia (NH3)	g	1.5E10−2
Monoethanolamine (MEA)	g	2.6E10−2

Table III.13 Inventory data for stream turbine tidal electricity generation, all data sourced from (Raugei et al., 2020).

Materials or process	**Unit**	**Quantity**
Cast Iron	kg	1.5E10−6
Cement	kg	2.5E10−5
Copper	kg	3.2E10−6
Electricity	kWh	1.9E10−2
Glass fibre reinforced plastics	kg	9.4E10−6
Polyethylene (PE)	kg	4.7E10−7
Steel (low alloyed)	kg	1.6E10−4

III.8.7 Solar PV technical specifications

Table III.14 Solar PV technical specifications (PVsyst SA, 2022; Terreal Solution PV3-1 S, 2017).

Parameter	**Unit**	**Value**
Manufacturer & model	–	Terreal Solutions PV3-1S
Technology	–	Multi-crystalline Silicon
Installation Type	–	Roof parallel
Number of panels	Piece	8
Module efficiency	%	15.4%
Performance ratio	%	84
Tilt angle	◦	30
Azimuth angle	◦	0
Module dimensions	m	1.64 m x 0.992 m
Albedo	%	20
Soil	%	0
Shadow	%	0
Inverter manufacturer	–	AEG
Lifetime expectancy	years	25

III.9 References

Autodesk, 2021. Revit for MEP Engineering. Industries. URL https://www.autodesk.com/products/revit/mep (accessed 7.15.22).

BRE, 2014. SAP 2012 - The Government' s Standard Assessment Proceedure for Energy Rating of Dwellings. Technical Report rev June 2014. Buiding Res. Establ. (on behalf DECC). Watford.

Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., Castell, A., 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.08.037

Causone, F., Tatti, A., Pietrobon, M., Zanghirella, F., Pagliano, L., 2019. Yearly operational performance of a nZEB in the Mediterranean climate. Energy Build. 198, 243–260. https://doi.org/10.1016/J.ENBUILD.2019.05.062

CCC, 2020. The Sixth Carbon Budget-The UK's path to Net Zero. Comm. Clim. Chang. URL http://www.theccc.org.uk/publications/ (accessed 5.9.21).

CCC, 2019. UK housing: Fit for the future?. Comm. Clim. Chang. URL https://www.theccc.org.uk/publications (accessed 12.28.21).

CEN, 2013. EN 15804:2012+A1:2013 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. Eur. Comm. Stand. URL https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=EN+15804%3A2012%2BA1%3A2013+Sustainability+of+construction+works+-+Environmental+product+declarations+-+Core+rules+for+the+product+category+of+construction+products&btnG=

CEN, 2012. EN 15804:2012 - Sustainability of Construction Works. Environmental Product Declarations. Core Rules for the Product Category of Construction Products. Eur. Comm. Stand. URL https://scholar.google.com/scholar_lookup?title=EN 15804%3A Sustainability of Construction Works. Environmental Product Declarations. Core Rules for the Product Category of Construction Products&publication_year=2012&author=European Committee for Standard (accessed 9.2.21).

CEN, 2011. EN 15978:2011 - Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method. Eur. Comm. Stand. URL https://scholar.google.com/scholar_lookup?title=EN 15978%3A2011 - Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method&publication_year=2011&author=%2FTC 350 CEN (accessed 9.17.22).

Chica, J.A., Apraiz, I., Elguezabal, P., Rrips, M.O., Sánchez, V., Tellado, B., 2011. Kubik: Open building approach for the construction of an unique experimental facility aimed to improve energy efficiency in buildings. Open House Int. 36, 63–72. https://doi.org/10.1108/OHI-01-2011-B0008

Colclough, S., Hewitt, N., Griffiths, P., 2020. Unlocking the potential - Low-Energy Dwelling & Heat Pump. Investigating their multiple benefits, and how to increase adoption rates, in: PLEA 2020 - Planning Post Carbon Cities - 35th International Conference on Passive and Low Energy Architecture : WestminsterResearch. University of A Coruña & Asoc. PLEA 2020 Planning Post Carbon Cities.

Colclough, S., McWilliams, M., 2019. Cost Optimal UK Deployment of the Passive House Standard. Proc. Int. Conf. Innov. Appl. Energy 14-15 March 2019. Oxford, UK, 261.

D'Agostino, D., Parker, D., 2018. A framework for the cost-optimal design of nearly zero energy buildings (NZEBs) in representative climates across Europe. Energy 149, 814–829. https://doi.org/10.1016/J.ENERGY.2018.02.020

Dahlstrøm, O., Sørnes, K., Eriksen, S.T., Hertwich, E.G., 2012. Life cycle assessment of a single-family residence built to either conventional- or passive house standard. Energy Build. https://doi.org/10.1016/j.enbuild.2012.07.029

de Bruijn, H., van Duin, R., Huijbregts, M.A.J., 2002. Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards, Eco-Efficiency in Industry and Science. Springer Netherlands, Dordrecht. https://doi.org/10.1007/0-306-48055-7

De Wolf, C., Pomponi, F., Moncaster, A., 2017. Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. Energy Build. 140, 68–80. https://doi.org/10.1016/J.ENBUILD.2017.01.075

Debbarma, M., Sudhakar, K., Baredar, P., 2017a. Comparison of BIPV and BIPVT: A review. Resour. Technol. 3, 263–271. https://doi.org/10.1016/J.REFFIT.2016.11.013

Debbarma, M., Sudhakar, K., Baredar, P., 2017b. Thermal modeling, exergy analysis, performance of BIPV and BIPVT: A review. Renew. Sustain. Energy Rev. 73, 1276–1288. https://doi.org/10.1016/J.RSER.2017.02.035

DECC, 2009. The Government's Standard Assessment Procedure for Energy Rating of Dwellings. Watford, UK Build. Res. Establ. URL https://www.bregroup.com/sap/standard-assessment-procedure-sap-2009/ (accessed 4.19.21).

DEFRA, 2012. Wood waste: A short review of recent research. Dep. Environ. Food Rural Aff. URL http://www.defra.gov.uk/consult/ (accessed 9.18.22).

Dias, A.C., Arroja, L., 2012. Environmental impacts of eucalypt and maritime pine wood production in Portugal. J. Clean. Prod. 37, 368–376. https://doi.org/10.1016/j.jclepro.2012.07.056

Dixit, M.K., Fernández-Solís, J.L., Lavy, S., Culp, C.H., 2012. Need for an embodied energy measurement protocol for buildings: A review paper. Renew. Sustain. Energy Rev. 16, 3730–3743. https://doi.org/10.1016/J.RSER.2012.03.021

Dong, Y., Ng, S.T., Liu, P., 2021. A comprehensive analysis towards benchmarking of life cycle assessment of buildings based on systematic review. Build. Environ. 204, 108162. https://doi.org/10.1016/J.BUILDENV.2021.108162

Dossche, C., Boel, V., De Corte, W., 2017. Use of Life Cycle Assessments in the Construction Sector: Critical Review. Procedia Eng. 171, 302–311. https://doi.org/10.1016/J.PROENG.2017.01.338

DUKES, 2020. Digest of UK Energy Statistics (DUKES). Dep. Business, Energy Ind. Strateg. URL https://www.gov.uk/government/statistics/dukes-calorific-values (accessed 4.7.21).

DUKES, 2019. Digest of UK Energy Statistics (DUKES). Dep. Business, Energy Ind. Strateg. URL https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes (accessed 4.5.21).

EASAC, 2021. European Academies’ Science AdvisoryCouncil - Decarbonisation of buildings: for climate, health and jobs : EASAC policy report 43.

ELCD, 2018. European Commission Joint Research Centre. Eur. Life Cycle Database (ELCD). Eur. Platf. life cycle Assess. URL http://eplca.jrc.ec.europa.eu/ELCD3/ (accessed 4.5.21).

EN 16449, 2014. EN 16449:2014–Wood and wood-based products - Calculation of the Biogenic Carbon Content of wood and Conversion to Carbon Dioxide. Eur. Stand. URL https://www.en-standard.eu/csn-en-16449-wood-and-wood-based-products-calculation-of-the-biogenic-carbon-content-of-wood-and-conversion-to-carbon-dioxide/ (accessed 9.16.22).

European Commission, 2019. LEVEL(S) - Taking action on the TOTAL impact of the construction sector. Luxemb. Publ. Off. Eur. Union, 2019. https://doi.org/10.2779/458570

European Commission, 2017. Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3. URL https://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm (accessed 4.10.21).

European Parliament, 2020. European Parliament Resolution of 15 January 2020 on the European Green Deal (2019/2956 (RSP)). Eur. Parliam. URL https://www.europarl.europa.eu/doceo/document/TA-9-2020-0005_EN.html (accessed 9.20.22).

Frischknecht, R., Wyss, F., Knöpfel, S.B., Lützkendorf, T., Balouktsi, M., 2015. Cumulative energy demand in LCA: the energy harvested approach. Int. J. Life Cycle Assess. 2015 207 20, 957–969. https://doi.org/10.1007/S11367-015-0897-4

Guinee, J.B., 2002. Handbook on life cycle assessment operational guide to the ISO standards. Int. J. Life Cycle Assess. 2002 75 7, 311–313. https://doi.org/10.1007/BF02978897

Gustavsson, L., Joelsson, A., 2010. Life cycle primary energy analysis of residential buildings. Energy Build. https://doi.org/10.1016/j.enbuild.2009.08.017

HCS, 2016. Northern Ireland House Condition Survey 2016. Res. Unit North. Irel. Hous. Exec. Belfast. URL https://www.nihe.gov.uk/Working-With-Us/Research/House-Condition-Survey (accessed 4.4.21).

Hossain, Y., Marsik, T., 2019. Conducting life cycle assessments (LCAs) to determine carbon payback: A case study of a highly energy-efficient house in rural Alaska. Energies 12. https://doi.org/10.3390/en12091732

Hoxha, E., Passer, A., Ruschi, M., Saade, M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., Habert, G., 2020. Biogenic carbon in buildings: a critical overview of LCA methods. Build. Cities 1, 504–524. https://doi.org/10.5334/BC.46

ISO 14040, 2006. Environmental Management — Life Cycle Assessment — Principles and Framework. Int. Organ. Stand. Switz. URL https://www.iso.org/standard/37456.html (accessed 8.20.22).

ISO 14044, 2006. Environmental Management — Life Cycle Assessment — Requirements and Guidelines. Int. Organ. Stand. Switz. URL https://www.iso.org/standard/72357.html (accessed 9.20.22).

Itten, R., Frischknecht, R., Stucki, M., Scherrer, P., PSI, I., 2014. Life Cycle Inventories of Electricity Mixes and Grid. Version 1.3.

Jaber, S., Ajib, S., 2011. Optimum design of Trombe wall system in mediterranean region. Sol. Energy 85, 1891–1898. https://doi.org/10.1016/J.SOLENER.2011.04.025

Khasreen, M.M., Banfill, P.F.G., Menzies, G.F., 2009. Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. Sustain. 2009, Vol. 1, Pages 674-701 1, 674–701. https://doi.org/10.3390/SU1030674

Kiss, B., Kácsor, E., Szalay, Z., 2020. Environmental assessment of future electricity mix – Linking an hourly economic model with LCA. J. Clean. Prod. 264, 121536. https://doi.org/10.1016/J.JCLEPRO.2020.121536

Kumar, D.A., 2014. Solar Energy for Passive House Design. Int. J. Eng. Res. Technol. 3.

Lee, B., Trcka, M., Hensen, J.L.M., 2013. Building energy simulation and optimization: A case study of industrial halls with varying process loads and occupancy patterns. Build. Simul. 2013 73 7, 229–236. https://doi.org/10.1007/S12273-013-0154-3

Litjens, G.B.M.A., Worrell, E., van Sark, W.G.J.H.M., 2018. Lowering greenhouse gas emissions in the built environment by combining ground source heat pumps, photovoltaics and battery storage. Energy Build. 180, 51–71. https://doi.org/10.1016/J.ENBUILD.2018.09.026

Louwen, A., van Sark, W.G.J.H.M., Faaij, A.P.C., Schropp, R.E.I., 2016. Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development. Nat. Commun. 2016 71 7, 1–9. https://doi.org/10.1038/ncomms13728

Magrini, A., Lentini, G., Cuman, S., Bodrato, A., Marenco, L., 2020. From nearly zero energy buildings (NZEB) to positive energy buildings (PEB): The next challenge - The most recent European trends with some notes on the energy analysis of a forerunner PEB example. Dev. Built Environ. 3, 100019. https://doi.org/10.1016/J.DIBE.2020.100019

Mahdavi, A., Doppelbauer, E.M., 2010. A performance comparison of passive and low-energy buildings. Energy Build. 42, 1314–1319. https://doi.org/10.1016/J.ENBUILD.2010.02.025

Martani, C., Lee, D., Robinson, P., Britter, R., Ratti, C., 2012. ENERNET: Studying the dynamic relationship between building occupancy and energy consumption. Energy Build. 47, 584–591. https://doi.org/10.1016/J.ENBUILD.2011.12.037

Mirzaie, S., Thuring, M., Allacker, K., 2020. End-of-life modelling of buildings to support more informed decisions towards achieving circular economy targets. Int. J. Life Cycle Assess. 25, 2122–2139. https://doi.org/10.1007/S11367-020-01807-8/FIGURES/8

Monahan, J., Powell, J.C., 2011. A comparison of the energy and carbon implications of new systems of energy provision in new build housing in the UK. Energy Policy 39, 290–298. https://doi.org/10.1016/J.ENPOL.2010.09.041

Moran, F., Blight, T., Natarajan, S., Shea, A., 2014. The use of Passive House Planning Package to reduce energy use and CO2 emissions in historic dwellings. Energy Build. 75, 216–227. https://doi.org/10.1016/J.ENBUILD.2013.12.043

Morris, F., Allen, S., Hawkins, W., 2021. On the embodied carbon of structural timber versus steel, and the influence of LCA methodology. Build. Environ. 206, 108285. https://doi.org/10.1016/J.BUILDENV.2021.108285

Mosteiro-Romero, M., Krogmann, U., Wallbaum, H., Ostermeyer, Y., Senick, J.S., Andrews, C.J., 2014. Relative importance of electricity sources and construction practices in residential buildings: A Swiss-US comparison of energy related life-cycle impacts. Energy Build. 68, 620–631. https://doi.org/10.1016/J.ENBUILD.2013.09.046

Motuziene, V., Rogoža, A., Lapinskiene, V., Vilutiene, T., 2016. Construction solutions for energy efficient single-family house based on its life cycle multi-criteria analysis: A case study. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2015.08.103

Moynihan, G.P., Triantafillu, D., 2012. Energy savings for a manufacturing facility using building simulation modeling: A case study. EMJ - Eng. Manag. J. 24, 73–84. https://doi.org/10.1080/10429247.2012.11431957

NISRA, DfE, 2019. Electricity Consumption and Renewable Generation Statistics. North. Irel. Stat. Res. Agency Stat. within Dep. Econ. Anal. Serv. Unit. URL https://www.economy-ni.gov.uk/articles/electricity-consumption-and-renewable-generation-statistics (accessed 4.5.21).

Ortiz-Rodríguez, O., Castells, F., Sonnemann, G., 2010. Life cycle assessment of two dwellings: One in Spain, a developed country, and one in Colombia, a country under development. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2010.02.021

Paris Agreement, 2015. The Paris Agreement -legally binding versus non-legally binding instruments. 12 December 2015.. United Nations Framew. Conv. Clim. Chang. URL https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en (accessed 4.12.21).

Passivhaus Institut, 2015. Passive house planning package (PHPP), version 9, user handbook. Darmstadt Passiv. House Inst. URL https://passivehouse.com/04_phpp/04_phpp.htm (accessed 7.6.21).

Penny, T., Collins, M., Aumônier, S., Ramchurn, K., Thiele, T., 2013. Embodied Energy as an Indicator for Environmental Impacts – A Case Study for Fire Sprinkler Systems. Smart Innov. Syst. Technol. 22, 555–565. https://doi.org/10.1007/978-3-642-36645-1_52

Pré Consultants, 2022. SimaPro. PRé Sustain. B.V. URL https://simapro.com/ (accessed 9.20.22).

Proietti, S., Sdringola, P., Desideri, U., Zepparelli, F., Masciarelli, F., Castellani, F., 2013. Life Cycle Assessment of a passive house in a seismic temperate zone. Energy Build. https://doi.org/10.1016/j.enbuild.2013.05.013

PVsyst SA, 2022. PV-syst 7.2, Photovoltaic System Software 7.2. URL https://www.pvsyst.com/ (accessed 9.14.22).

Quinteiro, P., Tarelho, L., Marques, P., Martín-Gamboa, M., Freire, F., Arroja, L., Dias, A.C., 2019. Life cycle assessment of wood pellets and wood split logs for residential heating. Sci. Total Environ. 689, 580–589. https://doi.org/10.1016/j.scitotenv.2019.06.420

Ramon, D., Allacker, K., 2021. Integrating long term temporal changes in the Belgian electricity mix in environmental attributional life cycle assessment of buildings. J. Clean. Prod. 297, 126624. https://doi.org/10.1016/J.JCLEPRO.2021.126624

Rasmussen, F.N., Ganassali, S., Zimmermann, R.K., Lavagna, M., Campioli, A., Birgisdóttir, H., 2019. LCA benchmarks for residential buildings in Northern Italy and Denmark–learnings from comparing two different contexts. Build. Res. Inf. 47, 833–849. https://doi.org/10.1080/09613218.2019.1613883

Raugei, M., Kamran, M., Hutchinson, A., 2020. A Prospective Net Energy and Environmental Life-Cycle Assessment of the UK Electricity Grid. Energies 2020, Vol. 13, Page 2207 13, 2207. https://doi.org/10.3390/EN13092207

RIBA, 2021. 2030 Climate Challenge. URL https://www-architecture-com.sabidi.urv.cat/about/policy/climate-action/2030-climate-challenge (accessed 12.28.21).

Richardson, I., Thomson, M., Infield, D., 2008. A high-resolution domestic building occupancy model for energy demand simulations. Energy Build. 40, 1560–1566. https://doi.org/10.1016/J.ENBUILD.2008.02.006

RICS, 2017. Whole life carbon assessment for the built environment. R. Inst. Chart. Surv. Parliam. Sq. London SW1P 3AD. URL https://www.rics.org/globalassets/rics-website/media/news/whole-life-carbon-assessment-for-the--built-environment-november-2017.pdf (accessed 9.14.22).

Röck, M., Saade, M.R.M., Balouktsi, M., Rasmussen, F.N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., Passer, A., 2020. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. Appl. Energy 258, 114107. https://doi.org/10.1016/J.APENERGY.2019.114107

Rodrigues, C., Freire, F., 2017. Environmental impact trade-offs in building envelope retrofit strategies. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-016-1064-2

Roetzel, A., Tsangrassoulis, A., Dietrich, U., 2014. Impact of building design and occupancy on office comfort and energy performance in different climates. Build. Environ. 71, 165–175. https://doi.org/10.1016/J.BUILDENV.2013.10.001

Rohrlich, M., Mistry, M., Martens, P.N., Buntenbach, S., Ruhrberg, M., Dienhart, M., Briem, S., Quinkertz, R., Alkan, Z., Kugeler, K., 2000. A method to calculate the cumulative energy demand (CED) of lignite extraction. Int. J. Life Cycle Assess. 2000 56 5, 369–373. https://doi.org/10.1007/BF02978675

Sandin, G., Peters, G.M., Svanström, M., 2014. Life cycle assessment of construction materials: The influence of assumptions in end-of-life modelling. Int. J. Life Cycle Assess. 19, 723–731. https://doi.org/10.1007/S11367-013-0686-X

SONI, 2020. Tomorrow’s Energy Scenarios Northern Ireland 2020 (TESNI)-Planning our Energy Future. SONI Ltd. 2020, Castlereagh House, 12 Manse Road, Belfast, BT6 9RT, North. Irel. URL https://www.soni.ltd.uk/customer-and-industry/energy-future/ (accessed 10.5.21).

Stamford, L., Azapagic, A., 2014. Life cycle sustainability assessment of UK electricity scenarios to 2070. Energy Sustain. Dev. 23, 194–211. https://doi.org/10.1016/J.ESD.2014.09.008

Su, S., Li, X., Zhu, Y., Lin, B., 2017. Dynamic LCA framework for environmental impact assessment of buildings. Energy Build. 149, 310–320. https://doi.org/10.1016/J.ENBUILD.2017.05.042

Terreal Solution PV3-1 S, 2017. PV system-EPD Ecopassport. pep-ecopassport.org. URL http://www.pep-ecopassport.org/ (accessed 9.11.22).

Thygesen, R., Karlsson, B., 2013. Economic and energy analysis of three solar assisted heat pump systems in near zero energy buildings. Energy Build. 66, 77–87. https://doi.org/10.1016/J.ENBUILD.2013.07.042

Tokbolat, S., Nazipov, F., Kim, J.R., Karaca, F., 2019. Evaluation of the environmental performance of residential building envelope components. Energies. https://doi.org/10.3390/en13010174

UK Government's National Calculation Methodology, 2021. Standard Assessment Procedure. Dep. Business, Energy Ind. Strateg. URL https://www.gov.uk/guidance/standard-assessment-procedure (accessed 12.25.21).

United Nations, 2015. Open Working Group proposal for Sustainable Development Goals. Sutainable Dev. - Knowl. Platf. URL https://sustainabledevelopment.un.org/focussdgs.html (accessed 2.25.21).

van Stijn, A., Malabi Eberhardt, L.C., Wouterszoon Jansen, B., Meijer, A., 2021. A Circular Economy Life Cycle Assessment (CE-LCA) model for building components. Resour. Conserv. Recycl. 174, 105683. https://doi.org/10.1016/J.RESCONREC.2021.105683

Vicente, E.D., Vicente, A.M., Musa Bandowe, B.A., Alves, C.A., 2016. Particulate phase emission of parent polycyclic aromatic hydrocarbons (PAHs) and their derivatives (alkyl-PAHs, oxygenated-PAHs, azaarenes and nitrated PAHs) from manually and automatically fired combustion appliances. Air Qual. Atmos. Heal. 9, 653–668. https://doi.org/10.1007/s11869-015-0364-1

Visa, I., Moldovan, M.D., Comsit, M., Duta, A., 2014. Improving the renewable energy mix in a building toward the nearly zero energy status. Energy Build. 68, 72–78. https://doi.org/10.1016/J.ENBUILD.2013.09.023

VITO, KU Leuven, TU Graz, 2018. PEF4Buildings—Study on the Application of the PEF Method and related guidance documents to a newly office building (ENV.B.1/ETU/2016/0052LV) 428. https://doi.org/10.2779/23505

Waide, P., 2019. The impact of the revision of the EPBD on energy savings from the use of building automation and controls. Manchester, UK: Waide Strategic Efficiency Ltd.

Wang, L., Gwilliam, J., Jones, P., 2009. Case study of zero energy house design in UK. Energy Build. 41, 1215–1222. https://doi.org/10.1016/J.ENBUILD.2009.07.001

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Zhang, T., Wang, M., Yang, H., 2018. A Review of the Energy Performance and Life-Cycle Assessment of Building-Integrated Photovoltaic (BIPV) Systems. Energies 2018, Vol. 11, Page 3157 11, 3157. https://doi.org/10.3390/EN11113157

Zhou, Z., Feng, L., Zhang, S., Wang, C., Chen, G., Du, T., Li, Y., Zuo, J., 2016. The operational performance of “net zero energy building”: A study in China. Appl. Energy 177, 716–728. https://doi.org/10.1016/J.APENERGY.2016.05.093

Zhu, L., Hurt, R., Correa, D., Boehm, R., 2009a. Comprehensive energy and economic analyses on a zero energy house versus a conventional house. Energy 34, 1043–1053. https://doi.org/10.1016/J.ENERGY.2009.03.010

Zhu, L., Hurt, R., Correia, D., Boehm, R., 2009b. Detailed energy saving performance analyses on thermal mass walls demonstrated in a zero energy house. Energy Build. 41, 303–310. https://doi.org/10.1016/J.ENBUILD.2008.10.003

Chapter IV

Whole-building LCA (*i.e.,* carbon footprint) of low-energy buildings by incorporating BIM, BEM, and EPD

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IV. Whole-building LCA (*i.e.*, carbon footprint) of low-energy buildings by incorporating BIM, BEM, and EPD

Carbon footprint of low-energy buildings in the United Kingdom: effects of mitigating technological pathways and decarbonization strategies

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IV.1 Introduction

Climate change, mainly associated with human activities (anthropogenic), is one of the most global challenges in damaging the environment (Mahmoud and Gan, 2018). Global warming, as a result of greenhouse gas (GHG) emissions, has been growing at an alarming rate, and they are considered to have the highest potential to intensify worldwide environmental concerns (Benato and Stoppato, 2019; López et al., 2023). To comply with the European Green Deal (European Parliament, 2020), the European Commission has put forward a plan to cut down GHG emissions by at least 55 % compared to 1990 levels by 2030, and an ambitious aim at a climate-neutral economy by 2050 (European Environment Agency (EEA), 2020). Among the various GHG emitters, the construction sector is a critical area for global carbon neutrality and achieving sustainable development (Chen et al., 2022; Norouzi et al., 2021). For example, in the United Kingdom (UK), the construction of buildings is directly responsible for 13 % of total emissions through manufacturing and construction activities, and indirectly responsible for a further 18 % due to heating, cooling, and lighting of buildings (CCC, 2021). Besides, due to the population growth and to ensure human well-being, the government set a target to build 300,000 new homes per year by the mid-2020s in England (about an annual 1.7 % increase trend by 2030) (Feng et al., 2022; POST, 2021), while continuously contributing to the GHG emission (*i.e.*, CO_2eq emission). In this light, stronger efforts are needed in the construction industry to shift from the current paradigm toward the co-benefits of low-carbon buildings through directives, building regulations, as well as proper environmental management (Din and Brotas, 2016).

The quantity of GHG emissions caused by buildings can be measured comprehensively, across their entire life cycle, through whole life-carbon assessment. The objective is two-fold: (i) reducing emissions associated with the various energy demands during the operational phase of a building including heating, cooling, ventilation, and lighting; and (ii) lowering those embodied carbon emissions in materials, associated with the GHG emissions produced by the manufacturing, renovation, maintenance, and end-of-life of building materials. So far, the main focus of policymakers and practitioners were primarily to concentrate on efforts the decarbonizing operational emissions, through improving energy efficiency to reduce the building energy demand (Röck et al., 2020). This enhancing energy efficiency in building design and systems may reduce the site energy-related emissions from the buildings, but it can potentially lead to an increase in environmental loads of source energy-related emissions from the electricity mix production, and the potential of buildings for efficient heating, ventilation, and air conditioning (HVAC) systems (Rahif et al., 2022). At present, central heating from a natural gas-fired boiler is the most common system in UK residential buildings (~92 % in 2017 (Lin et al., 2021)), while Government has set to end fossil-fuel heating systems in new houses from 2025 as a result of Future Homes Standard on a national scale (HM Government, 2019a). The potential of low-carbon HVAC systems such as heat pumps was underlined as a prominent option to reduce the use of fossil fuels, lowering GHG emissions (Scamman et al., 2020). However, their large-scale deployment is not widely spread in the UK, mainly due to three concerns: (i) it may lead to an increase in the peak demand of electricity consumption; (ii) their considerably higher investment cost than for gas boilers, even though the higher efficiency of heat pumps reduces the required heater capacity; and (iii) due to high carbon intensity of electricity, they may not necessarily result in lower environmental performance than condensing gas boilers (Greening and Azapagic, 2012; Lin et al., 2021). In this context, the Government has attempted to encourage manufacturers to reduce the costs of heat pumps by at least 25-50 % by 2025 (POST, 2021). Further, with respect to the decarbonization of power generation, there is significant progress made by the UK (from ~3 % in 2000 to ~43 % of electricity generation from renewable sources in 2020 (DUKES, 2021a)), while a net-zero emissions system necessitates radical changes across all energy sectors to mitigate carbon emissions (Wang et al., 2022). Under the EU Emissions Trading System (EU ETS) regulation, the UK is legally bound to speed up the transformation by 3–17 years for different parts of the electricity system and produce at least 74 % of the electricity from renewable resources by 2030 (Pietzcker et al., 2021).

Giving the focus solely on reducing the emissions from the building operation requires more extensive construction materials (*i.e.*, thicker insulation, energy-efficient glazing, etc), which might involve boundary passing the environmental impacts from the use phase to other building life cycle modules (Asdrubali et al., 2019). Moreover, it is suggested that improving the environmental performance of the operation phase can significantly increase the relative importance of embodied emissions, sometimes exceeding the impact of the operational phase (LETI, 2020b; Saade et al., 2020; UKGBC, 2019). Within this purview, focusing on material efficiency is critical for climate change mitigation of buildings (Lausselet et al., 2021). Several material efficiency strategies have been identified as more intense use of building materials and extending their lifetimes, using lighter and less emissions-intensive materials, improving construction waste processing, and applying circularity principles through the reuse and recycling of building components (Hertwich et al., 2019; Pomponi and Moncaster, 2016). At a national level, the UK

Green Building Council (UKGBC) has set out a framework definition that aims to support progress toward net-zero carbon buildings (UKGBC, 2019). To achieve these targets, identifying and applying the effectiveness and possible CO_2 emissions reductions in the building would, therefore, include tackling not only the operational carbon (OC) emissions but also the embodied carbon (EC) emissions (Brooks et al., 2021; POST, 2021). Hence, the broad analysis involving whole life-carbon (including particularly embodied carbon) would provide a more complete picture of the GHGs during the building's life cycle and enables the identification of carbon hotspots and optimal combined mitigation strategies.

Furthermore, the use of timber as a construction material for buildings is growing significantly in the UK over the last decade. According to the Structural Timber Association (STA), the timber frame market represented 28.4 % of UK houses in 2016, and its demand was expected to increase by an annual 10 % trend by 2021 (STA, 2016). The possibility of storing carbon and achieving carbon sink effects through the increased use of bio-based building materials is now included in the UK's Climate Change Committee (CCC) as one of the most effective options for zero-carbon buildings (CCC, 2018). According to the study (Hafner and Schäfer, 2017), single/two-family residential buildings can potentially reduce 35 % up to 56 % GHG emissions in timber houses compared to mineral buildings. Even though studies that compare methodological assumptions exist (Arehart et al., 2021; Hoxha et al., 2020), the treatment of biogenic carbon storage is an unsettled issue in the life cycle assessment (LCA) of buildings. Several researchers (Fouquet et al., 2015; Levasseur et al., 2013; Negishi et al., 2018; Santos et al., 2021) highlighted the importance of considering biogenic carbon, as well as how the choices related to the waste management scenarios of timber products, lead to a significant variation in the LCA results for buildings and could provide useful information for policy-making on the implementation of different solutions for emission reduction. However, the discussion around the effects of different modeling approaches and future scenarios with regard to the waste treatment of biogenic carbon flows of construction products and buildings is getting more attention within the LCA society (Andersen et al., 2022; Petrović et al., 2023).

There have been several studies investigating the strategies to reduce the environmental and resource footprints of buildings. For instance, the application of higher levels of fabric insulation (Lamy-Mendes et al., 2021; Rodrigues et al., 2023); building and service life extension (De Castro et al., 2014; Valencia-Barba et al., 2023); using phase change material (PCM) and Trombe wall (Al-Yasiri and Szabó, 2022; Aranda-Usón et al., 2013); alternative building materials and sustainable management of building waste (Gan et al., 2022; Hossain and Ng, 2020; Zhang et al., 2022); adopting energy-efficient systems and equipment (M. Smith et al., 2021; Wu et al., 2018); improving the occupant behavior profiles (Fajilla et al., 2020; Lam et al., 2022); and increases in renewable energy sources (RES) (Al-Shetwi, 2022; Zhang et al., 2018). Although these studies have attempted to investigate the various mitigation measures to help reduce the buildings' environmental burdens, most of them did not include the complete life cycle perspective in their case studies of building emissions. In addition, studies investigating emission reduction measures (Alaux et al., 2023; Crawford, 2011; Norouzi et al., 2021) have focused primarily on building operations and there are few efforts have been placed on measuring and reducing the impact of embodied emissions on the building life cycle.

Moreover, the vast majority of the existing LCA studies have conducted their analysis by applying the static approach which means that, for example in energy modeling, the current UK energy mix is considered to remain constant over the lifetime of the building (Collinge et al., 2013; De Wolf et al., 2017; Kiss et al., 2020). However, neglecting the impact of changes in the electricity mix is one of the most significant drawbacks of the current LCA practices (Negishi et al., 2018), as the decarbonization of electricity generation through increasing the share of renewable sources has a crucial role to decrease GHG emissions (Fouquet et al., 2015; Zhou et al., 2016). Therefore, the LCA of buildings should include temporal aspects to assess tracking the potential changes over a long period and help to make environmental assessment results more robust (Anand and Amor, 2017; Negishi et al., 2018). In this perspective, limited studies have taken this effect to improve their LCA studies. For instance, some studies only considered the time-dependent changes for certain pivotal moments during the use stage of buildings instead of variations over their entire life cycles (Collinge et al., 2014; Roux et al., 2016); some researchers considered only the heating system (Bianco et al., 2017; Neirotti et al., 2020); while others applied the theoretical concepts without a representative building application studies (Negishi et al., 2018; Su et al., 2017; Wang et al., 2021).

To the knowledge of the authors, there is no comprehensive LCA study that addresses the environmental performance of low-energy residential buildings in which the potential contribution of the UK's national strategies, in particular, the impact of the grid decarbonizing and technological changes in waste management treatments of timber materials, for achieving European climate policies and potential improvements to the future electricity systems was investigated. This study intends to fill this gap. Besides this paper investigates: (i) the relative impacts of different building life stages by considering the whole life-carbon emissions and particularly to further study whether the embodied emissions are significantly influenced by the building elements (*i.e.*, choice of materials); (ii) the influence of accounting carbon sequestration in the LCA results; (iii) the impact of widely used HVAC systems on the GHG emissions of the case studies; and (iv) the effect of different levels up of combustion or degradation practices at the end-of-life of timber products on the environmental performance of the buildings. Furthermore, the LCA results will be further compared with the UK benchmark regime for the buildings' carbon targets, aiming to provide insights to policymakers and building designers of the analyzed potential decarbonization solutions.

The remainder of this paper is strFigure I.4: Schematic representation of accounted biogenic carbon.uctured as follows. Section IV.2 provides an overview of the data and methodology used. First, the LCA methodology is described, followed by the data collection of the case studies, and the different scenarios analyses were undertaken. Section IV.3 presents the results of the baseline scenario and the effects of future decarbonization of electricity generation and technological progress on the waste management treatments of timber materials. Section IV.4 discusses the results, limitations, and future work in light of current building decarbonization literature. Section IV.5 summarizes the results of the work.

IV.2 Materials and methods

IV.2.1 Research methodology

A combination of scenario-based modeling and LCA methodology is used in this study. Figure IV.1 summarises the design framework employed in three main steps. The first step is the collection of building data from relevant databases (*e.g.*, environmental product declarations (EPDs)), and the development of a building information modeling (BIM) model for the case study. Besides, to illustrate different plausible directions, the methodological choices of dynamic aspects and prospective scenarios following government plans and targets are integrated into the results. It is, therefore, required to develop an LCA in accordance with the methodological modular approach of EN 15978 (CEN, 2011), as a baseline scenario, *i.e.*, existing technology and context should be assumed for the calculation (Collinge et al., 2013; Hart et al., 2021). Then, the prospective parameters for data collection and calculation describe a sensitivity analysis based on time-dependent values. In the second step, the changes are integrated using impact categories and environmental indicators into the LCA of the building. Finally, the LCA results of the different scenarios are analyzed and compared with the baseline scenario approach.

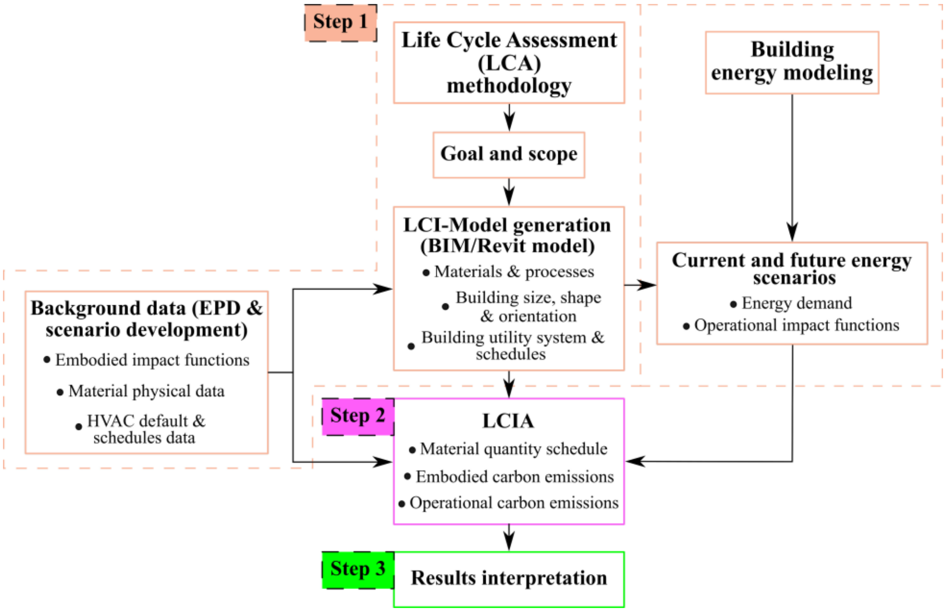

Figure IV.1: Framework scheme of the LCA research methodology.

IV.2.2 LCA methodological framework

The life cycle assessment (LCA) is a powerful decision support method that can determine the potential environmental impacts, especially the GHG emission, of a process/product through its entire life cycle (cradle-to-grave or cradle-to-cradle).

As shown in Figure IV.1, building information modeling (BIM) is oriented to the modeling and communication of both graphic and non-graphic information to organize, store, exchange, and allow access to the building data during its life cycle to increase productivity in building design and construction. The application of BIM in this approach is a significant contribution to improving the processes of building life cycle assessment as it allows managing the semi-automatic calculations of the life cycle assessment through the link of an excel-based database (Shin and Cho, 2015). The BIM-based LCA approach still has several limitations, such as concerns regarding data interoperability among BIM applications, human-made errors, and lack of database flexibilities (*e.g.*, the possibility to add materials) (Najjar et al., 2019; Santos et al., 2020b, 2020a). Even though some recent studies have focused on improving the inclusion of environmental information in the BIM model to address these limitations, a more regulated approach is required (Santos et al., 2020b).

In this study, the preferred LCA methodology in accordance with ISO 14040 and 14044 (ISO 14040, 2006; ISO 14044, 2006), and the European EN 15978 and 15804 framework for the "Sustainability of Construction Works – Assessment of Buildings"

(CEN, 2019, 2011) are conducted for assessing the whole life-carbon emissions of building according to the following four steps: (i) definition of the goal and scope of LCA; (ii) life cycle inventory analysis (LCI); (iii) life cycle impact assessment (LCIA); and (iv) interpretation.

IV.2.2.1 Application to a real case study

In order to verify the LCA model, a semi-detached dwelling built to satisfy the requirements of the "Passivhaus" standard (Feist, 2011) and evaluated with the Standard Assessment Procedure (SAP) to comply with UK's buildings regulations (UK Government's National Calculation Methodology, 2021) is chosen as a reference case study. Appendix IV.8.1 in Supplementary Materials shows the layout and elevation of the reference case study. The dwelling, which represents the most common characteristics of a British two-story timber-framed structure, is constructed with a timber frame kit system to external leaf, insulated with the high-performance thermal layer in the wall and the roof, and sheathed with oriented strand board (OSB). The ground floor and foundations are made of a reinforced concrete slab with three layers of expanded polystyrene (EPS) insulation. The internal walls are made of timber stud framework and insulation in between with sheets of plasterboards on both sides. The construction details for the external walls, roofs, internal walls, and foundation of the studied building system are described in Appendix IV.8.2 in Supplementary Materials. The building benefits from the application of argon gas-filled triple glazing with high-performance UPVC framing. In the reference case building model (*i.e.*, BS1), the cooling and heating are provided by a combination of mechanical ventilation with heat recovery (MVHR) and an efficient condensing gas boiler that is directly connected to the storage tank. Based on the target from UK's building regulations, resulting from the implementation of nearly zero-energy buildings (nZEB) targets, the adoption of low-carbon technologies (*e.g.*, electric heat pump) could achieve a substantial reduction in the energy consumption of buildings (D'Agostino, 2015). Moreover, to further reduce energy consumption, the use of heat pumps when combined with the photovoltaic system is a solution of current interest for the UK's building policies which plays a crucial role in the energy balance of an nZEB (De Masi et al., 2021; EASAC, 2021). Therefore, three strategies that are among the widely applicable HVAC systems in UK houses are implemented through efficient energy options: (i) a gas-fired boiler + MVHR (*i.e.*, reference case BS1); (ii) an electric compact heat pump unit as a replacement for condensing gas boiler and MVHR (*i.e.*, BS2); and (iii) a photovoltaic system along with the electric compact heat pump (*i.e.*, BS3).

The compact heat pump unit is an 'All-In-One' Air-to-Water and Air-to-Air system for a complete home climate solution with a seasonal coefficient of performance (SCOP) equal to 5.11. The main thermal characteristics of the building envelope components and integrated technical systems are given in Appendix IV.8.3 in Supplementary Materials.

Based on the real data obtained from the as-built construction drawings, the BIM models were developed by Autodesk Revit (Autodesk, 2021). The embodied environmental impacts are obtained from product-specific EPD data and the scenarios development procedure of the processes in the model (see section IV.2.2.3.1). The measurement of operational energy use is performed using DesignBuilder (DB) v6.1 energy simulation software to quantify the annual energy consumption (DesignBuilder, 2021). The DB software calculates the operation phase of the dwelling including energy systems from households' use of heat energy and electricity for space and water heating, and lighting (de Rubeis et al., 2018). These parameters were assessed according to the UK-based building standards and the ASHRAE-approved heat balance method using real hourly data from the EnergyPlus database (EnergyPlus, 2022). The life cycle operational flow used in the LCA is further elaborated in section IV.2.2.3.2. To evaluate the effect of varying the composition of the energy source in building operations, a dynamic dataset is explored to account for the development of future electricity mixes in a sensitivity analysis (see section IV.2.4.1). For these scenario predictions, official national statistics of energy mix over the lifespan of the building are combined with data describing these processes from Ecoinvent (Wernet et al., 2016), and analyzed in SimaPro (Pré Consultants, 2022).

The electricity produced from the PV system is injected into the grid displaces, and therefore, according to the UKGBC 'Renewable Energy Procurement & Carbon Offsetting Guidance for net zero carbon buildings' (UKGBC, 2021), it is assumed that offsets produced by exporting on-site produced electricity can be discounted from the operational emissions. The carbon savings are calculated using the same amount of emission intensity of the low-voltage electricity grid for that given year. Fourteen multi-Si PV panels are mounted on the roof with an efficiency of 15.4 % and a total peak power of 3 kW. The solar PV component was simulated using PVsyst (PVsyst SA, 2022), and quantified an average annual electricity generation of ~2630 kWh/y. Appendix IV.8.4 in Supplementary Materials reports the technical specifications of the solar PV panels.

IV.2.2.2 Research goal and scope

The initial part of the model constitutes the goal and scope definition, where the research goal, system boundary, functional unit (FU), and reference study period (RSP) are analyzed. The research goal is to evaluate the GHG emissions of a representative timber-frame low-energy building based on a standard practice of LCA as a reference point (*i.e.,* baseline scenario). The baseline scenario represents the current LCA practice employed, as suggested by EN 15978 (Bianco et al., 2017; CEN, 2011; RICS, 2017). In this model, we performed the LCA system using static characterization factors and assuming the current technologies and practices remained constant into the calculation, whereas other prospective scenarios are compared with the baseline scenario to discuss the potential changes by parameters describing alternative future developments (Andersen et al., 2022; Fouquet et al., 2015). To initiate this task, the present paper compares three different levels of HVAC strategies, including a gas-fired boiler + mechanical ventilation with heat recovery (MVHR), an electric compact heat pump unit (SCOP: 5.11), and an electric compact heat pump unit (SCOP: 5.11) + 3 kW photovoltaic (PV) panels. More importantly, to better represent the possible development of technological progress to climate change mitigation at the national level, a sensitivity analysis is investigated to assess the influence of future scenarios of the electricity mix pathways and the technological changes in waste management treatments of timber materials.

The FU defines the quantification of the identified function of the studied systems, which is the basis for the quantification of all environmental impacts (de Simone Souza et al., 2021; ISO 14040, 2006). One square meter of gross internal area (GIA) is proposed as a FU to compute the impacts on the buildings; this choice allows further contributions with other studies and building benchmarks (LETI, 2021). According to the Royal Institution of Charted Surveyors (RICS) (RICS, 2017), an average RSP of 60 years was chosen for the service life, which is the standard lifespan of UK buildings and consistent with the Green Guide to Specification standard (BRE, 2021).

The modular structure setup from EN 15978 (CEN, 2011), as shown in Figure IV.2, is considered in this study to allow the incorporation of the whole model of the building's life cycle, including the production stage (modules A1–A3); construction process stage (modules A4–A5); use stage, differentiated into modules related to embodied impacts (modules B1–B5) and impacts from operational energy and water use (modules B6–B7); end-of-life (modules C1–C4); additionally, the benefits and loads beyond the system boundary (module D). Building material boundary corresponds to the imported raw materials under study which they characterized in the area, including the building structure, finishing elements, and mechanical systems (such as concrete and cement products, steel and other metals, insulation, plastics, painting, …). Sanitary fittings and installations are excluded from this study. It should be noted that the details pertaining to the goal and scope used for the LCA are consistent with the RICS guidance (RICS, 2017) to enable investigating the whole life carbon assessment of the building case studies and the possibility of comparison with the target values (LETI, 2021).

Building life cycle																Supplement
Production			Construction		Use							End-of-life				Beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Row materials supply	Transport to manufacturer	Manufacturing	Transport to construction site	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/demolition	Transport	Waste processing	Disposal	Recovery/Reuse/Recycling
Embodied impact										Operational impact		Embodied impact				Potential benefits and loads

Figure IV.2: Building's life cycle stages from EN15804 and EN15978 (CEN, 2019, 2011).

IV.2.2.3 Inventory analysis

In the LCI, the primary data of resources and energy consumptions are collected for modeling the foreground processes and the datasets for quantification of relevant inputs and outputs throughout the product life cycle are elaborated (Wang et al., 2022). The primary data related to the amount and type of building materials used is performed based on a BIM/Revit model (Autodesk, 2021). The BIM model (*i.e.*, level 2 standard) is generated based on the building design layout and the data about construction products provided by the construction company. The data quantities exported from the BIM model were then post-processed to provide the accurate mining and aggregation of the materials used in the building design (Maierhofer et al., 2022). The materials obtained based on the BIM model are grouped with similar functions in general waste treatment categories, for example, concrete, timber and timber-based, steel and other metals, oil-based (*e.g.*, expanded polystyrene (EPS), extruded polystyrene (XPS), and polyurethane (PUR)), inert (gravel, plasterboard, paint, render, and adhesive mortar), composite (windows, and doors), etc. The list of quantities of material categories for different building case studies is presented in Appendix IV.8.5 in Supplementary Materials. In the energy simulation, the material information provided by the BIM model has been used as the input for the thermal analysis.

To deliver reliable and consistent results, the data collection process, scenarios development procedure, and cut-off rule are considered in this step (AzariJafari et al., 2021). The cut-off rule, as indicated in EN 15804 (CEN, 2019), is applied to the processes within the system boundaries described in section IV.2.2.2. This means that data needs to correspond to the system boundaries set for the assessment. Based on this, the cumulative total of all neglected inputs should not exceed 5 % of energy usage and mass allocated, while it is a maximum of 1 % for each unit process. However, this cut-off rule does not apply to hazardous materials and substances.

IV.2.2.3.1. Life cycle embodied flow

As a data collection and calculation process, the use of product-specific data in the form of third-party verified EPD for each material/product based on the local market could obtain not only consistent and accurate life-cycle inventory and data, but also provide comparable and transparent LCA results (CEN, 2011). EPDs summarise the description of the product's life-cycle environmental impact that has been developed in accordance with the standardized product category rules, which are transparent and verified documents (Honarvar et al., 2022). As the main source of information used in this environmental assessment, we resorted to several EPD databases to collect nationally published EPDs of materials that exist in the UK market (*e.g.,* The International EPD System (EPD International AB, 2023), Wood for Good Lifecycle Database (Wood for Good, 2023), ECO Platform (EcoPlatform, 2023), and GreenBookLive (BRE Group, 2023)). The shortcomings of the datasets were carefully retrieved from European countries with a similar carrier portfolio to the UK (*e.g.,* Netherlands, Ireland, and Belgium). All EPDs selected in this study were produced to the following requirements of EN 15804 (CEN, 2019), due to EPD standardization, and the comparability of EPDs, as well as inconsistencies in the material denomination. However, the use of EPD data at different stages to conduct a whole building's life cycle presents several challenges, as EPDs are based on one probable scenario and they are not always context-specific (AzariJafari et al., 2021; Fufa et al., 2018). In this study, according to RICS (RICS, 2017) guidance, the most accurate information data for modules (A1–A3), (B1–B3), (C3–C4), and (D) are retrieved from the manufacturers' EPDs. For the remaining life stages and to increase consistency, the background data are obtained based on a project-specific basis (*i.e.,* considering the project location, anticipated operation, and waste management scenarios) (RICS, 2017). In this sense, the scenarios development procedure is employed to clearly identify the appropriate assumptions and estimations for the UK conditions, according to the RICS and IStructE guidance (IStructE, 2022; RICS, 2017), when the data situation is unclear (Yan Wang et al., 2022).

To estimate the emissions of transportation from the manufacturing facility to the construction site (A4), building elements are classified into three transport categories depending on the product sourcing locations and the default scenarios of the UK's projects specified by RICS (RICS, 2017). These categories are used in combination with the standard transportation distances and applied in the datasets (Appendix IV.8.6 in Supplementary Materials). The impact from the construction energy use (A5) is calculated for the fuel (*i.e.*, electricity, and diesel) consumption of on-site equipment for wood frame buildings using the estimated values of 15 MJ/m^2 of diesel and 2 kWh/m^2 of electricity (Balasbaneh and Sher, 2021). Moreover, the NetWaste (WRAP, 2008) factors are accounted for material wastage of the activities during the construction of the building and then applied to the overall values of inventoried construction materials from the production stage (Appendix IV.8.7 in Supplementary Materials). The UK Government emission conversion factors (BEIS, 2021) are used for the carbon equivalent (CO_2eq) impact of electricity, transport, and fuel consumption.

Any carbon emissions released from building components (*e.g.*, refrigerant leakage by the mechanical systems), and the impact of potential carbon uptake of concrete during the life of the building are accounted for the module B1. Calculation of the emission concerning the refrigerant leakage is based on the manufacture report, while the assessment of carbonation is explained in section IV.2.3. To calculate the impacts of materials with lower estimated service life (ESL) than the reference study period (RSP) of the building, the quantity of new items and their end-of-life stage and transportation to the site needed for regular maintenance and replacements are modeled based on the material use percentage and life expectancy of different components and systems (Appendix IV.8.8 in Supplementary Materials).

During the end-of-life (EoL) stage, the most environmentally feasible option is selected, as it is assumed that the actual practices will be the same at the end of the lifespan (Larivière-Lajoie et al., 2022). The carbon emission from any deconstruction and demolition activities (C1) is estimated based on an average value for building demolition of 3.4 $kgCO_2eq/m^2$ (GIA) (RICS, 2017). The transportation of waste to the disposal facility or intermediate waste processing location (C2) is calculated with a standard distance of 50 km (Hart et al., 2021). In processing and disposal of the waste treatment and any benefit beyond of system boundary (C3–C4, and D), the percentage allocation of waste materials going to different treatments is based on the current practices and facilities of the building sector in the UK for different types of waste materials, as assessed jointly with the construction company based on the representative EPDs of the chosen building context. When the data for the product's end-of-life is not reflected in the same context as the UK waste practices defined in the RICS recommendation (RICS, 2017), the EPDs used can allow the building assessor to choose and calculate the correct scenario based on the assumption that 100 % of the material was disposed of solely via one means (Barrett et al., 2019). For those with unavailable data, the default carbon factors according to the IStructE (IStructE, 2022) guidance are considered in the calculation. The default rates for the EoL situation of the building elements are summarized in Appendix IV.8.9 in Supplementary Materials. According to UK practices, 90 % of the general waste mass is recycled or recovered at the end-of-life of the buildings and used for a secondary application (RICS, 2017); however, wool insulation and gypsum board are assumed to be sent to the landfill (Balasbaneh and Sher, 2021). For timber materials, one aspect of the EoL stage is the considerably sensitive results to the inclusion of biogenic carbon (Peñaloza et al., 2016), which has already been discussed in section IV.2.3. Another important aspect is how timber materials are treated after demolition. According to the RICS recommendation and in line with the Department for Environment, Food and Rural Affairs (DEFRA) of the UK (DEFRA, 2012), the assumption made for timber waste materials was that 25 % is considered to be landfilled (with no gas recovery) and 75 % incinerated with energy recovery (to generate electricity). It is used for the baseline EoL scenario for timber materials; however, this is a conservative approach, as the implication of landfilling wood in the UK is declining (Symons et al., 2013), and consequently, recycling and biomass recovery of timber is expected to become an increasingly common practice in the upcoming years (Peñaloza et al., 2016). With respect to this advantage from a sustainability perspective, the scenario analysis for modeling different future waste treatments of timber materials is carried out in section IV.2.4.2. Concerning timber degradation in landfill, a proportion of carbon contained is released into the atmosphere as CO_2 and methane (CH4) (note that CH4 has a GWP 25 times higher than CO_2 (IPCC, 2007)). In this study, it is assumed that 20 % of the timber is decomposed into carbon, from which 60 % into CH4 and 40 % into CO_2, and none of the landfill gas is recovered, as this is the common practice for timber waste management in the UK (Symons et al., 2013). The key parameters used for the carbon impact of the timber EoL scenarios are shown in Appendix IV.8.10 in Supplementary Materials. It should be noted that the benefits and burdens regarding the reuse, recovery, and recycling of materials after the end-of-life are included to measure the influence on the results but are accounted for separately to the system boundary according to EN 15978 and EN 15804 (CEN, 2019, 2011).

IV.2.2.3.2. Life cycle operational flow

The dynamic building energy simulation is performed using DesignBuilder (DB) for the energy assessment of environmental performance during the operational stage of the case studies (DesignBuilder, 2021). The data exchange from BIM/Revit model was first exported as a gbXML file and then imported into DB. The default DB profiles were applied harmonized with the ‘standard user’ based on the local climate conditions, and characteristics of the building shell extracted from the models' information, while the energy use pattern and users' behavior parameters are set according to the SAP 2012 (BRE, 2014), and ASHRAE guide (Ben and Steemers, 2014). The DB model was generated according to the analytical model and included the building envelope which they have a significant impact on the overall U-value of the building (Bughio et al., 2021). The weather file used for this study is extracted from the EnergyPlus database (EnergyPlus, 2022) and used in DB simulation software. Operational emissions are calculated by linking final energy results from DB to the specific fuel emissions factors (BEIS, 2021). A summary of the characteristics made in the energy simulations has been provided in Appendix IV.8.11 in Supplementary Materials. As part of the operational use of water stage (B7), it is assumed that the house is occupied by 2.3 people for an average UK household unit with daily water consumption of 150L per person per day (Cuéllar-Franca and Azapagic, 2012).

IV.2.2.4 Impact assessment

After the data collection for each module, inputs, and outputs listed in LCI are assigned to the corresponding impact indicators of the materials and products throughout their life cycles to be consistent with the goal and scope of the study and then quantified to get the environmental impact results (Rosenbaum et al., 2017). In this study, the environmental indicators in terms of carbon dioxide equivalents (CO_2eq) via the Climate Change-Global Warming Potential (GWP100-year) are provided from published literature (*e.g.,* EPDs), and presented in metrics of the environmental impact functions for each life cycle module. The reason for this single indicator is two-fold: (i) it is based on the goal of the study in the response to the current climate crisis and follows the approach for construction types in the Green Guide to Specification (BRE, 2021); and (ii) it is an accurate indicator of the overall impacts and more often used as the sole impact metric on the environmental performance of the buildings, despite the risk of neglecting other environmental impacts such as; resource use, and resource depletion (Anand and Amor, 2017; Balasbaneh and Sher, 2021; Laurent et al., 2012). LCIA could be further developed to quantify environmental impacts through the application of impact factors over time (Röck et al., 2021).

IV.2.3 Carbon sequestration

One of the features of bio-based materials such as timber consists of biogenic carbon. Biogenic carbon absorbs atmospheric CO_2 during plant growth involving photosynthetic processes and is temporarily stored in a bio-based product throughout its service life and then re-emitted CO_2 at its end-of-life through combustion or decay (Hoxha et al., 2020). It is common practice in the current LCIA methods (*e.g.,* EN15978 (CEN, 2011)) that do not account effects of biogenic carbon as a factor of climate change (Fouquet et al., 2015). As highlighted by multiple studies (Peñaloza et al., 2018, 2016; Santos et al., 2021), it is important considering biogenic carbon into account for a building composed of significant amounts of wood as can influence significantly the LCA outcomes of wood-frame buildings for climate change impact. However, there is no consensus on how to deal with biogenic carbon in LCAs, and therefore it can be a source of confusion (Hawkins et al., 2021; Hoxha et al., 2020). To avoid this, the present study assumed that the timber originates from sustainably managed forests consistent with the forestry practice (certified by the Programme for the Endorsement of Forest Certification (PEFC) and the Forest Stewardship Council (FSC)), and the carbon assessment includes the whole of life cycle perspective (RICS, 2017). According to these suppositions, the biogenic carbon emissions from bio-based materials and residues are effectively zero, as the emissions are balanced through the sustainably managed forest on the landscape level. Therefore, according to RICS guidance (RICS, 2017), the biogenic carbon storage figures can be included in the product stage (A1–A3), effectively modeling sequestration as an instantaneous pulse but should be reported separately as a “negative emission” from storing the carbon. Consequently, an equivalent amount of this biogenic carbon is added at the EoL (C) stage of the product system instantaneously as it is re-released into the atmosphere or in the case of new material (*e.g.,* recycling) which is further transferred to a subsequent product system; however, in both cases with a “positive emission” impact (Hoxha et al., 2020). It is worth noting that the treatment of time for carbon emissions and the influence of rotation periods (due to slow forest growth and carbon absorption) of the bio-based material growth are not taken into account in this study, as it is assumed that the calculation of climate change impacts was based on static characterization factors (Lukić et al., 2021). The quantity of biogenic carbon sequestration in the wood products is taken in the material EPD, as this is now required to present separately as additional environmental information for EPDs specified in the latest version of EN 15804:2019 (CEN, 2019). When EPDs were lacking (for the case of EN 15804:2012 (CEN, 2012)), the estimation is calculated according to EN 16449 (EN 16449, 2014). It is assumed that the carbon fraction of woody biomass (dry) is 50 %, while the moisture content of 12 % is taken for timber materials.

In addition, an inherent characteristic of building cementitious materials (*e.g.*, concrete) is their ability to carbon sequestration through the process known as carbonation. The carbonation of concrete in buildings occurs over the lifespan of the products in the use phase (B1) and takes place also in the waste treatment phase (C3–C4), while burdens from replacement are directly accounted for in module B4 (resulting as a negative impact). The CO_2 uptake due to carbonation of the concrete is seldom investigated in LCAs (García-Segura et al., 2014) but is included in this study with the purpose of extracting important design drivers. For carbonation, product-specific EPDs are considered to account for when the information was available. If EPDs do not provide this information, as given in the IStructE guidance (IStructE, 2022), the estimation to take up a 2.5 % re-absorption part of the CO_2eq from the production stage (A1–A3) emissions throughout the use phase (B1) over a 60-year lifespan, and a further 5 % in the waste treatment phase (C3–C4) due to the surface area exposure after the crushing for recycling purposes (Hawkins et al., 2021; MPA The Concrete Centre, 2016).

IV.2.4 Future scenario analysis

In this study, we applied scenario analysis to investigate how the system reacts due to the alteration in the mitigation potential of the environmental impacts. Scenario analysis is a type of sensitivity analysis often used in LCA to obtain robust design decisions (Khan et al., 2021). Therefore, the influence of decarbonization of future electricity mix, and changes in waste treatments of timber materials are analyzed.

IV.2.4.1 Projections of the future electricity mix

After performing a baseline scenario using the current (static) energy modeling following the EN 15978 standard (CEN, 2011), we developed a dynamic energy modeling framework able to describe the sensitivity to some decarbonization scenarios. As shown in Figure 3, the current electricity mix in the UK still heavily relies on fossil sources, where the share of the mix is 36 % from natural gas, wind 24 %, nuclear 16 %, solar 4 %, and others 20 % (DUKES, 2021a). With the tightening regulation, the key climate policy was to drive the decarbonization of the electricity system (Pietzcker et al., 2021).

For the assessment of future decarbonization of the electricity mix, different prospective scenarios depending on the national context defined in Future Energy Scenarios (FES) are used. In this projection, two potential energy pathways are described based on the different speeds of decarbonization for the UK: “Steady Progression”, and “Two Degrees” (FES, 2019). The “Two Degrees” can match the 2050 carbon reduction target of the UK and it indicates to reduce the GHG emissions by at least 80 % from the 1990 levels by 2050; while the slowest decarbonization happens in the “Steady Progression” scenario, which doesn't get to reach the target by 2050 (FES, 2019). The "Steady Progression" provides a usual approach to ensuring low costs for consumers and is expected to exhibit approximately half the rate of emissions reduction in 2050 (FES, 2019). Implementing the scenario "Two Degrees" paves the way for the fastest credible decarbonization journey by combining high consumer engagement and more "large-scale" centralized electricity generation. The description for these scenarios which are representative of the UK electricity projection is not detailed here but is reported in (FES, 2019).

The share of each technology used in electricity generation for the current electricity matrix (DUKES, 2021a), and for future projections (FES, 2019), are presented in Figure IV.3.

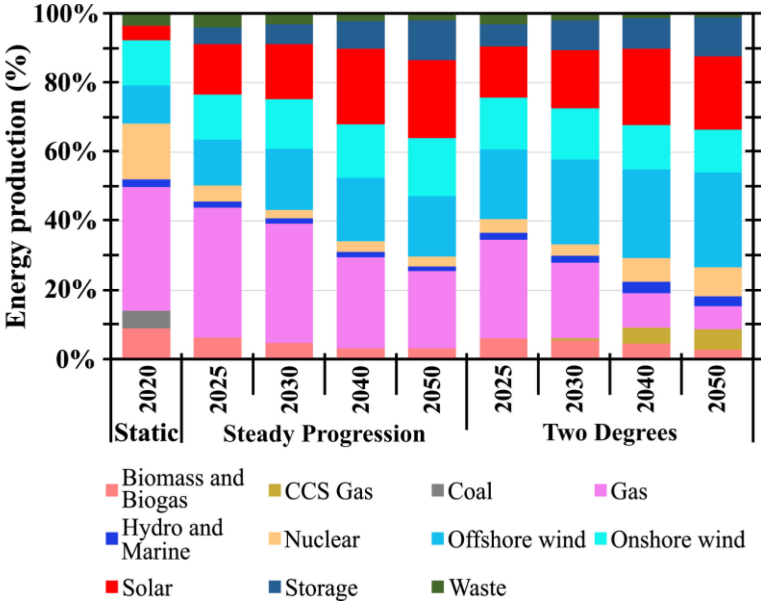

Figure IV.3: Mix scenarios of electricity production in the UK (DUKES, 2021a; FES, 2019).

To calculate the yearly CO_2 emissions factors for a unit of the low-voltage electricity mix over the building lifespan, the annual average CO_2 coefficient of electricity production in 2020 (BEIS, 2021) is considered for different scenarios, while this CO_2 factor is fixed for the current situation (static) scenario over the lifespan. To compute the carbon factors of the projection scenarios, the future relative shares of electricity sources reported for certain moments (Figure IV.3) are modeled with the corresponding energy source-specific unit impacts existent in Ecoinvent 3.8 (Wernet et al., 2016) using Simapro (Pré Consultants, 2022) according to the data described from the FES and the literature studies (Stamford and Azapagic, 2014; Zhao and Baker, 2022). It should be noted that the interconnection network (*i.e.,* import and export of electricity) and technological evolutions in the generation processes are beyond the scope of this study and are not considered (Appendix IV.8.12 in Supplementary Materials). The conversion between different voltage levels and the electricity losses are accounted for in the product system (Itten et al., 2014; World bank, 2018). A gradual annual evolution of the electricity CO_2 factors is considered using linear regression to cover eventual gaps between the values obtained for the key moments over the 60 years of the building service life. As prospective scenarios are provided up to 2050, no further changes are assumed after this year, and thus the impacts of these emission levels are assumed to be identical until the end of the model timeframe. Appendix IV.8.13 in Supplementary Materials shows the CO_2 emission factors in terms of kg/kWh electricity produced from different scenarios.

IV.2.4.2 Additional timber scenarios

Given the long lifespan of buildings, the potential alternative solutions from current waste management practices to future scenarios are considered as it is a significant factor for the embodied carbon reduction of timber materials (Robati and Oldfield, 2022). Two additional scenarios are included to provide different possible results for the end-of-life of timber materials, alongside the initial approach already described. An alternative scenario is proposed in which the current waste management practice of timber materials indicated in the baseline scenario is developed to consider future technologies to achieve higher emissions reduction. An optimistic “BECCS” scenario explores the potential future ability impact of the sequestration of CO_2 at EoL, through a combination of two well-known technologies: bioenergy and carbon capture and storage (CCS) (Jeswani et al., 2022). The latter is particularly important as it plays a significant part in the Climate Change Committee's framework for the UK to help achieve the net-zero emissions target by 2050 (CCC, 2019b). Due to the already significant BECCS for the UK plans (20 to 70 Mt CO_2 annual negative emissions (Smith et al., 2016)), and the arguably greater potential of biomass sources to balance GHG emissions, we focus on quantifying the role of this option that could reduce emissions of biogenic CO_2 back to the atmosphere in a geological formation (Almena et al., 2022). At present, the deployment of BECCS is often described as context-dependent, and it still requires time to be established on a centralized large scale (Almena et al., 2022). According to the UK's strong policy incentives and attractive feedstock of waste wood for future BECCS application (due to appropriate technical characteristics and economics) (Cooper et al., 2019; Hawkins et al., 2021), it has been demonstrated that this technique can capture 90 % of the CO_2 emitted in the combustion of timber waste treatment from the power plant (CCC, 2019b;

Leonzio et al., 2023). Similar carbon removal from the combustion processing is considered in the BECCS scenario of the present study.

This study also analyzes another deterministic scenario that considers future penetration strategies from existing technologies (Hart and Pomponi, 2020). Based on this vision, the current pressure to minimize climate change impacts is forcing us to keep waste out of landfills and to increase the proportion of recycling rate (Peñaloza et al., 2016), as the recycling process would likely result in a delayed re-release of biogenic carbon (Hawkins et al., 2021). In line with this, Wood for Good (WfG) LCA proposed 55 % recycling of products such as animal bedding or particleboard, 44 % incineration for energy recovery, and 1 % disposal in a landfill (Wood for Good, 2017). Information on the unit processes used for the EoL scenario of timber products is included in Appendix IV.8.10 in Supplementary Materials.

IV.3 Results and discussion

The results obtained are interpreted by performing contribution and sensitivity analysis in two aspects: (i) evaluate the GHG emissions of the building's case studies with an LCA in accordance with EN 15978 standard as a baseline scenario and compare the results with UK benchmarks for developing knowledge area; and (ii) the parametric study of the influence of the decarbonization of electricity production and changes in the waste treatment of timber on the GHGs results.

IV.3.1 Life cycle impact assessment of baseline scenario

Figure IV.4a presents the variation of the baseline cumulative life cycle (embodied + operational) emissions of the different case studies, including the benefit of the PV system in terms of avoided emissions over the 60-year time horizon, and Figure IV-4b makes a distinction between operational and embodied impacts of the buildings (detailed results can be found in Appendix IV.8.14 in Supplementary Materials). The initial peak is due to the increase in the emissions of both production (A1–A3), and construction (A4–A5) stages, as we assumed they happen in the same year (see Figure 4a). The contribution of the production (A1–A3) stage in this figure includes manufacture (fossil) emissions and sequestered (biogenic) emissions. Comparing the life cycle outcomes, it can be noted that they have the same trends while showing an advantage associated with the case studies using the heat pump and/or renewable technologies (*i.e.*, BS2, and BS3), being primary due to their more efficient energy systems and relative to a cleaner combination of energy consumption. As shown in Figure IV.4a and Appendix IV.8.14 in Supplementary Materials, the annual saving for the case study using a compact heat pump unit (*i.e.*, BS2), is responsible for ~19 % fewer emissions during the 60-year time horizon with respect to the case study equipped with condensing gas boiler (*i.e.*, BS1).

Adding the PV panel to the heat pump (*i.e.*, BS3) significantly reduces the amount of grid electricity, therefore lowering the cumulative emissions by ~20 % compared to the BS2; while the environmental benefits can be also reinforced when the PVs are associated with the heat pump, as ~36 % fewer emissions relative to BS1 are achieved.

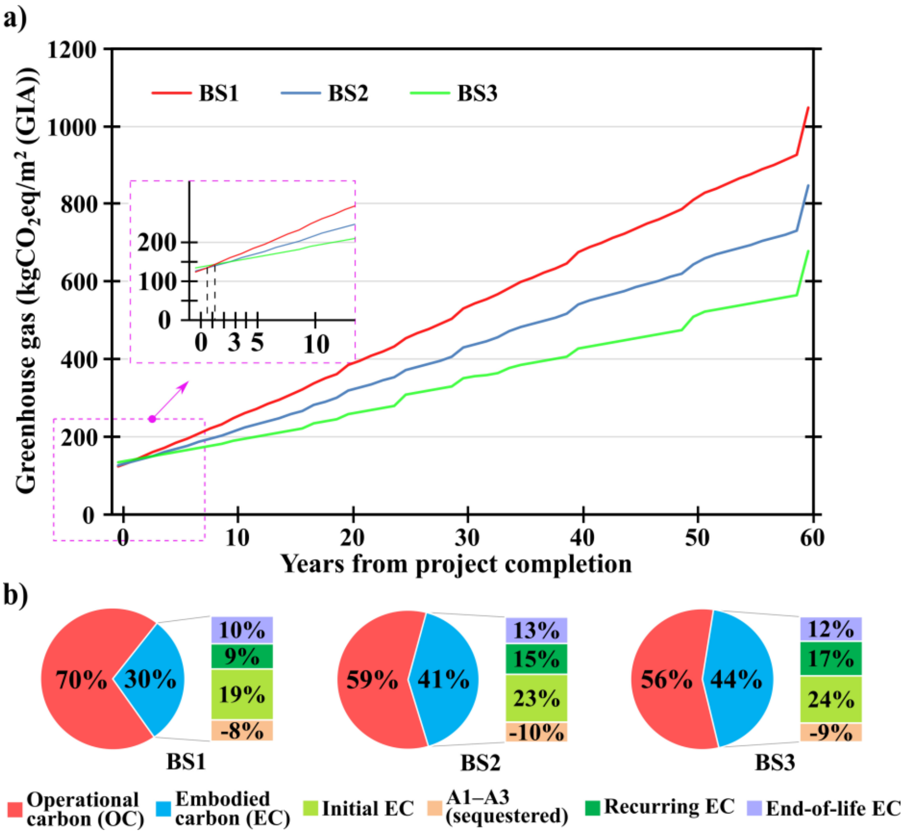

Figure IV.4: Building life-cycle emissions for different case studies for (a): Total cumulative GHG emissions over a 60-year; and (b): Contribution of embodied and operational carbon emissions to the whole life-carbon. (Note that Figure IV.4 considers the baseline scenario, assuming the current electricity mix scenario and RICS scenario for waste treatment of the timber materials.)

From Figure IV.4a, the case studies BS2 and BS3 have around ~6 %, and ~17 % higher impacts, respectively, during the first year compared to the reference case study, due to the additional initial embodied emissions related to the production and construction process of those pieces of equipment and PV system (*i.e.*, modules A1–A5). However, due to a lower annual OC emissions rate during the 60-year lifespan of the dwelling, the case studies designed with better (advancements) energy improvement options (*i.e.*, BS2 and BS3) outperform the case study with the installation of a heating condensing gas boiler (*i.e.,* BS1).

As shown in Figure IV.4b, the share of operational and embodied emissions to whole life-carbon for the different case studies are represented to 56–70 %, and 30–44 %, respectively. Since the building structure and enclosure were similar in each case study, regardless of the significantly larger effects of OC emissions on the total emissions, the EC of the case study buildings differs at most by ~25 %. The contribution differences associated with the EC in the different life cycle stages can be attributed to two factors: (i) tend to have higher emission-intensive materials of the technical equipment and PV system; and (ii) the relatively high maintenance and replacement of the heat pump-based buildings (due to the direct emissions from refrigerant leakage in BS2 and BS3) than the heating gas boiler-based building (*i.e.,* BS1). These observations are comparable to previous studies of low-energy buildings that discuss how advancements in buildings' operational energy performance led to an increase in embodied loads' contribution (30–60 % of life cycle GHG emissions) (Larivière-Lajoie et al., 2022; RICS, 2017; Röck et al., 2020).

Moreover, the carbon payback period (CPBP) is determined to indicate how long it would take for the operational savings to outweigh the increase of the EC caused by implementing a certain CO_2eq mitigation process (Roberts et al., 2020). As shown in Figure IV.4a, the CPBP of the increase in the embodied impact emission of the strategy that focuses on the use of heat pumps (*i.e.,* BS2) is 1.7 years. The increased implementation details existing in the building coupled with heat pumps and PV system (*i.e.,* BS3) resulted in a CPBP of 2.2 years.

The contribution analyses of the EC (in kgCO_2eq per m^2 (GIA)) are presented in Figure IV.5 for the reference case study (*i.e.,* BS1). The contribution analysis is performed to understand the influence of the choices of the different parameters on the EC, including the life cycle modules, the building element families, and the classification of the emissions into the material categories. The first notable part of the Sankey chart is the allocation of the emissions into the distinct life cycle modules according to EN 15978 (CEN, 2011), as presented in Figure IV.5b. The A1–A3 (manufacture) represents the most significant single contribution toward the EC emissions of the building due to the extraction of raw materials as well as the transportation and manufacturing of the building materials. Modules A1–A3 (manufacture) are responsible for 32 % of the EC calculated (*e.g.,* 155.9 kgCO_2eq/m^2). In terms of the in-use stage (B1–B5), GHG emissions have 95.5 kgCO_2eq/m^2 (*e.g.,* ~20 % of the EC), mostly because of the contribution of the replacement during the service life of the building (B4), which highlights the importance of recurring EC to the total impacts.

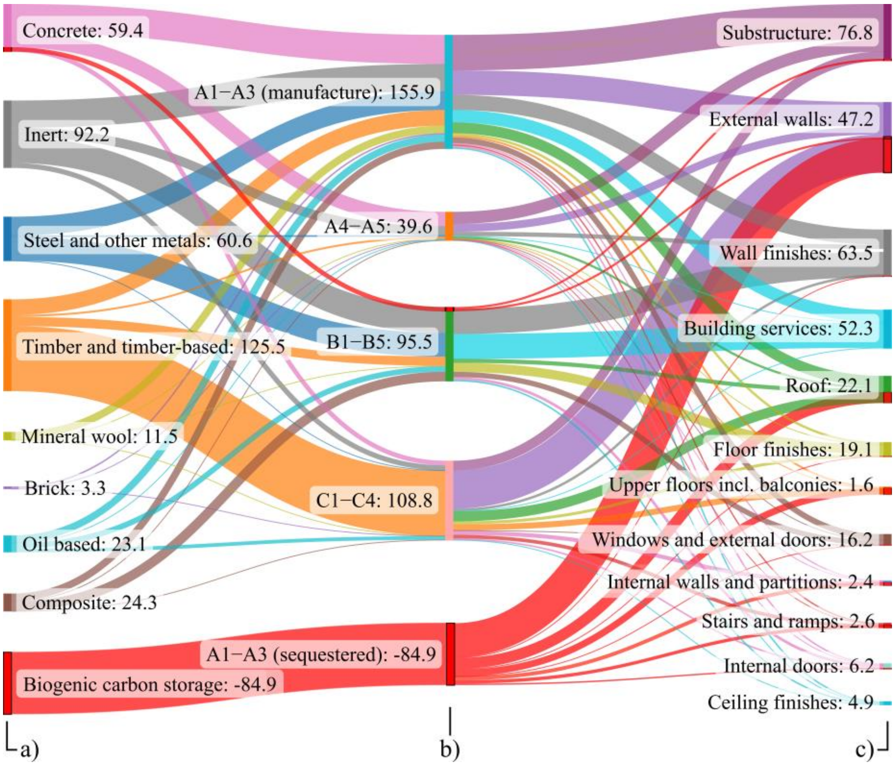

Figure IV.5: Embodied carbon emissions of the reference case study in $kgCO_2eq/m^2$ (GIA). It allocates the emissions into three parameters: (a): Material categories based on general waste treatment practices; (b): Distinct life cycle modules according to EN 15978 (CEN, 2011); and (c): Building element families according to the RICS guidance (RICS, 2017).

The EoL stage has a considerable contribution to the GHGs emitted by 108.8 $kgCO_2eq/m^2$ emission over the whole building life cycle (*i.e.*, ~22 % of the EC), which is mainly due to impacts from the emissions associated with the incineration of timber materials in waste processing and final disposal (*i.e.*, released back the carbon sequestration into the atmosphere). The scenario for biogenic carbon storage of the timber materials associated with modules A1–A3 (sequestered) is caused by –84.9 $kgCO_2eq/m^2$ emission (*e.g.*, by avoiding 16.55-ton CO_2eq, equal to ~18 % reduction of EC over 60 years), in which a negative sign indicated an environmental gain.

In terms of the construction stage (A4–A5), the transportation of concrete and inert materials resulted in higher carbon emissions, accounting for ~50 % of the total construction stage emissions. However, the results also show that the emissions associated with this stage are not relatively significant compared to other life cycle phases, resulting in ~8 % of the EC emissions.

Another notable result derived from Figure IV.5c is the emissions in the distinct life cycle modules in relation to the element contribution, which points to further details of the EC emissions. The higher GHG is induced by the contribution of the "Substructure" system, accounting for ~50 % of the emissions in modules A1–A3 (manufacture) and ~24 % of the EC emissions calculated. The reason for this is that the "Substructure" is comprised almost entirely of concrete and steel, which tend to have significant embodied emissions when it is used in much larger amounts than other building materials. The embodied emission of the exterior enclosure (*i.e.*, clustering "External walls", "Windows and external doors", and "Roof") is responsible for ~27 % of total EC emissions. Due to the use of extensive timber materials in "External walls", and "Roof", their GHG impact are decreased by 50 % and 40 %, respectively.

The third largest contribution to the total embodied impacts is the "Building services", being mainly by "Steel and other metals", which are generally allocated a high fraction of EC emissions and need to be replaced on a regular basis during the use stage. This is assessed by adding 52.3 $kgCO_2eq/m^2$ (*e.g.,* ~10.19-ton CO_2eq) to the overall GHGs. The results identified architectural finishes as a significant impact contributor (~28 % of the EC emissions), which are mainly driven by the high replacement rates of the building elements associated with the silicone-based render and the paint for the "Wall finishes", as well as the vinyl floor covering for the "Floor finishes". These elements accumulate large amounts of EC over the building lifespan while their recurring embodied contributions can be comparable to or higher than the values of their initial embodied impacts (A1–A5).

Finally, the GHG emissions are also allocated to distinct material categories in Figure IV.5a. It can be observed that the "Timber and timber-based" material used in the building envelope components (*e.g.,* "External walls" and "Roof"), stands out as the major contributor to EC emissions (~26 %). The substantial contribution of the "Timber and timber-based" materials is mainly originated from end-of-life treatment (*i.e.,* incineration processing), as they are representing a relative share of 82 % of the demolition EC emissions. Therefore, the choice of changing the waste management treatment of timbers can be identified as a key parameter to reduce the environmental impacts of a timber building, which is further illustrated in section IV.3.3.2. The results implied that "Inert" materials (*e.g.,* plasterboard, paint, and render), a component mainly of the finishes, were the second highest contributor to the EC emissions (~19 %), followed by "Biogenic carbon storage" (~−18 %), "Concrete" (~12 %), and "Steel and other metals" (~12 %). According to Figure IV.5a and Appendix IV.8.14 in Supplementary Materials, there is also a substantial contribution from "Oil-based" and "Mineral wool", accounting for ~7 % of the EC emissions in each case study (for both material categories, it is mainly due to having the high-intensity insulation materials embedded in the building envelope components), whereas the quantity of these materials is less than ~1.5 % of the total weight. It is important to point out here that if the concern is to reduce further emissions of the EC emissions, the designer should focus on a careful selection to replace these materials, with an alternative that reduces materials' quantity or emission intensity (these suggestions would serve the same purpose and with similar functionality to the project (Pamenter and Myers, 2021)). For this purpose, the substitution of the cement with supplementary cementitious materials (SCMs) (*e.g.*, ground granulated blast-furnace slag (GGBFS), a by-product of the steel industry) in ordinary Portland cement (OPC) based concrete is the most common method used in the UK cement and concrete industries (Shanks et al., 2019). The average percentage of substitutions could increase to up to 50 % corresponding to a potential reduction in the UK industry that maintains the structural performance (Pamenter and Myers, 2021). By changing the raw materials mix from OPC-based concrete to 50 % GGBFS, the total EC emissions can be reduced by ~2 %. Similarly, insulation is changed to blown cellulose, instead of the rigid polystyrene board within the floor, and of the glass wool within the roof and external walls but with similar thermal performance. With this switch in the case study, the total EC emissions can be reduced by ~3 %, as a result of emission saving of the overall carbon sequestration within the product. Choosing resilient Linoleum floor covering instead of vinyl covering has less impactful alternative materials, as a result of the combination of natural renewable materials and high recycled content. This is assessed by saving ~1 % to the overall embodied impacts. Therefore, focusing on building elements with the greatest potential for improvement in the possible retrofit scenario of existing buildings or designing new buildings with the assessed low environmental impact substitutions can potentially achieve a noticeable reduction in EC emissions.

IV.3.2 Comparison to benchmark

To further interpretation of the results obtained and understand if the analyzed case studies will match the UK's environmental targets, a comparison is made with the benchmark described in the LETI Climate Emergency Design Guide (LETI, 2020a). The LETI, developed by the London Energy Transformation Initiative, is a collaborative network of built environment professionals that proposed voluntary targets for the reduction of EC and OC for residential and non-domestic buildings (*e.g.*, offices and schools). These targets have been incorporated into the policy guidance to push the carbon emissions to become part of legislation to achieve net zero carbon (LETI, 2020a).

Figure IV.6Figure IV.6: The performance of the case studies and target values of LETI Climate Emergency Design Guide (LETI, 2020a) for (a): Whole embodied carbon emissions (excl. refrigerant leakage and PV system); and (b): Operational energy.a shows the design targets of the LETI for the ambition across various typologies and portfolios of total EC emissions (A1–B5, C1–C4, including sequestration) based on an A++ to a C rating system (LETI, 2021), and the performance of all case studies. The embodied carbon targets are assessed under consideration of the whole life-carbon assessment and the building elements required in RICS while excluding refrigerant leakage and renewable electricity generation (*e.g.*, PVs). From this figure, the LETI provides metrics aligned with the letter banding for residential buildings as follows: LETI 2020 Target, it should be equivalent to letter banding of C (less than 800 $kgCO_2eq/m^2$ (GIA)); and LETI 2030 Target, equivalent with letter banding of A (less than 450 $kgCO_2eq/m^2$ (GIA)) (LETI, 2021). As shown in Figure IV.6b in terms of operational energy, this standard also set out performance targets of 35 kWh/m^2/year (GIA) (LETI, 2020a). The comparison of the results obtained in the present study with LETI targets showed that the case studies aligned with band A and meet not only the objectives for the EC of the year 2020 but also for 2030. With respect to operational energy, the case study BS1 does not meet the required performance target, while BS2 and BS3 can match this benchmark.

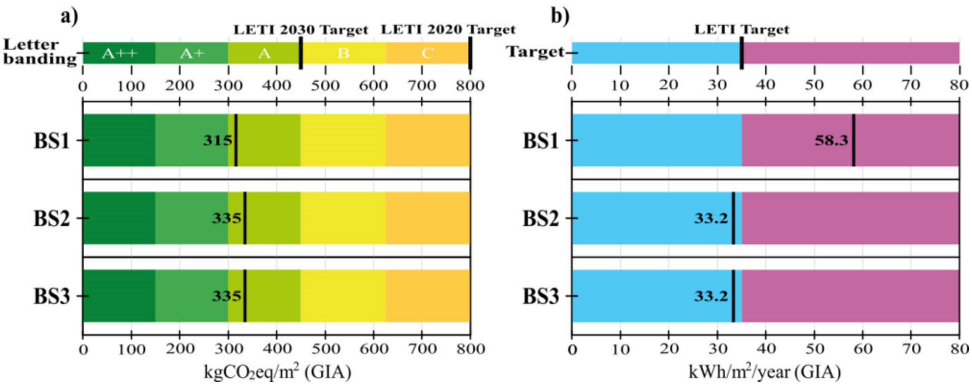

Figure IV.6: The performance of the case studies and target values of LETI Climate Emergency Design Guide (LETI, 2020a) for (a): Whole embodied carbon emissions (excl. refrigerant leakage and PV system); and (b): Operational energy.

IV.3.3 CO_2eq emission for different scenarios

IV.3.3.1 <u>Effect of decarbonization on electricity production</u>

To facilitate a detailed comparison of the scenarios, the results for different case studies are displayed for the baseline (current electricity mix) scenario and two future electricity decarbonization scenarios. Figure IV.7 shows the contribution of embodied and operational carbon emissions, benefits impact, as well as their relative saving GHG of the different case studies in relation to the baseline's reference case study (*i.e.*, BS1 in the current electricity mix) over a 60-year lifespan of the building. Overall, the total cumulative GHG impact of the case studies decreases significantly (~50 %) when the grid energy is shifting toward increasingly more renewable sources. For example, the two degrees scenario shows the highest improvement in GHG balance emissions, representing ~29 %, ~37 %, and ~50 % reduction in BS1, BS3, and BS2, respectively when scenarios using the same construction techniques are compared.

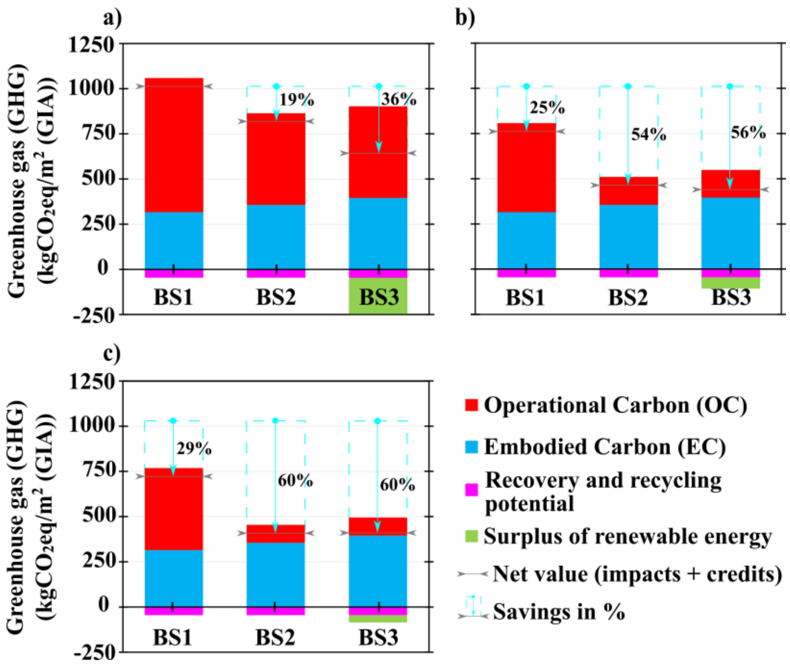

Figure IV.7: The effect of decarbonization of electricity mix on greenhouse gas emissions for different case studies over the building lifespan. It includes three scenarios: (a): Static (current) energy mix (Note that panel a considers the same approach as Figure IV-4); (b): Steady Progression; and (c): Two Degrees.

From the steady progression scenario, the case study BS3 can achieve a 56 % GHG saving over the building's life cycle relative to the baseline's reference case study, being essentially due to a full electricity-based HVAC, and thus, higher energy savings in the use phase and related benefits from an increase in the share of renewables. In this sense, it can be concluded that in order to get the maximum benefits from the electricity production sector and can support the clean energy transition in buildings, it is necessary to: (i) "electrification" the building elements (*e.g.*, from fossil-fuel-based to efficient electricity-based heat pump system); and (ii) improving electricity generation in the cleanest possible way (*e.g.*, two degrees scenario).

Considering the future electricity scenarios (Figure IV.7), the benefit from the surplus (PV) electricity production over the building's life cycle is significantly reduced when the electricity grid becomes more decarbonized. This is due to the assumption that the benefit provided by the delivered electricity generation by the PV system is accounted to have the same emission intensity given the evolution of the electricity grid over the lifespan of the building, while the PV modules have the same efficiency of today's perspective. This can be explained by the fact that, if future electricity production is made to more renewable sources, the net performance of PV systems (*i.e.,* impacts + credits) are lowered, while also breaking even; as an example, in certain scenario of the BS3 compared to the BS2 in the two degrees scenario, which this technology produces negative credits to the system during its lifespan, and consequently, the CPBP of PV system exceeds the whole building service life.

From Figure IV.7, as the OC impacts of the case studies are reduced significantly, due to improved technological systems and grid decarbonization, the magnitude of EC is increased dramatically. As an example, comparing the baseline's reference case study (*i.e.,* BS1 in Figure IV.7) with the case study equipped with the heat pump and PV panel in a prevalent grid decarbonization scenario (*i.e.,* BS3 in Figure 7c), it can be seen the ratio between embodied and operational carbon from the current situation and future electricity mix may vary considerably (*e.g.,* ~30 % for BS1 in the current electricity mix, reaching ~500 % for BS3 in two degrees scenario).

IV.3.3.2 <u>Effect of technological progress on the waste treatment of the timber materials</u>

In the previous subsection, a sensitivity of LCA results regarding the energy mix was illustrated. Additionally, the effect of waste management treatments of timbers is explored in a scenario analysis by considering alternative solutions.

Figure IV.8 demonstrates the EC emissions differentiated into its modules to the building life cycle for the baseline scenario (as assessed by the RICS scenario) and two technological progress scenarios in the waste treatment of timber materials (*i.e.,* Wood for Good (WfG) and BECCS scenarios). The variation of EoL strategies of timber products has a significant impact on the EC reduction for the case studies by up to 23 %, under sustainable forest management and re-emitted the sequestered carbon at the product's end-of-life. Considering the improvement in the recycling share of waste treatment options (*i.e.,* Wood for Good scenario) for timbers in a cradle-to-grave basis of different case studies, could reduce EC impacts by ~3 % as compared to the same construction technology of the baseline scenario (Figure IV.8a and b).

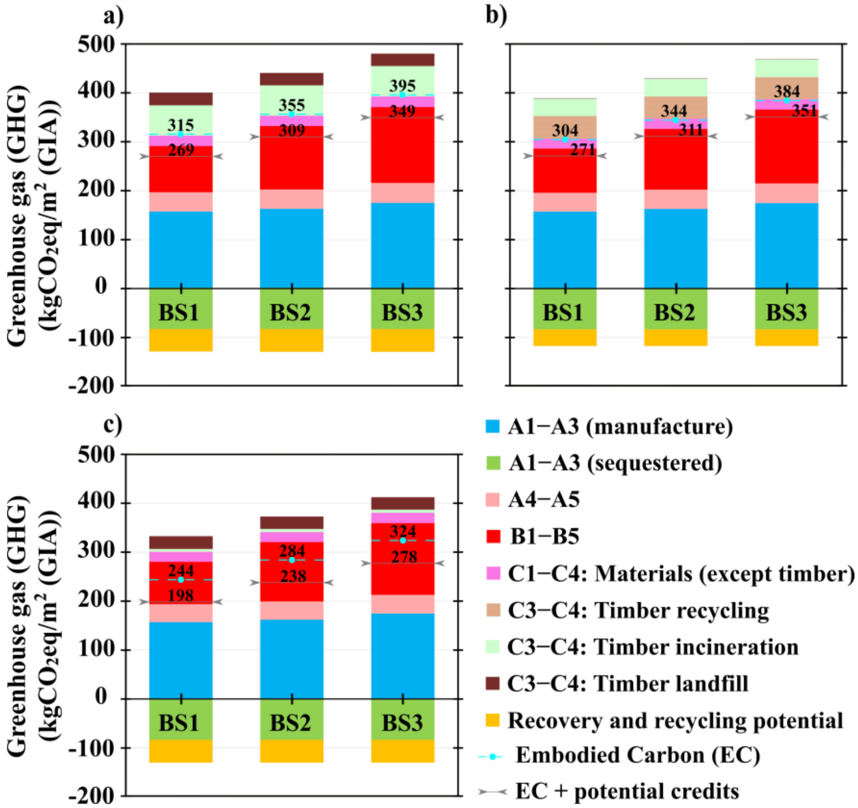

Figure IV.8: The effect of technological progress in the waste treatment of timber materials on embodied carbon emissions for different case studies. It includes three scenarios: (a): RICS; (b): Wood for Good (WfG); and (c): Bioenergy with carbon capture and storage (BECCS).

As shown in Figure IV.8, the inclusion of environmental credits from the analysis can lead to different overall rankings between scenarios and the relevance of life cycle stages. The figure shows that the case studies in the WfG scenario have ~2 % higher CO_2eq emissions when using the same construction technology of the baseline scenario are compared. The different result obtained for overall GHG emissions between scenarios, which is a consequence of including credits, is explained by the differences in the higher proportion of timber waste that is used directly for electricity generation treatment from incineration for the RICS scenario compared to the WfG scenario. This implies that considerably higher emission is avoided relative to the lower benefits received for recycling processing (*e.g.*, animal bedding or particleboard).

The results strongly suggested that widespread adoption of the BECCS scenario in timber end-of-life could substantially reduce embodied impacts of BS1, BS2, and BS3 by ~23 %, ~20 %, and ~18 %, respectively, compared with the baseline scenario. This contribution makes up to ~84 % of the waste processing stage (*i.e.,* C3–C4), up to ~20 % of the replacement module (*i.e.,* B4), and up to ~1 % of the construction stage (*i.e.,* A5). In this optimistic scenario, there are substitution benefits associated with the use of future carbon-capture technology (*i.e.,* BECCS) to reduce the emission emitted in the EoL of the timbers, which demonstrates the possibility of using wood products with low long-term climate impacts.

IV.4 Discussion

Addressing the whole life-cycle carbon emissions of buildings is crucial in meeting national and global targets for mitigating climate change in numerous countries. This research focuses on reducing the carbon footprint of a typical low-energy timber-frame residence in the UK, in line with the country's goal of achieving net-zero carbon emissions by 2050, and is intended to inform future construction trends. Currently, the introduction of enhancing building energy efficiency in design and systems can effectively reduce the GHG emissions of buildings over their lifespan, but it passes the load to the electricity mix production, more efficient HVAC systems, or embodied carbon emissions (*e.g.,* material choice and end-of-life measures) (Nematchoua et al., 2022; Rahif et al., 2022).

The findings of this study indicate that installing a compact heat pump unit (*i.e.,* BS2) can reduce total CO_2eq emissions by approximately 19 % when compared to the current electricity mix (*i.e.,* baseline scenario BS1). Furthermore, implementing a coupled PV system with an electric compact heat pump unit (*i.e.,* BS2) may reduce the amount of electricity supply taken from the grid, exhibiting a 36 % reduction of CO_2eq emission. Comparing the results obtained for the analyzed case buildings with other European dwellings (Houlihan Wiberg et al., 2014; Satola et al., 2022) reveals a noticeable contribution of the heat pump and/or PV systems in emission reduction over the building lifespan. This reduction can be particularly attributed to the current situation with a high-carbon electricity emission factor in the UK's grid (~0.25 kgCO_2eq/kWh) compared to those countries with cleaner electricity production (*e.g.,* Sweden or Norway). Therefore, the results that identify and implement cleaner energy sources while fostering the use of technologically advanced building systems (*e.g.,* efficient electric compact heat pump unit) play an important role in minimizing energy demand and achieving the target value (Fenner et al., 2018; Ligardo-Herrera et al., 2022).

Due to the high amount of wood used in the studied timber frame dwelling, biogenic carbon accounting in the analyses tends to have a significant contribution to the embodied impact (*i.e.,* ~18 % of EC). However, it should be noted that when biogenic carbon is considered on a cradle-to-gate basis (A1–A3), the EC analysis of timber products might mislead the conclusions, giving an incomplete picture of describing its subsequent release back in the EoL (C) stage. This concluding remark is also highlighted in a few other studies (Morris et al., 2021; Petrović et al., 2023). Indeed, this may also encourage the use of wood products in construction, resulting in possible negative impacts on landscapes. Therefore, it is imperative to consider the entire life-cycle carbon emissions of timber products and buildings to fully comprehend the impact of wood-based materials and make more informed decisions in efficient construction design.

The majority of LCA studies have not assessed the impact of “Building services” mainly because of: (i) the difficulty in quantifying their impacts (*e.g.*, challenging to quantify the life cycle inventory phase of these components) (Rodriguez et al., 2020), and (ii) as their environmental impact appeared to be relatively small in magnitude in earlier studies when compared to operational emissions, thus they are often left outside of the assessment boundaries (Moncaster and Symons, 2013). However, the present study indicates considerably high embodied effects of the “Building services” compared to other building elements, with the latter accounting for ~17 % of EC emissions. This highlights the importance of considering the “Building services” in the embodied carbon assessment of the buildings.

Furthermore, the sensitivity analysis of the future electricity mix projections demonstrated an increased share of renewable sources that is reflected in the lower GHG emissions of the case studies, by up to ~50 % when scenarios with the same construction technologies are compared. Additionally, results suggest that the emission saving of the grid decarbonization can be reinforced through implementing the evaluated energy improvement technologies by ~60 % reduction in the building case study of BS2. In this sense, it can be concluded that in order to get the maximum benefits from the electricity production sector and to support the clean energy transition in buildings, it is necessary: (i) to follow “electrification” of the building elements (*e.g.*, from fossil-fuel-based to efficient electricity-based heat pump system); and (ii) to improve the electricity generation in the cleanest possible way (*e.g.*, two degrees scenario). The use of renewable electricity for running heat pumps can be included in any further effort aiming to move toward the complete phasing out of fossil fuels in residential heating (Lin et al., 2021). As a result of these significant operational saving measures, the contribution of embodied to operational carbon emissions can subsequently become more relevant in the environmental balance (*e.g.*, ~30 % for BS1 in the current electricity mix, reaching about ~500 % for BS3 in the prevalent electricity decarbonization scenario). While in agreement with (CCC, 2020b; HM Government, 2019a), the results of this study imply that operational savings are large in magnitude to reduce residential UK GHG emissions while achieving a zero-carbon building requires the explicit incorporation of EC emissions. Moreover, the magnitude of the initial emission savings associated with the initial EC is of paramount importance since it can be easily achieved through the implementation of several material efficiency strategies (Azzouz et al., 2017). In this context, the findings also indicated that the use of 50 % ground granulated blast-furnace slag (GGBFS) concrete, blown cellulose insulation, and resilient Linoleum floor covering can attain further savings by ~6 % on embodied carbon emissions. Hence, increasing attention should be placed on the material choice to substantially decrease the initial embodied impacts and immediate contributions to reduce the carbon footprint of buildings.

Moreover, since the compensation of the avoided impacts associated with the surplus (PV) electricity production is sensitive to shifts in the decarbonization of the electricity grid, the benefits from the PV system over the UK building's life cycle are not always feasible. Therefore, both new and retrofit buildings should find a permanent improvement in the net performance of the PV system by developing more environmentally friendly materials and manufacturing techniques. As the possible solutions, the importance of integrating PV panels into building structures such as Building Integrated Photovoltaic (BIPV), and Building Integrated Photovoltaic-Thermal (BIPVT) systems (Lamnatou et al., 2020; Zhang et al., 2018); adopting a photovoltaic system with reused cells in the PV modules (Contreras Lisperguer et al., 2020; Kristjansdottir et al., 2016); and the use of growing waste battery from the automotive sector in the coming years (Cusenza et al., 2019) could be considered.

Additionally, the results illustrated that the adoption of potential technological progress in the waste treatments of timber products and buildings could substantially reduce embodied emissions, by ~3 % through increasing the recycling rate and by ~23 % through introducing carbon capture and storage with bioenergy (BECCS) scenario, as the scenarios with the same construction technology of the baseline end-of-life scenario (landfilling + incineration) are compared. The recycling practice of timber waste materials through secondary uses (*e.g.,* animal bedding or particleboard) does not seem to differ greatly from having landfill and incineration treatments in the baseline scenario. This observation can be explained by the way that biogenic carbon is treated by the EN 15804 standard (CEN, 2019) due to future recirculation options. Through this perspective, as explained in section IV.2.3, all the carbon sequestrated in timber products is modeled as being emitted at the end-of-life stage to the atmosphere and is debited accordingly, and a credit is applied reflecting the substitution benefit. However, concerning recycling treatment, the biogenic carbon storage is not actually released into the atmosphere to the first product, but instead transferred in the subsequent products utilizing the recycled biogenic material. It is worth noting that treating carbon transferred to new material as being released is respected based on an accounting convention adopted to avoid double counting the benefits from the biogenic carbon (Morris et al., 2021). Thus, in alignment with the UK path to net-zero carbon (HM Government, 2019b), it is essential to increase the recycling rate of timbers (*e.g.,* WfG scenario) rather than incineration with electricity generation, which can contribute to the long-term carbon storage products, providing the buildings as a temporal carbon sink to slow down climate change (Allen et al., 2022), and consequently, it can allow more time for developing the sustainability transformations of the society envisaged under the Sustainable Development Goals (SDGs) (Andersen et al., 2022).

While modeling benefits outside the system boundary can present methodological challenges (Meex et al., 2018), it is important to note that module D has a significant impact on the overall results, particularly in the case of bio-based products (Häfliger et al., 2017), and it should be taken into account. For instance, in the case of the incineration of timber materials, as shown in Figure 8a, a large credit is awarded in the recovery and recycling potential stage for the assumed substitution of alternative electricity production. However, as the energy supplied will become more decarbonized, this choice of substitution credits is likely to be very low compared to today's perspective. Therefore, from a climate change perspective, expanding the analysis to include the avoided burdens can lead to different conclusions estimated from LCA studies of timber products and exceed the total debits from other stages. Nonetheless, there is a high uncertainty about the avoided impacts at the time of demolition, particularly considering the relative benefits associated with the current electricity substitution of the recovered energy that might look less favorable option (Hart and Pomponi, 2020).

The temporal perspective of carbon emissions, especially regarding the use phase (*e.g.,* electricity mix) and end-of-life of the building (*e.g.,* waste management treatment) are other topics which are not been covered properly by the previous studies in assessing impacts related to climate change (Luisa F Cabeza et al., 2014; Meex et al., 2018). It is believed that both technological changes in the electricity mix and the waste management scenarios at the building end-of-life are aspects that should be considered in future GHG emissions calculations, especially for timber products and buildings.

All the results of this study refer to one square meter of gross internal area (GIA) as a functional unit. This choice is in accordance with the RICS guidance to facilitate the incorporation of further contributions with other studies and building benchmarks

(LETI, 2021). However, the use of an area-based basis may potentially distort the results, as it attributes both building and occupant-related emissions emitted to the area of the house, thereby wiping out any improvements achieved by increasing the area efficiency (*e.g.*, area per occupant) (Stephan et al., 2013). When the number of occupants in the house is increased, the overall emissions for area per occupant may effectively be reduced. This clearly depicts that a smaller floor area per occupant and the sharing of cars by a higher number of people could contribute considerably to meeting climate targets (Cabrera Serrenho et al., 2019; Roca-Puigròs et al., 2020). Therefore, the area per occupant functional units is judged as a more appropriate metric for comparing buildings with varying floor areas and the number of occupants (Fuller and Crawford, 2011; Stephan et al., 2013).

There are several environmental indicators for quantifying the LCA of buildings. Using only GWP as an environmental impact category has the benefit of increasing clarity for decision-makers, and often correlates with other environmental impacts (Wiik et al., 2018). Moreover, some other studies have found that GWP will be a reasonable proxy for other impact categories, particularly for those categories linked to non-renewable energy consumption, or related emissions (*e.g.*, acidification, photochemical ozone formation, etc.) (Häfliger et al., 2017; Lasvaux et al., 2015). However, this sole focus may increase the risk of burden shifting to other impact categories that do not always correlate with GWP, such as resource use and resource depletion (Anand and Amor, 2017; Laurent et al., 2012). Thus, to ensure comparability, it is recommended to conduct further LCA studies considering the broad range of indicators instead of solely focusing on GWP.

Previous studies also suggested that the robustness of LCA results for timber materials in the construction of buildings may be further improved by considering the forest management activities associated with the growth and harvesting of trees as well as the carbon stock changes (Fouquet et al., 2015). Hence, future research steps should address the issue of time differences between the uptake and release of carbon in the timber building sector.

IV.5 Conclusions

This study aimed to address the concerns regarding mitigating the carbon footprint of a representative timber-frame low-energy dwelling in the UK in terms of HVAC GHG emissions through three different energy improvement options, *i.e.*, the reference case BS1: a gas-fired boiler + mechanical ventilation with heat recovery (MVHR); BS2: electrical compact heat pump unit; and BS3: electrical compact heat pump unit + photovoltaic (PV) panels. More particularly, future decarbonization potential from the national perspective concerning the changes in electricity mix production and technological evolution of the waste treatment of timber products used in the building were investigated, aiming at providing a sensitivity analysis of climate change mitigation. The whole life-carbon emissions for a total of eight investigated scenarios were analyzed considering the potential improvements of carbon footprint to fulfill future projections for the new UK building sector, and the results were compared to the LCA results of a baseline scenario, where the existing technology and context were considered fixed over time.

The results of this study show that considering temporal changes in electricity mix production and technological progress in the waste treatment of timber materials significantly alters the predicted climate impacts of the building over its lifespan. For example, the findings indicated that using an efficient electric compact heat pump in parallel with the national decarbonization targets of the electricity mix can significantly reduce the whole life-cycle emissions of long-term climate impact assessment at the UK building by ~60 %. Moreover, the results of this research implied that the adoption of potential technological progress in the waste treatments of timber products and buildings could substantially reduce buildings' embodied emissions, representing by ~3 % through increasing the recycling rate and by ~23 % through introducing carbon capture and storage with bioenergy (BECCS) scenario, as the scenarios with the same construction technology of the baseline end-of-life scenario (landfilling + incineration) are compared.

Results showed that it is of high importance to consider biogenic carbon in evaluating the climate impact of a building composed of significant amounts of wood as it can significantly influence the embodied impact of timber-frame buildings, by ~18 % in the present study, that is expected to support/incentivize the more use of timber-based products in the building sector. Moreover, the inclusion of “Building services” in the climate impact assessment of the residential building is emphasized to obtain a more accurate outcome as it could affect the embodied carbon estimations, *e.g.*, increasing CO_2eq by ~17 % in the current study.

The evaluation of whole life-carbon emissions of the dwellings demonstrates the relative importance of the operations phase in the baseline scenario, compared to the materials, construction, and end-of-life phases. Nonetheless, the sensitivity analysis suggests that the decarbonization of electricity mix production and advancements in the treatment of timber waste can considerably reduce the environmental impact of the building's operation and end-of-life phases compared to the material and construction phases. These emission-saving measures highlight the importance of material efficiency strategies for achieving more embodied carbon savings in future construction practices.

IV.6 Acknowledgements

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IV.7 Nomenclature

ASHRAE	The American society of heating, refrigerating and air-conditioning engineers [-]
BECCS	Bioenergy with Carbon Capture and Storage [-]
BIM	Building Information Modeling [-]
BIPV	Building Integrated Photovoltaics [-]
BIPVT	Building Integrated Photovoltaic with Thermal [-]
CCC	Climate Change Committee [-]
CCS	Carbon Capture and Storage [-]
CO_2	Carbon dioxide [$kgCO_2$]
CO_2eq	Carbon dioxide equivalent [$kgCO_2eq$]
CH4	Methane [$kgCO_2eq$]
DEFRA	Department for Environment, Food and Rural Affairs [-]
DB	DesignBuilder software [-]
EC	Embodied Carbon [$kgCO_2eq$]
EoL	End-of-Life [-]
EPD	Environmental Product Declaration [-]
EPS	Expanded Polystyrene Insulation [-]
ESL	Estimated Service Life [year]
FES	Future Energy Scenarios [-]
FSC	Forest Stewardship Council [-]
FU	Functional Unit [-]
gbXML	Green Building Extensible Markup Language [-]
GGBFS	Ground Granulated Blast-Furnace Slag [-]
GHG	Greenhouse Gas [$kgCO_2eq$]
GIA	Gross Internal Area [m^2]
GWP	Global Warming Potential [$kgCO_2eq$]

HVAC	Heating, Ventilation and Air Conditioning [-]
ISO	International Organization for Standardization [-]
LCA	Life Cycle Assessment [-]
LCI	Life Cycle Inventory [-]
LCIA	Life Cycle Impact Assessment [-]
LETI	London Energy Transformation Initiative [-]
MVHR	Mechanical Ventilation with Heat Recovery [-]
nZEB	Nearly Zero-Energy Building [-]
OC	Operational Carbon [kgCO_2eq]
PCRs	Product Category Rules [-]
PEFC	Programme for the Endorsement of Forest Certification [-]
PV	Photovoltaic [-]
RES	Renewable Energy sources [-]
RICS	Royal Institution of Chartered Surveyors [-]
RSP	Reference Service Period [year]
SAP	Standard Assessment Procedure [-]
SCOP	Seasonal Coefficient of Performance [-]
SCMs	Supplementary Cementitious Materials [-]
U-value	Thermal Transmittance [W/(m^2K)]
UKGBC	UK Green Building Council [-]
WRAP	Waste and Resources Action Programme, UK organisation [-]
XPS	Extruded polystyrene Insulation [-]

IV.8 Appendix

The supplementary materials for the article “Carbon footprint of low-energy buildings in the United Kingdom: Effects of mitigating technological pathways and decarbonization strategies” are presented in this section. The Appendix is organized as follows:

IV.8.1 Plan view and 3D of the reference case study

This appendix shows the layout and elevation of the reference case study used (see Figure IV.9).

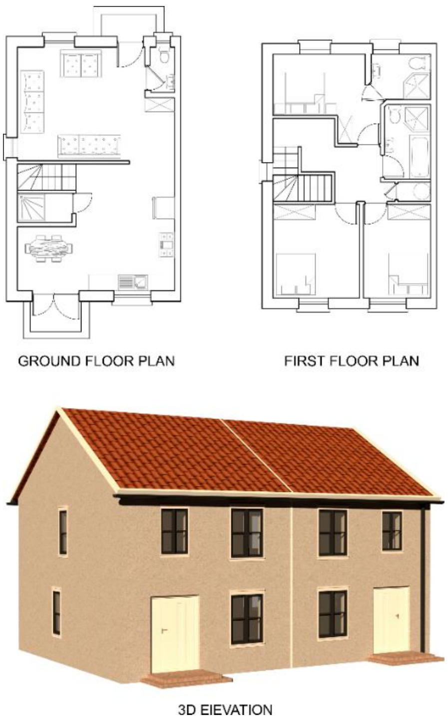
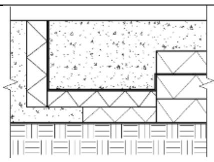
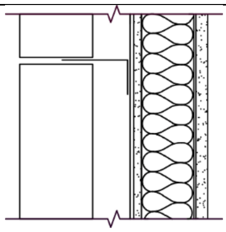
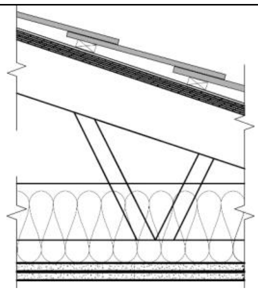
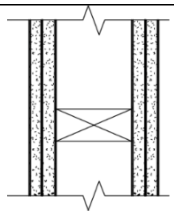


Figure IV.9 Plan view and 3D of the reference case study.

IV.8.2 Construction details for the floor, external walls, roofs, and internal walls of the studied building

Table IV.1 Construction details for the floor, external walls, roofs, and internal walls of the studied building systems.

Building element	Description	
	Details	**Layers**
Floor		750 x 300 concrete; 350 blockwork; dpc
		100 thick screed; 500g dpm; 175 thick TF70 insulation; 100 concrete; 1200 g dpm; hardcore
External walls		100mm thick outer leaf of blockwork; fixing only wall ties
		Keystone steel lintels; for timber kit with 50mm cavity; galvanised & pre-painted
		Wall insulation; Isover Metac Insulation OEA; 220 thick; fitted between studs

		100 timber studs @ 400 centres; 100 thick frametherm 35
		Plasterboard to walls; 12 thick Gyproc wallboard
Roofing		Concrete Flat Smooth interlocking roof tiles; on 38 x 25 treated battens; on heavy grade waterproof and vapour permeable underlay
		Timber rafters, 390 thick Frametherm 35 insulation
		Plasterboard ceilings; 12thick Gyproc board; include for 3 thick skim finish
Internal walls		Wall insulation; Isover Metac insulation OEA; 75 thick; fitted between studs
		25 thick rockwool RWA45 insulation
		Plasterboard to walls; 12 thick Gyproc wallboard
		Skim finish to plasterboard; painting

IV.8.3 Design specifications of the building envelope and technical specifications of the HVAC system

Table IV.2 Design specifications of the building envelope and technical specifications of the HVAC system.

Building case study	**U-value (W/ (m^2 K))**				**Ventilation**	**Heating**	**Energy generation - multi-Si PV (m^2)**
	External wall	Roof	Floor	Window			
BS1	0.13	0.085	0.12	0.75	MVHR (EHS: 83%)	Condensing gas boiler (EHS: 93%)	N/A
BS2	0.13	0.085	0.12	0.75	Compact P unit (EHS: 80%)	Compact heat pump unit (SCOP: 5.11)	N/A
BS3	0.13	0.085	0.12	0.75	Compact P unit (EHS: 80%)	Compact heat pump unit (SCOP: 5.11)	19.2

U-value = Thermal Transmittance; MVHR = Mechanical Ventilation with Heat Recovery; EHS = Efficiency Heating System; SCOP = seasonal coefficient of performance; multi-Si PV = Multi-crystalline Silicon photovoltaics panels; N/A = Not Available.

IV.8.4 Main features of the PV modules

Table IV.3 Main features of the PV module (PVsyst SA, 2022; Terreal Solution PV3-1 S, 2017).

Parameter	**Value**
Manufacturer & model (–)	Terreal Solutions PV3-1S
Cell technology (–)	Multi-crystalline Silicon
Installation type (–)	Roof parallel
Number of panels (Piece)	14
Module efficiency (%)	15.4%
Performance ratio (%)	84
Tilt PV panels (◦)	30
Azimuth PV panels (◦)	0
Module dimensions (m)	1.64 m x 0.992 m
Albedo (%)	20
Inverter manufacturer (–)	AEG
Lifetime expectancy (years)	25

IV.8.5 Bill of materials used in each building case study and their corresponding density and expected lifespan

Table IV.4 Reports the bill of materials used in each building case study and their corresponding density and expected lifespan.

Material categories name	**Material type**	**Density (kg/m^3) [1]**	**Expected lifespan (years) [2]**	**Quantity (Ton)**			**Building element families**
				BS1	BS2	BS3	
Brick	Brick	1485	150	2.4	2.4	2.4	External walls, Substructure
Composite	Boiler, gas condensing	–	17	0.2	0	0	Building services
	Door, wood with timber frame and glass panel	73 (each)	25	0.7	0.7	0.7	Internal doors
	Doors, triple glazed	39.83 (kg/m^2)	60	0.2	0.2	0.2	Windows and external doors

	Compact Heat Pump unit	–	17	0	3	3	Building services
	Windows, triple glazed	71.9 (kg/m^2)	40	1.6	1.6	1.6	Windows and external doors
Concrete	Block, concrete typical medium	1425	150	34.9	34.9	34.9	External walls, Substructure
	Readymix concrete	2439	60	31	31	31	Substructure
	Screed, Cemfloor	2103	60	11.5	11.5	11.5	Substructure
Inert	Adhesive mortar	1400	60	1.2	1.2	1.2	External walls
	Ceramic tile	19.9 (kg/m^2)	50	0.5	0.5	0.5	Wall finishes
	Paint, water based	0.30 (kg/m^2)	10	1	1	1	Ceiling finishes, Internal doors, Wall finishes, Windows and external doors
	Plaster, typical gypsum	1000	60	2.1	2.1	2.1	Wall finishes
	Plasterboard, Gyproc wallboard	744	60	6.5	6.5	6.5	Ceiling finishes, Wall finishes
	Plasterboard, higher density	950	60	0	0	0	Roof
	Render, Baumit silicone based	1575	17.5	6.8	6.8	6.8	Wall finishes
	Render, cement mortar	1800	30	4.2	4.2	4.2	Wall finishes
	Roofing clay tiles	2000	60	3.6	3.6	3.6	Roof
	Stone, sandstone	2350	60	35.6	35.6	35.6	Substructure
Mineral wool	Mineral wool, blown	35	60	0	0	0	Internal walls and partitions
	Mineral wool, isover glass wool	16.5	60	0.9	0.9	0.9	External walls, Internal walls and partitions, Roof, Stairs and ramps, Wall finishes
	Mineral wool, Knauf	10.5	60	0.3	0.3	0.3	Roof
Oil-based	Bitumen thick coating	800	60	0.1	0.1	0.1	External walls, Substructure
	EPS, EPS150	25	60	0.1	0.1	0.1	Substructure
	Flexible Polyolefin (PFO)	2.21 (kg/m^2)	35	0.1	0.1	0.1	Substructure
	Phenolic, Kingspan Kooltherm K12	35	60	0	0	0	External walls

	Phenolic, Kingspan Kooltherm K15	35	60	0.1	0.1	0.1	Ceiling finishes, External walls
	Polythene, Polyethylene	0.22 (kg/m^2)	20	0.3	0.3	0.3	Building services, Substructure
	DPC, and DPM	0.27 (kg/m^2)	60	0.1	0.1	0.1	Ceiling finishes, Wall finishes, Windows and external doors
	Polythene, Polyethylene, vapour barrier	0.11 (kg/m^2)	60	0.1	0.1	0.1	External walls, Internal walls and partitions, Roof
	PVC	2	30	0.1	0.1	0.1	Roof
	PVC floor vinyl	9.35 (kg/m^2)	25	2.9	2.9	2.9	Floor finishes
	PVC-P Bauder Thermofol	1.94 (kg/m^2)	25	0.1	0.1	0.1	Wall finishes
	XPS	40	60	0.1	0.1	0.1	Substructure
PV	PV, monocrystalline	–	25	0	0	1.4	Renewable electricity generation
Steel and other metals	Aluminum extrusion	2700	30	0.5	0.5	0.5	Building services, External walls, Roof
	T-beam	33.4 (kg/ml)	100	0.4	0.4	0.4	External walls
	Copper, pipe	0.26 (kg/ml)	25	0	0	0	Building services
	Mains cable	0.11 (kg/ml)	30	0.1	0.1	0.1	Building services
	MVHR	–	17	0.2	0	0	Building services
	Radiator, steel	–	50	0.3	0.6	0.6	Building services
	Rebar, UK recycled steel	7900	60	1.2	1.2	1.2	Substructure
	Steel spiral duct	3.59 (kg/ml)	20	0.5	0.6	0.6	Building services
	Steel, galvanised	7900	60	0.1	0.1	0.1	External walls
	Steel, stainless	7850	20	0.4	0.4	0.4	Building services
Timber	Easi-Joist	0.97 (kg/ml)	60	0.1	0.1	0.1	Upper floors incl. balconies

Timber frame kit system	483	60	5.3	5.3	5.3	External walls, Internal walls and partitions
Batten, stud or beam	483	60	0.3	0.3	0.3	Roof
Hardwood	750	60	0.2	0.2	0.2	Internal doors, Stairs and ramps
Plywood, high density	700	60	0.3	0.3	0.3	Stairs and ramps, Wall finishes
Plywood, low density	500	60	0.2	0.2	0.2	Internal doors
Roof truss	11.19 (kg/m^2)	60	0.6	0.6	0.6	Roof
Smartply OSB3	600	60	1.9	1.9	1.9	External walls, Roof, Upper floors incl. balconies
Softwood	483	60	0.6	0.6	0.6	Floor finishes, Stairs and ramps, Windows and external doors

[1] The different characteristics of the materials (*e.g.*, density) are obtained from the EPDs, which may support a unit conversion function to be performed where it was necessary between Revit material quantities and environmental impact data.
[2] The life expectancy of different materials relies on values indicated in the materials manufacturer EPDs, and the durability of fabric components taken from RICS default service life (see Appendix IV.8.8) (RICS, 2017). The number of replacements obtained is thereby rounded up to the next integer value according to the standard EN 15978 (CEN, 2011).

IV.8.6 Default transportation scenarios of material transportation for the UK projects

In this appendix, the default scenarios used for the UK projects of material transportation to the building site (module A4) are classified into three categories, and a default scenario for waste processing (C2) is explained (RICS, 2017). However, the transportation of new items is included in the replacement (B4) stage.

Table IV.5 Default transportation scenarios based on RICS (RICS, 2017).

Materials	**A4 (km by road)**	**C2 (km by road) [1]**
Locally manufactured	50	50
Nationally manufactured	300	–

European manufactured	1500	–

[1] Transportation for both waste sorting and processing site of different materials.

IV.8.7 Wastage rate data for construction materials

The wastage rate (WR) accounts for wasted material during production, transportation, and disposal processes (due to the amount of unused material, broken materials, and scraps). This factor is derived based on the data from the WRAP Net Waste Tool: Guide to reference data (WRAP, 2008) and can be multiplied by the same material quantity used for the production stage (A1–A3). However, waste share calculations are not considered for prefabricated elements as these are delivered as complete building modules (Andersen et al., 2022).

Table IV.6 Wastage rate data for materials derived from the WRAP Net Waste Tool: Guide to reference data (WRAP, 2008).

Material/product	**Wastage rate (WR)**
Aggregates	5%
Bricks	10%
Building services/MEP	0%
Cementitious sprays (*e.g.*, fire protection to steel)	5%
Ceramic sanitary, fixtures and fittings	1%
Components based on off-site manufacture	0%
Concrete blocks	5%
Concrete *in situ*	2.5%
Fibre glass insulation	5%
Glass	2.5%
Gravel and sand	5.5%
Gypsum products	2.5%
Insulation	5%
Non-Ferrous metal	2.5%
Plasterboard (for boarding)	15%
Plastic	2%
Precast concrete components	2%
Processed timer (*e.g.*, skirting)	5%
Screed	2.5%
Steel reinforcement	5%
Steel stud components	2%

Stone	5%
Structural and roofing frame (*e.g.*, beams, columns, braces)	0%
Structural waterproofing	5%
Tiled soft flooring	2%
Tiles and ceramics	5%
Timber floors (joists, board)	3%
Timber formwork	5%

IV.8.8 Lifespan of the different building components

The life expectancy for those components lacking data obtained from EPDs are based on the RISC default lifespan provided in Table IV.7.

Table IV.7 Lifespan of the different components according to the RICS guidance (RICS, 2017).

Building part	**Building components**	**Life expectancy (years)**
Roof	Roof coverings	30
Superstructure	Internal partitioning and dry lining	30
Finishes	Render	30
	Paint	10
	Floor finishes	30
	Raised Access Floor (RAF)/Finish layers	10
	Ceiling substrate	20
	Ceiling paint	10
Services/MEP	Heat source *e.g.*, boilers, …	20
	Space heating and air treatment	20
	Ductwork	20
	Electrical installations	30
Facade	Opaque modular cladding *e.g.*, rain screens, timber panels	30
	Glazed cladding/Curtain walling	35
	Windows and external doors	30

IV.8.9 End-of-life scenarios for different building materials

The end-of-life scenarios for UK projects are considered based on RICS recommendations (RICS, 2017). According to the RICS proportions, 90% of the general waste mass was assumed to be recycled, while the remaining 10% was landfilled. The information for timber waste is provided in Table IV.9. The mineral wool and natural wastes are assumed to be fully landfilled.

Table IV.8 End-of-life scenarios are based on RICS (RICS, 2017).

Materials and products used in the case studies	**RICS proportions**		
	Landfill	**Recycling**	**Incineration**
Reinforcing steel, stainless steel, steel, galvanised steel, aluminium	4%	96%	0%
Copper	35%	65%	0%
Brick, concrete block, plaster boards, cement mortar, plaster coat, ceramic tiles, polystyrene, polyurethane, XPS, PE, PP, LDPE pipes, PS, PVC	10%	90%	0%

IV.8.10 Timber product end-of-Life scenarios and corresponding carbon factor values used for processing and disposal of the waste material

Table IV.9 Timber product end-of-Life scenarios and corresponding carbon factor values used for processing and disposal of the waste material (C3−C4).

End-of-Life scenario	**Emissions factors for modules C3 and C4**	**RICS scenario [2]**	**Wood for Good (WfG) scenario [3]**
Recycling	1.67 $kgCO_2eq/kg$ [3]	–	55%
Incineration for energy recovery	1.64 $kgCO_2eq/kg$ [2]	75%	44%
Landfill (no gas recovery) [1]	2.15 $kgCO_2eq/kg$ [2]	25%	1%

[1] Modern landfill sites often employ techniques to capture the gases arising from organic matter decomposition (RICS, 2017).

[2] Factors are derived from the default timber product end-of-life scenario of the RICS guide (RICS, 2017).

[3] Factors are obtained according to the Wood for Good (WfG) LCA guide for timber end-of-life scenarios (Wood for Good, 2017).

IV.8.11 Main input parameter used in DesignBuilder simulation software

Table IV.10 Main input parameter used in DesignBuilder simulation software (DesignBuilder, 2021).

Parameters	**Key variables**
Heating [1, 2]	Setpoint: 21 °C Set back: 15 °C
	Heating on from 7am–9am/4pm–11pm for weekdays, and from 7am–11pm for weekends; else time not specified above, the heating is set back.
Mechanical ventilation [2, 3]	Air change rate: 8 l/s per person; Inside thermal envelope: 25 °C; Indoor min temperature: 22 °C
Air infiltration rate [3]	2 m^3/m^2h @ 50 Pa
Lighting power density [2]	12 W/m^2–100 lx
	The usage profile has the same trend based on schedule and daylight availability.
Peak heat load [3]	10 W/m^2
Domestic hot water (DHW) [2]	25 L/person/day; Delivery efficiency: 0.80; Hot water supply: 60 °C; Storage volume: 100 L

[1] The input parameters are adjusted according to the activity data from the UK building regulation (BRE, 2014; CIBSE, 2017).
[2] The input parameters are obtained according to the ASHRAE and CIBSE Guide (Ben and Steemers, 2014).
[3] The input parameters are derived from the requirement of the Passivhaus standard (Feist, 2011).

IV.8.12 UK electricity grid mix into different technologies and associated Ecoinvent unit processes

Table IV.11 UK electricity grid mix into different technologies and associated Ecoinvent unit processes used for modelling the electricity mix sources.

Electricity source	**Generation technology**	**Ecoinvent process used (Wernet et al., 2016)**
Biogas	Combine heat and power	{GB}| heat and power co-generation, biogas, gas engine
Biomass	Combine heat and power	{GB}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014

Coal	Fired power plant	{GB}| electricity production, hard coal
Hydro power [1]	Large-scale water turbine (dam-reservoir)	{DE}| electricity production, hydro, reservoir, non-alpine region
	Small-scale water turbine (run-of-river)	{GB}| electricity production, hydro, run-of-river
Marine	Tidal	See note 2
Natural gas (NGCC)	Combined cycle gas technology	{GB}| electricity production, natural gas, combined cycle power plant
Natural gas CCS [3]	Combined cycle gas technology	See note 3
Nuclear	Nuclear power	{GB}| electricity production, nuclear, pressure water reactor
Solar [4]	Photovoltaic roof installations	{GB}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si
	Photovoltaic ground arrays	{GB}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted
Storage	Pumped hydro storage	See note 5
	Adiabatic-compressed air energy storage	See note 6
	Battery stationary storage	See note 7
Waste	Incineration plant	{GB}| electricity, from municipal waste incineration to generic market for electricity
Wind	Wind onshore	{GB}| electricity production, wind, 1-3MW turbine, onshore
	Wind offshore	{GB}| electricity production, wind, 1-3MW turbine, offshore

[1] According to the Digest of UK Energy Statistics (DUKES) (DUKES, 2021b), hydro power in the UK is divided by 23% for run-of-river and 77% for reservoir technologies.
[2] The life cycle inventory for tidal technology is provided in Table IV.14.
[3] Fossil fuel-based power with carbon capture and storage (CCS) is modelled according to the generic process and only post-combustion CCS is considered. The carbon capture efficiency of 90% from fuel combustion of the generic process is assumed for CCS installations (CCC,

2019b). The inventories for the adjusted model with the conventional plants for CCS are modeled based on Table IV.12 and Table IV.13.
[4] An split equally between photovoltaic rooftop installations and ground arrays are considered (FES, 2019).
[5] The pumped hydro storage facilities for the UK need to combine with pre-existing hydro reservoir systems. The impact is based on a literature study (Raugei et al., 2020).
[6] The life cycle inventory for adiabatic compressed air energy storage (A-CAES) technology is provided in Table IV.15 (Bouman et al., 2016).
[7] The battery stationary storage is lithium iron phosphate type. The impact is based on a literature study (Liu et al., 2015).

Table IV.12 The life cycle inventory data for carbon capture and storage (CCS) technology (Raugei et al., 2020).

Materials or process	**Unit**	**Quantity**
Activated Carbon	kg	3.2E10−5
Concrete	kg	2.1E10−7
Electricity	kWh	4.7E10−2
Monoethanolamine (MEA)	kg	1.8E10−4
Polyethylene, high density (HDPE)	kg	7.1E10−7
Sodium hydroxide (NaOH)	kg	5.5E10−5
Steel (low alloyed)	kg	7.7E10−5

Table IV.13 The life cycle inventory data of use-phase emissions, expressed per unit of electricity generated (Raugei et al., 2020).

Materials or process	**Unit**	**Quantity**
Carbon dioxide (CO_2)	g	47
Nitrogen oxides (NOx)	g	1.7E10−1
Sulphur dioxide (SO_2)	g	3.8E10−3
Particulate matter (PM)	g	2.2E10−3
Formaldehyde	g	1.1E10−1
Acetaldehyde	g	7.0E10−2
Ammonia (NH_3)	g	1.5E10−2
Monoethanolamine (MEA)	g	2.6E10−2

Table IV.14 The life cycle inventory data for stream turbine tidal electricity generation (Raugei et al., 2020).

Materials or process	**Unit**	**Quantity**

Cast iron	kg	1.5E10−6
Cement	kg	2.5E10−5
Copper	kg	3.2E10−6
Electricity	kWh	1.9E10−2
Glass fiber-reinforced plastics	kg	9.4E10−6
Polyethylene (PE)	kg	4.7E10−7
Steel (low alloyed)	kg	1.6E10−4

Table IV.15 The life cycle inventory for adiabatic compressed air energy storage (A-CAES) technology (Bouman et al., 2016).

Materials or process	**Unit**	**Quantity**
Aluminium	kg	$4.4E10^{-1}$
Cast Iron	kg	48
Concrete	kg	$5.2E10^{2}$
Copper	kg	4.0
Diesel (burnt in building machines)	MJ	$9.1E10^{2}$
Electricity (for plant construction)	kWh	18
Foam Glass	kg	3.2
Heavy fuel oil (burnt in industrial machines)	MJ	$9.1E10^{2}$
Insulation (rock wool)	kg	19
Limestone	kg	4.6
Lubricating oil	kg	$2.5E10^{3}$
Polypropylene (PP)	kg	$6.3E10^{-1}$
Sand-lime brick	kg	24
Steel (high alloyed)	kg	91
Steel (low alloyed)	kg	$1.3E10^{2}$
Steel (unalloyed)	kg	$1.1E10^{2}$

IV.8.13 Electricity CO_2 emission factors of the different scenarios considered

This appendix shows the CO_2 emission factors in terms of kg/kWh electricity produced from different scenarios.

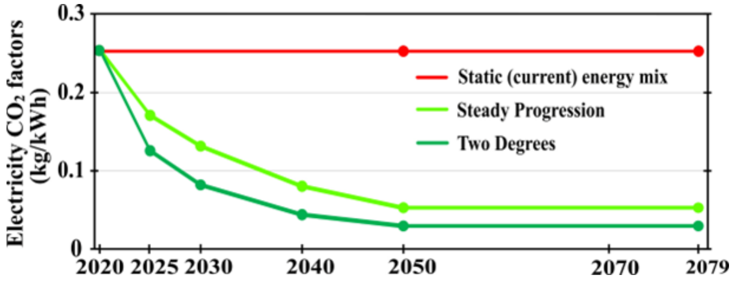


Figure IV.10 Electricity CO_2 emission factors of the different scenarios considered.

IV.8.14 Full results of different building case studies by each stage

Table IV.16 Full results of different building case studies by each stage.

	Information module	**GHG emissions ($kgCO_2eq/m^2$ (GIA))**		
		BS1	BS2	BS3
Materials production stage	A1−A3 (manufacture)	155.9	161.5	174.0
	A1−A3 (sequestered)	-84.9	-84.9	-84.9
Construction stage	A4	23.7	24.3	24.6
	A5	15.9	15.9	15.9
Use stage	B1−B3	-5.7	15.0	15.0
	B4−B5	101.3	114.7	141.2
	B6	740.1	503.8	503.8
	B7	3.7	3.7	3.7
End-of-life stage	C1	3.4	3.5	3.8
	C2	7.0	7.0	7.0
	C3−C4	98.4	98.5	98.5
Benefits and loads beyond the building life cycle stage	Recovery and recycling potential	-46.0	-46.3	-46.3
	Surplus of renewable energy	0.0	0.0	-204.9

IV.9 Reference

Al-Shetwi, A.Q., 2022. Sustainable development of renewable energy integrated power sector: Trends, environmental impacts, and recent challenges. Sci. Total Environ. 822, 153645. https://doi.org/10.1016/J.SCITOTENV.2022.153645

Al-Yasiri, Q., Szabó, M., 2022. Phase change material coupled building envelope for thermal comfort and energy-saving: Effect of natural night ventilation under hot climate. J. Clean. Prod. 365, 132839. https://doi.org/10.1016/J.JCLEPRO.2022.132839

Alaux, N., Ruschi Mendes Saade, M., Hoxha, E., Truger, B., Passer, A., 2023. Future trends in materials manufacturing for low carbon building stocks: A prospective macro-scale analysis at the provincial level. J. Clean. Prod. 382. https://doi.org/10.1016/j.jclepro.2022.135278

Allen, C., Oldfield, P., Teh, S.H., Wiedmann, T., Langdon, S., Yu, M., Yang, J., 2022. Modelling ambitious climate mitigation pathways for Australia's built environment. Sustain. Cities Soc. 77, 103554. https://doi.org/10.1016/J.SCS.2021.103554

Almena, A., Thornley, P., Chong, K., Röder, M., 2022. Carbon dioxide removal potential from decentralised bioenergy with carbon capture and storage (BECCS) and the relevance of operational choices. Biomass and Bioenergy 159, 106406. https://doi.org/10.1016/J.BIOMBIOE.2022.106406

Anand, C.K., Amor, B., 2017. Recent developments, future challenges and new research directions in LCA of buildings: A critical review. Renew. Sustain. Energy Rev. 67, 408–416. https://doi.org/10.1016/J.RSER.2016.09.058

Andersen, J.H., Rasmussen, N.L., Ryberg, M.W., 2022. Comparative life cycle assessment of cross laminated timber building and concrete building with special focus on biogenic carbon. Energy Build. 254, 111604. https://doi.org/10.1016/J.ENBUILD.2021.111604

Aranda-Usón, A., Ferreira, G., López-Sabirón, A.M., Mainar-Toledo, M.D., Zabalza Bribián, I., 2013. Phase change material applications in buildings: An environmental assessment for some Spanish climate severities. Sci. Total Environ. 444, 16–25. https://doi.org/10.1016/J.SCITOTENV.2012.11.012

Arehart, J.H., Hart, J., Pomponi, F., D'Amico, B., 2021. Carbon sequestration and storage in the built environment. Sustain. Prod. Consum. 27, 1047–1063. https://doi.org/10.1016/J.SPC.2021.02.028

Asdrubali, F., Ballarini, I., Corrado, V., Evangelisti, L., Grazieschi, G., Guattari, C., 2019. Energy and environmental payback times for an NZEB retrofit. Build. Environ. 147, 461–472. https://doi.org/10.1016/J.BUILDENV.2018.10.047

Autodesk, 2021. Revit for MEP Engineering. Industries. URL https://www.autodesk.com/products/revit/mep (accessed 7.15.22).

AzariJafari, H., Guest, G., Kirchain, R., Gregory, J., Amor, B., 2021. Towards comparable environmental product declarations of construction materials: Insights from a probabilistic comparative LCA approach. Build. Environ. 190, 107542. https://doi.org/10.1016/J.BUILDENV.2020.107542

Azzouz, A., Borchers, M., Moreira, J., Mavrogianni, A., 2017. Life cycle assessment of energy conservation measures during early stage office building design: A case study in London, UK. Energy Build. 139, 547–568. https://doi.org/10.1016/j.enbuild.2016.12.089

Balasbaneh, A.T., Sher, W., 2021. Comparative sustainability evaluation of two engineered wood-based construction materials: Life cycle analysis of CLT versus GLT. Build. Environ. 204, 108112. https://doi.org/10.1016/J.BUILDENV.2021.108112

Barrett, D.J., Linley, M.D., Best, S.M., -, al, Parsi Benehkohal, N., Sussman, M.J., Chiu, H., 2019. The Reporting of End of Life and Module D Data and Scenarios in EPD for Building level Life Cycle Assessment. IOP Conf. Ser. Earth Environ. Sci. 323, 012051. https://doi.org/10.1088/1755-1315/323/1/012051

BEIS, 2021. Greenhouse gas reporting: conversion factors 2021. Dep. Business, Energy Ind. Strateg. London, BEIS. URL https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021 (accessed 9.16.22).

Ben, H., Steemers, K., 2014. Energy retrofit and occupant behaviour in protected housing: A case study of the Brunswick Centre in London. Energy Build. 80, 120–130. https://doi.org/10.1016/J.ENBUILD.2014.05.019

Benato, A., Stoppato, A., 2019. Integrated Thermal Electricity Storage System: Energetic and cost performance. Energy Convers. Manag. 197, 111833. https://doi.org/10.1016/J.ENCONMAN.2019.111833

Bianco, V., Scarpa, F., Tagliafico, L.A., 2017. Estimation of primary energy savings by using heat pumps for heating purposes in the residential sector. Appl. Therm. Eng. 114, 938–947. https://doi.org/10.1016/J.APPLTHERMALENG.2016.12.058

Bouman, E.A., Øberg, M.M., Hertwich, E.G., 2016. Environmental impacts of balancing offshore wind power with compressed air energy storage (CAES). Energy 95, 91–98. https://doi.org/10.1016/J.ENERGY.2015.11.041

BRE, 2021. Green Guide to Specification. URL https://tools.bregroup.com/greenguide/podpage.jsp?id=2126 (accessed 7.10.22).

BRE, 2014. SAP 2012 - The Government' s Standard Assessment Proceedure for Energy Rating of Dwellings. Technical Report rev June 2014. Buiding Res. Establ. (on behalf DECC). Watford.

BRE Group, 2023. GreenBook Live. BRE Glob. URL https://www.greenbooklive.com/index.jsp (accessed 3.15.23).

Brooks, M., Abdellatif, M., Alkhaddar, R., 2021. Application of life cycle carbon assessment for a sustainable building design: a case study in the UK. Int. J. Green Energy 18, 351–362. https://doi.org/10.1080/15435075.2020.1865360

Bughio, M., Khan, M.S., Mahar, W.A., Schuetze, T., 2021. Impact of Passive Energy Efficiency Measures on Cooling Energy Demand in an Architectural Campus Building in Karachi, Pakistan. Sustain. 2021, Vol. 13, Page 7251 13, 7251. https://doi.org/10.3390/SU13137251

Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., Castell, A., 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.08.037

Cabrera Serrenho, A., Drewniok, M., Dunant, C., Allwood, J.M., 2019. Testing the greenhouse gas emissions reduction potential of alternative strategies for the english housing stock. Resour. Conserv. Recycl. 144, 267–275. https://doi.org/10.1016/J.RESCONREC.2019.02.001

CCC, 2021. 2021 Progress Report to Parliament. Progress in reducing emissions. Clim. Chang. Comm. URL https://www.theccc.org.uk/publication/2021-progress-report-to-parliament/ (accessed 9.10.22).

CCC, 2020. The Sixth Carbon Budget: The UK's path to Net Zero. Comm. Clim. Chang. URL https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf (accessed 3.20.23).

CCC, 2019. Net zero: The UK's contribution to stopping global warming. Comm. Clim. Chang. URL https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/ (accessed 7.10.22).

CCC, 2018. Reducing UK emissions - 2018 Progress Report to Parliament. Clim. Chang. Comm. URL https://www.theccc.org.uk/publication/reducing-uk-emissions-2018-progress-report-to-parliament/ (accessed 8.14.22).

CEN, 2019. 15804: 2012+A2: 2019—Sustainability of Construction. Eur. Comm. Stand. URL https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=15804%3A+2012%2B+A2%3A+2019—Sustainability+of+Construction+Works—Environmental+Product+Declarations—Core+Rules+for+the+Product+Category+of+…&btnG= (accessed 9.17.22).

CEN, 2012. EN 15804:2012 - Sustainability of Construction Works. Environmental Product Declarations. Core Rules for the Product Category of Construction Products. Eur. Comm. Stand. URL https://scholar.google.com/scholar_lookup?title=EN 15804%3A Sustainability of Construction Works. Environmental Product Declarations. Core Rules for the Product Category of Construction Products&publication_year=2012&author=European Committee for Standard (accessed 9.2.21).

CEN, 2011. EN 15978:2011 - Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method. Eur. Comm. Stand. URL https://scholar.google.com/scholar_lookup?title=EN 15978%3A2011 - Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method&publication_year=2011&author=%2FTC 350 CEN (accessed 9.17.22).

Chen, M., Ma, M., Lin, Y., Ma, Z., Li, K., 2022. Carbon Kuznets curve in China's building operations: Retrospective and prospective trajectories. Sci. Total Environ. 803, 150104. https://doi.org/10.1016/J.SCITOTENV.2021.150104

CIBSE, 2017. TM59: Design Methodology for the Assessment of Overheating Risk in Homes. Chart. Inst. Build. Serv. Eng. London. URL https://www.cibse.org/knowledge-research/knowledge-portal/technical-memorandum-59-design-methodology-for-the-assessment-of-overheating-risk-in-homes (accessed 9.22.22).

Collinge, W.O., Landis, A.E., Jones, A.K., Schaefer, L.A., Bilec, M.M., 2014. Productivity metrics in dynamic LCA for whole buildings: Using a post-occupancy evaluation of energy and indoor environmental quality tradeoffs. Build. Environ. 82, 339–348. https://doi.org/10.1016/J.BUILDENV.2014.08.032

Collinge, W.O., Landis, A.E., Jones, A.K., Schaefer, L.A., Bilec, M.M., 2013. Dynamic life cycle assessment: Framework and application to an institutional building. Int. J. Life Cycle Assess. 18, 538–552. https://doi.org/10.1007/S11367-012-0528-2/FIGURES/6

Contreras Lisperguer, R., Muñoz Cerón, E., de la Casa Higueras, J., Martín, R.D., 2020. Environmental Impact Assessment of crystalline solar photovoltaic panels' End-of-Life phase: Open and Closed-Loop Material Flow scenarios. Sustain. Prod. Consum. 23, 157–173. https://doi.org/10.1016/J.SPC.2020.05.008

Cooper, S., Blanco-Sanchez, P., Welfle, A., McManus, M., 2019. Bioenergy and waste gasification in the UK: barriers and research needs. Supergen Bioenergy Hub.

Crawford, R., 2011. Life cycle assessment in the built environment.

Cuéllar-Franca, R.M., Azapagic, A., 2012. Environmental impacts of the UK residential sector: Life cycle assessment of houses. Build. Environ. 54, 86–99. https://doi.org/10.1016/j.buildenv.2012.02.005

Cusenza, M.A., Guarino, F., Longo, S., Mistretta, M., Cellura, M., 2019. Reuse of electric vehicle batteries in buildings: An integrated load match analysis and life cycle assessment approach. Energy Build. 186, 339–354. https://doi.org/10.1016/J.ENBUILD.2019.01.032

D'Agostino, D., 2015. Assessment of the progress towards the establishment of definitions of Nearly Zero Energy Buildings (nZEBs) in European Member States. J. Build. Eng. 1, 20–32. https://doi.org/10.1016/J.JOBE.2015.01.002

De Castro, E.B.P., Mequignon, M., Adolphe, L., Koptschitz, P., 2014. Impact of the lifespan of different external walls of buildings on greenhouse gas emissions under tropical climate conditions. Energy Build. 76, 228–237. https://doi.org/10.1016/J.ENBUILD.2014.02.071

De Masi, R.F., Gigante, A., Vanoli, G.P., 2021. Are nZEB design solutions environmental sustainable? Sensitive analysis for building envelope configurations and photovoltaic integration in different climates. J. Build. Eng. 39, 102292. https://doi.org/10.1016/J.JOBE.2021.102292 de Rubeis, T., Nardi, I., Ambrosini, D., Paoletti, D., 2018. Is a self-sufficient building energy efficient? Lesson learned from a case study in Mediterranean climate. Appl. Energy 218, 131–145. https://doi.org/10.1016/J.APENERGY.2018.02.166

de Simone Souza, H.H., de Abreu Evangelista, P.P., Medeiros, D.L., Albertí, J., Fullana-i-Palmer, P., Boncz, M.Á., Kiperstok, A., Gonçalves, J.P., 2021. Functional unit influence on building life cycle assessment. Int. J. Life Cycle Assess. 26, 435–454. https://doi.org/10.1007/S11367-020-01854-1/FIGURES/4

De Wolf, C., Pomponi, F., Moncaster, A., 2017. Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. Energy Build. 140, 68–80. https://doi.org/10.1016/J.ENBUILD.2017.01.075

DEFRA, 2012. Wood waste: A short review of recent research. Dep. Environ. Food Rural Aff. URL http://www.defra.gov.uk/consult/ (accessed 9.18.22).

DesignBuilder, 2021. DesignBuilder Version 6.1.8.021. Des. Softw. Ltd. URL https://designbuilder.co.uk// (accessed 9.12.22).

Din, A., Brotas, L., 2016. Exploration of life cycle data calculation: Lessons from a Passivhaus case study. Energy Build. 118, 82–92. https://doi.org/10.1016/J.ENBUILD.2016.02.032

DUKES, 2021a. Digest of UK Energy Statistics (DUKES): electricity. Dep. Business, Energy Ind. Strateg. URL https://www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes (accessed 10.20.22).

DUKES, 2021b. Digest of UK Energy Statistics (DUKES): renewable sources of energy. Dep. Business, Energy Ind. Strateg. URL https://www.gov.uk/government/statistics/renewable-sources-of-energy-chapter-6-digest-of-united-kingdom-energy-statistics-dukes (accessed 9.26.22).

EASAC, 2021. European Academies’ Science AdvisoryCouncil - Decarbonisation of buildings: for climate, health and jobs : EASAC policy report 43.

EcoPlatform, 2023. ECO Portal. ECO Platf. AISBL. URL https://www.eco-platform.org/eco-portal-access-point-to-digital-product-data.html (accessed 3.12.23).

EN 16449, 2014. EN 16449:2014–Wood and wood-based products - Calculation of the Biogenic Carbon Content of wood and Conversion to Carbon Dioxide. Eur. Stand. URL https://www.en-standard.eu/csn-en-16449-wood-and-wood-based-products-calculation-of-the-biogenic-carbon-content-of-wood-and-conversion-to-carbon-dioxide/ (accessed 9.16.22).

EnergyPlus, 2022. Weather data by region - EnergyPlus. Natl. Renew. Energy Lab. URL https://energyplus.net/weather-region/europe_wmo_region_6/GBR (accessed 9.12.22).

EPD International AB, 2023. The International EPD System. Int. EPD Syst. URL https://www.environdec.com/home (accessed 3.12.23).

European Environment Agency (EEA), 2020. Total greenhouse gas emission trends and projections in Europe. Eur. Comm. URL https://www.eea.europa.eu/data-and-maps/indicators/greenhouse-gas-emission-trends-7/assessment (accessed 9.20.22).

European Parliament, 2020. European Parliament Resolution of 15 January 2020 on the European Green Deal (2019/2956 (RSP)). Eur. Parliam. URL https://www.europarl.europa.eu/doceo/document/TA-9-2020-0005_EN.html (accessed 9.20.22).

Fajilla, G., Simone, M. De, Cabeza, L.F., Bragança, L., 2020. Assessment of the Impact of Occupants' Behavior and Climate Change on Heating and Cooling Energy Needs of Buildings. Energies 2020, Vol. 13, Page 6468 13, 6468. https://doi.org/10.3390/EN13236468

Feist, W., 2011. Certified Passive House—Certification Criteria for Residential Passive House Buildings. Passiv. House Institute, Darmstadt, Ger. URL https://scholar.google.com/scholar?cluster=13112177155049035575&hl=en&as_sdt=2005&sciodt=0,5 (accessed 9.5.22).

Feng, H., Zhao, J., Zhang, H., Zhu, S., Li, D., Thurairajah, N., 2022. Uncertainties in whole-building life cycle assessment: A systematic review. J. Build. Eng. 50, 104191. https://doi.org/10.1016/J.JOBE.2022.104191

Fenner, A.E., Kibert, C.J., Woo, J., Morque, S., Razkenari, M., Hakim, H., Lu, X., 2018. The carbon footprint of buildings: A review of methodologies and applications. Renew. Sustain. Energy Rev. 94, 1142–1152. https://doi.org/10.1016/J.RSER.2018.07.012

FES, 2019. Future Energy Scenarios resources - National Grid ESO. Natl. Grid ESO. URL https://www.nationalgrideso.com/document/170756/download (accessed 10.2.22).

Fouquet, M., Levasseur, A., Margni, M., Lebert, A., Lasvaux, S., Souyri, B., Buhé, C., Woloszyn, M., 2015. Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment. Build. Environ. 90, 51–59. https://doi.org/10.1016/J.BUILDENV.2015.03.022

Fufa, S.M., Skaar, C., Gradeci, K., Labonnote, N., 2018. Assessment of greenhouse gas emissions of ventilated timber wall constructions based on parametric LCA. J. Clean. Prod. 197, 34–46. https://doi.org/10.1016/J.JCLEPRO.2018.06.006

Fuller, R.J., Crawford, R.H., 2011. Impact of past and future residential housing development patterns on energy demand and related emissions. J. Hous. Built Environ. 26, 165–183. https://doi.org/10.1007/S10901-011-9212-2/FIGURES/7

Gan, J., Chen, M., Semple, K., Liu, X., Dai, C., Tu, Q., 2022. Life cycle assessment of bamboo products: Review and harmonization. Sci. Total Environ. 849, 157937. https://doi.org/10.1016/J.SCITOTENV.2022.157937

García-Segura, T., Yepes, V., Alcalá, J., 2014. Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability. Int. J. Life Cycle Assess. 19, 3–12. https://doi.org/10.1007/S11367-013-0614-0/TABLES/8

Greening, B., Azapagic, A., 2012. Domestic heat pumps: Life cycle environmental impacts and potential implications for the UK. Energy 39, 205–217. https://doi.org/10.1016/J.ENERGY.2012.01.028

Häfliger, I.F., John, V., Passer, A., Lasvaux, S., Hoxha, E., Saade, M.R.M., Habert, G., 2017. Buildings environmental impacts’ sensitivity related to LCA modelling choices of construction materials. J. Clean. Prod. 156, 805–816. https://doi.org/10.1016/J.JCLEPRO.2017.04.052

Hafner, A., Schäfer, S., 2017. Comparative LCA study of different timber and mineral buildings and calculation method for substitution factors on building level. J. Clean. Prod. 167, 630–642. https://doi.org/10.1016/J.JCLEPRO.2017.08.203

Hart, J., D’Amico, B., Pomponi, F., 2021. Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures. J. Ind. Ecol. 25, 403–418. https://doi.org/10.1111/JIEC.13139

Hart, J., Pomponi, F., 2020. More Timber in Construction: Unanswered Questions and Future Challenges. Sustain. 2020, Vol. 12, Page 3473 12, 3473. https://doi.org/10.3390/SU12083473

Hawkins, W., Cooper, S., Allen, S., Roynon, J., Ibell, T., 2021. Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure. Structures 33, 90–98. https://doi.org/10.1016/J.ISTRUC.2020.12.013

Hertwich, E.G., Ali, S., Ciacci, L., Fishman, T., Heeren, N., Masanet, E., Asghari, F.N., Olivetti, E., Pauliuk, S., Tu, Q., Wolfram, P., 2019. Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. Environ. Res. Lett. 14, 043004. https://doi.org/10.1088/1748-9326/AB0FE3

HM Government, 2019a. The Future Homes Standard: 2019 Consultation on changes to Part L (conservation of fuel and power) and Part F (ventilation) of the Building Regulations for new dwellings. Minist. Housing, Communities Local Gov. URL https://www.gov.uk/government/consultations/the-future-buildings-standard (accessed 3.23.23).

HM Government, 2019b. The Climate Change Act 2008 (2050 Target Amendment) Order 2019. Queen’s Print. Acts Parliam.

Honarvar, S.M.H., Golabchi, M., Ledari, M.B., 2022. Building circularity as a measure of sustainability in the old and modern architecture: A case study of architecture development in the hot and dry climate. Energy Build. 275, 112469. https://doi.org/10.1016/J.ENBUILD.2022.112469

Hossain, M.U., Ng, S.T., 2020. Strategies for enhancing the accuracy of evaluation and sustainability performance of building. J. Environ. Manage. 261, 110230. https://doi.org/10.1016/J.JENVMAN.2020.110230

Houlihan Wiberg, A., Georges, L., Dokka, T.H., Haase, M., Time, B., Lien, A.G., Mellegård, S., Maltha, M., 2014. A net zero emission concept analysis of a single-family house. Energy Build. 74, 101–110. https://doi.org/10.1016/J.ENBUILD.2014.01.037

Hoxha, E., Passer, A., Ruschi, M., Saade, M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., Habert, G., 2020. Biogenic carbon in buildings: a critical overview of LCA methods. Build. Cities 1, 504–524. https://doi.org/10.5334/BC.46

IPCC, 2007. Changes in Atmospheric Constituents and in Radiative Forcing. Intergov. Panel Clim. Chang. 19–92.

ISO 14040, 2006. Environmental Management — Life Cycle Assessment — Principles and Framework. Int. Organ. Stand. Switz. URL https://www.iso.org/standard/37456.html (accessed 8.20.22).

ISO 14044, 2006. Environmental Management — Life Cycle Assessment — Requirements and Guidelines. Int. Organ. Stand. Switz. URL https://www.iso.org/standard/72357.html (accessed 9.20.22).

IStructE, 2022. How to calculate embodied carbon (Second edition). Inst. Struct. Eng. URL https://www.istructe.org/resources/guidance/how-to-calculate-embodied-carbon/ (accessed 9.20.22).

Itten, R., Frischknecht, R., Stucki, M., Scherrer, P., PSI, I., 2014. Life Cycle Inventories of Electricity Mixes and Grid. Version 1.3.

Jeswani, H.K., Saharudin, D.M., Azapagic, A., 2022. Environmental sustainability of negative emissions technologies: A review. Sustain. Prod. Consum. 33, 608–635. https://doi.org/10.1016/J.SPC.2022.06.028

Khan, M.M.H., Deviatkin, I., Havukainen, J., Horttanainen, M., 2021. Environmental impacts of wooden, plastic, and wood-polymer composite pallet: a life cycle assessment approach. Int. J. Life Cycle Assess. 26, 1607–1622. https://doi.org/10.1007/S11367-021-01953-7/FIGURES/6

Kiss, B., Kácsor, E., Szalay, Z., 2020. Environmental assessment of future electricity mix – Linking an hourly economic model with LCA. J. Clean. Prod. 264, 121536. https://doi.org/10.1016/J.JCLEPRO.2020.121536

Kristjansdottir, T.F., Good, C.S., Inman, M.R., Schlanbusch, R.D., Andresen, I., 2016. Embodied greenhouse gas emissions from PV systems in Norwegian residential Zero Emission Pilot Buildings. Sol. Energy 133, 155–171. https://doi.org/10.1016/J.SOLENER.2016.03.063

Lam, T.W.L., Tsui, Y.C.J., Fok, L., Cheung, L.T.O., Tsang, E.P.K., Lee, J.C.K., 2022. The influences of emotional factors on householders' decarbonizing cooling behaviour in a subtropical Metropolitan City: An application of the extended theory of planned behaviour. Sci. Total Environ. 807, 150826. https://doi.org/10.1016/J.SCITOTENV.2021.150826

Lamnatou, C., Notton, G., Chemisana, D., Cristofari, C., 2020. Storage systems for building-integrated photovoltaic (BIPV) and building-integrated photovoltaic/thermal (BIPVT) installations: Environmental profile and other aspects.

Sci. Total Environ. 699, 134269. https://doi.org/10.1016/J.SCITOTENV.2019.134269

Lamy-Mendes, A., Pontinha, A.D.R., Alves, P., Santos, P., Durães, L., 2021. Progress in silica aerogel-containing materials for buildings' thermal insulation. Constr. Build. Mater. 286, 122815. https://doi.org/10.1016/J.CONBUILDMAT.2021.122815

Larivière-Lajoie, R., Blanchet, P., Amor, B., 2022. Evaluating the importance of the embodied impacts of wall assemblies in the context of a low environmental impact energy mix. Build. Environ. 207, 108534. https://doi.org/10.1016/J.BUILDENV.2021.108534

Lasvaux, S., Habert, G., Peuportier, B., Chevalier, J., 2015. Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies. Int. J. Life Cycle Assess. 2015 2011 20, 1473–1490. https://doi.org/10.1007/S11367-015-0938-Z

Laurent, A., Olsen, S.I., Hauschild, M.Z., 2012. Limitations of carbon footprint as indicator of environmental sustainability. Environ. Sci. Technol. 46, 4100–4108. https://doi.org/10.1021/ES204163F/SUPPL_FILE/ES204163F_SI_001.PDF

Lausselet, C., Urrego, J.P.F., Resch, E., Brattebø, H., 2021. Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock. J. Ind. Ecol. 25, 419–434. https://doi.org/10.1111/JIEC.13049

Leonzio, G., Bogle, I.D.L., Ugo Foscolo, P., 2023. Life cycle assessment of a carbon capture utilization and storage supply chain in Italy and Germany: Comparison between carbon dioxide storage and utilization systems. Sustain. Energy Technol. Assessments 55, 102743. https://doi.org/10.1016/J.SETA.2022.102743

LETI, 2021. LETI Embodied Carbon Target Alignment. London Energy Transform. Initiat. URL https://www.leti.uk/carbonalignment (accessed 10.20.22).

LETI, 2020a. LETI Embodied Carbon Primer, Supplementary Guidance to the Climate Emergency Design Guide. London Energy Transform. Initiat. URL https://www.leti.uk/ecp (accessed 10.20.22).

LETI, 2020b. LETI Climate Emergency Design Guide, how new buildings can meet UK climate change targets. London Energy Transform. Initiat. URL https://www.leti.uk/cedg (accessed 10.20.22).

Levasseur, A., Lesage, P., Margni, M., Samson, R., 2013. Biogenic Carbon and Temporary Storage Addressed with Dynamic Life Cycle Assessment. J. Ind. Ecol. 17, 117–128. https://doi.org/10.1111/J.1530-9290.2012.00503.X

Ligardo-Herrera, I., Quintana-Gallardo, A., Stascheit, C.W., Gómez-Navarro, T., 2022. Make your home carbon-free. An open access planning tool to calculate energy-related carbon emissions in districts and dwellings. Energy Reports 8, 11404–11415. https://doi.org/10.1016/J.EGYR.2022.08.263

Lin, H., Clavreul, J., Jeandaux, C., Crawley, J., Butnar, I., 2021. Environmental life cycle assessment of heating systems in the UK: Comparative assessment of hybrid heat pumps vs. condensing gas boilers. Energy Build. 240, 110865. https://doi.org/10.1016/J.ENBUILD.2021.110865

Liu, W., Sang, J., Chen, L., Tian, J., Zhang, H., Olvera Palma, G., 2015. Life cycle assessment of lead-acid batteries used in electric bicycles in China. J. Clean. Prod. 108, 1149–1156. https://doi.org/10.1016/J.JCLEPRO.2015.07.026

López, L.R., Dessì, P., Cabrera-Codony, A., Rocha-Melogno, L., Kraakman, B., Naddeo, V., Balaguer, M.D., Puig, S., 2023. CO2 in indoor environments: From environmental and health risk to potential renewable carbon source. Sci. Total Environ. 856, 159088. https://doi.org/10.1016/J.SCITOTENV.2022.159088

Lukić, I., Premrov, M., Passer, A., Žegarac Leskovar, V., 2021. Embodied energy and GHG emissions of residential multi-storey timber buildings by height – A case with structural connectors and mechanical fasteners. Energy Build. 252, 111387. https://doi.org/10.1016/J.ENBUILD.2021.111387

Mahmoud, S.H., Gan, T.Y., 2018. Impact of anthropogenic climate change and human activities on environment and ecosystem services in arid regions. Sci. Total Environ. 633, 1329–1344. https://doi.org/10.1016/J.SCITOTENV.2018.03.290

Maierhofer, D., Röck, M., Ruschi Mendes Saade, M., Hoxha, E., Passer, A., 2022. Critical life cycle assessment of the innovative passive nZEB building concept 'be 2226' in view of net-zero carbon targets. Build. Environ. 223, 109476. https://doi.org/10.1016/J.BUILDENV.2022.109476

Meex, E., Hollberg, A., Knapen, E., Hildebrand, L., Verbeeck, G., 2018. Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design. Build. Environ. 133, 228–236. https://doi.org/10.1016/J.BUILDENV.2018.02.016

Moncaster, A.M., Symons, K.E., 2013. A method and tool for ‘cradle to grave’ embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards. Energy Build. 66, 514–523. https://doi.org/10.1016/J.ENBUILD.2013.07.046

Morris, F., Allen, S., Hawkins, W., 2021. On the embodied carbon of structural timber versus steel, and the influence of LCA methodology. Build. Environ. 206, 108285. https://doi.org/10.1016/J.BUILDENV.2021.108285

MPA The Concrete Centre, 2016. Whole-Life Carbon and Buildings: Concrete solutions for reducing embodied and operational CO2. Circ. Econ. 24.

Najjar, M., Figueiredo, K., Hammad, A.W.A., Haddad, A., 2019. Integrated optimization with building information modeling and life cycle assessment for generating energy efficient buildings. Appl. Energy 250, 1366–1382. https://doi.org/10.1016/J.APENERGY.2019.05.101

Negishi, K., Tiruta-Barna, L., Schiopu, N., Lebert, A., Chevalier, J., 2018. An operational methodology for applying dynamic Life Cycle Assessment to buildings. Build. Environ. 144, 611–621. https://doi.org/10.1016/J.BUILDENV.2018.09.005

Neirotti, F., Noussan, M., Simonetti, M., 2020. Towards the electrification of buildings heating - Real heat pumps electricity mixes based on high resolution operational profiles. Energy 195, 116974. https://doi.org/10.1016/J.ENERGY.2020.116974

Nematchoua, M.K., Sendrahasina, R.M., Malmedy, C., Orosa, J.A., Simo, E., Reiter, S., 2022. Analysis of environmental impacts and costs of a residential building over its entire life cycle to achieve nearly zero energy and low emission objectives. J. Clean. Prod. 373, 133834. https://doi.org/10.1016/J.JCLEPRO.2022.133834

Norouzi, Masoud, Chàfer, M., Cabeza, L.F., Jiménez, L., Boer, D., 2021. Circular economy in the building and construction sector: A scientific evolution analysis. J. Build. Eng. 44. https://doi.org/10.1016/J.JOBE.2021.102704

Norouzi, Mohsen, Rafienia, M., Poorazizi, E., Setayeshmehr, M., 2021. Adipose-derived Stem Cells Growth and Proliferation Enhancement Using Poly (lactic-co-glycolic acid) (PLGA)/Fibrin Nanofiber Mats. J. Appl. Biotechnol. Reports 8, 361–369. https://doi.org/10.30491/JABR.2020.223551.1199

Pamenter, S., Myers, R.J., 2021. Decarbonizing the cementitious materials cycle: A whole-systems review of measures to decarbonize the cement supply chain in the UK and European contexts. J. Ind. Ecol. 25, 359–376. https://doi.org/10.1111/JIEC.13105

Peñaloza, D., Erlandsson, M., Berlin, J., Wålinder, M., Falk, A., 2018. Future scenarios for climate mitigation of new construction in Sweden: Effects of different technological pathways. J. Clean. Prod. 187, 1025–1035. https://doi.org/10.1016/J.JCLEPRO.2018.03.285

Peñaloza, D., Erlandsson, M., Falk, A., 2016. Exploring the climate impact effects of increased use of bio-based materials in buildings. Constr. Build. Mater. 125, 219–226. https://doi.org/10.1016/J.CONBUILDMAT.2016.08.041

Petrović, B., Eriksson, O., Zhang, X., 2023. Carbon assessment of a wooden single-family building – A novel deep green design and elaborating on assessment parameters. Build. Environ. 233, 110093. https://doi.org/10.1016/J.BUILDENV.2023.110093

Pietzcker, R.C., Osorio, S., Rodrigues, R., 2021. Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector. Appl. Energy 293, 116914. https://doi.org/10.1016/J.APENERGY.2021.116914

Pomponi, F., Moncaster, A., 2016. Embodied carbon mitigation and reduction in the built environment – What does the evidence say? J. Environ. Manage. 181, 687–700. https://doi.org/10.1016/J.JENVMAN.2016.08.036

POST, 2021. Reducing the whole life carbon impact of buildings. Parliam. Off. Sci. Technol. UK Parliam. Postbr. 44. URL https://researchbriefings.files.parliament.uk/documents/POST-PB-0044/POST-PB-0044.pdf (accessed 9.10.22).

Pré Consultants, 2022. SimaPro. PRé Sustain. B.V. URL https://simapro.com/ (accessed 9.20.22).

PVsyst SA, 2022. PV-syst 7.2, Photovoltaic System Software 7.2. URL https://www.pvsyst.com/ (accessed 9.14.22).

Rahif, R., Norouziasas, A., Elnagar, E., Doutreloup, S., Pourkiaei, S.M., Amaripadath, D., Romain, A.C., Fettweis, X., Attia, S., 2022. Impact of climate change on nearly zero-energy dwelling in temperate climate: Time-integrated discomfort, HVAC energy performance, and GHG emissions. Build. Environ. 223, 109397. https://doi.org/10.1016/J.BUILDENV.2022.109397

Raugei, M., Kamran, M., Hutchinson, A., 2020. A Prospective Net Energy and Environmental Life-Cycle Assessment of the UK Electricity Grid. Energies 2020, Vol. 13, Page 2207 13, 2207. https://doi.org/10.3390/EN13092207

RICS, 2017. Whole life carbon assessment for the built environment. R. Inst. Chart. Surv. Parliam. Sq. London SW1P 3AD. URL https://www.rics.org/globalassets/rics-website/media/news/whole-life-carbon-assessment-for-the--built-environment-november-2017.pdf (accessed 9.14.22).

Robati, M., Oldfield, P., 2022. The embodied carbon of mass timber and concrete buildings in Australia: An uncertainty analysis. Build. Environ. 214, 108944. https://doi.org/10.1016/J.BUILDENV.2022.108944

Roberts, M., Allen, S., Coley, D., 2020. Life cycle assessment in the building design process – A systematic literature review. Build. Environ. 185, 107274. https://doi.org/10.1016/J.BUILDENV.2020.107274

Roca-Puigròs, M., Billy, R.G., Gerber, A., Wäger, P., Müller, D.B., 2020. Pathways toward a carbon-neutral Swiss residential building stock. Build. Cities 1, 579–593. https://doi.org/10.5334/BC.61

Röck, M., Baldereschi, E., Verellen, E., Passer, A., Sala, S., Allacker, K., 2021. Environmental modelling of building stocks – An integrated review of life cycle-based assessment models to support EU policy making. Renew. Sustain. Energy Rev. 151, 111550. https://doi.org/10.1016/J.RSER.2021.111550

Röck, M., Saade, M.R.M., Balouktsi, M., Rasmussen, F.N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., Passer, A., 2020. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. Appl. Energy 258, 114107. https://doi.org/10.1016/J.APENERGY.2019.114107

Rodrigues, C., König, J., Freire, F., 2023. Prospective life cycle assessment of a novel building system with improved foam glass incorporating high recycled content. Sustain. Prod. Consum. 36, 161–170. https://doi.org/10.1016/J.SPC.2023.01.002

Rodriguez, B.X., Huang, M., Lee, H.W., Simonen, K., Ditto, J., 2020. Mechanical, electrical, plumbing and tenant improvements over the building lifetime: Estimating material quantities and embodied carbon for climate change mitigation. Energy Build. 226, 110324. https://doi.org/10.1016/J.ENBUILD.2020.110324

Rosenbaum, R.K., Hauschild, M.Z., Boulay, A.M., Fantke, P., Laurent, A., Núñez, M., Vieira, M., 2017. Life cycle impact assessment. Life Cycle Assess. Theory Pract. 167–270. https://doi.org/10.1007/978-3-319-56475-3_10/FIGURES/28

Roux, C., Schalbart, P., Peuportier, B., 2016. Accounting for temporal variation of electricity production and consumption in the LCA of an energy-efficient house. J. Clean. Prod. 113, 532–540. https://doi.org/10.1016/J.JCLEPRO.2015.11.052

Saade, M.R.M., Guest, G., Amor, B., 2020. Comparative whole building LCAs: How far are our expectations from the documented evidence? Build. Environ. 167, 106449. https://doi.org/10.1016/J.BUILDENV.2019.106449

Santos, P., Correia, J.R., Godinho, L., Dias, A.M.P.G., Dias, A., 2021. Life cycle analysis of cross-insulated timber panels. Structures 31, 1311–1324. https://doi.org/10.1016/J.ISTRUC.2020.12.008

Santos, R., Aguiar Costa, A., Silvestre, J.D., Pyl, L., 2020a. Development of a BIM-based Environmental and Economic Life Cycle Assessment tool. J. Clean. Prod. 265, 121705. https://doi.org/10.1016/J.JCLEPRO.2020.121705

Santos, R., Costa, A.A., Silvestre, J.D., Vandenbergh, T., Pyl, L., 2020b. BIM-based life cycle assessment and life cycle costing of an office building in Western Europe. Build. Environ. 169, 106568. https://doi.org/10.1016/J.BUILDENV.2019.106568

Satola, D., Wiberg, A.H., Singh, M., Babu, S., James, B., Dixit, M., Sharston, R., Grynberg, Y., Gustavsen, A., 2022. Comparative review of international approaches to net-zero buildings: Knowledge-sharing initiative to develop design strategies for greenhouse gas emissions reduction. Energy Sustain. Dev. 71, 291–306. https://doi.org/10.1016/J.ESD.2022.10.005

Scamman, D., Solano-Rodríguez, B., Pye, S., Chiu, L.F., Smith, A.Z.P., Cassarino, T.G., Barrett, M., Lowe, R., 2020. Heat Decarbonisation Modelling Approaches in the UK: An Energy System Architecture Perspective. Energies 2020, Vol. 13, Page 1869 13, 1869. https://doi.org/10.3390/EN13081869

Shanks, W., Dunant, C.F., Drewniok, M.P., Lupton, R.C., Serrenho, A., Allwood, J.M., 2019. How much cement can we do without? Lessons from cement material flows in the UK. Resour. Conserv. Recycl. 141, 441–454. https://doi.org/10.1016/J.RESCONREC.2018.11.002

Shin, Y.S., Cho, K., 2015. BIM application to select appropriate design alternative with consideration of LCA and LCCA. Math. Probl. Eng. 2015. https://doi.org/10.1155/2015/281640

Smith, M., Bevacqua, A., Tembe, S., Lal, P., 2021. Life cycle analysis (LCA) of residential ground source heat pump systems: A comparative analysis of energy efficiency in New Jersey. Sustain. Energy Technol. Assessments 47, 101364. https://doi.org/10.1016/J.SETA.2021.101364

Smith, P., Haszeldine, R.S., Smith, S.M., 2016. Preliminary assessment of the potential for, and limitations to, terrestrial negative emission technologies in the UK. Environ. Sci. Process. Impacts 18, 1400–1405. https://doi.org/10.1039/C6EM00386A

STA, 2016. STA Annual Survey of UK Structural Timber Markets. Struct. Timber. URL https://www.structuraltimbermagazine.co.uk/news/sta-annual-survey-of-uk-structural-timber-markets/ (accessed 3.25.23).

Stamford, L., Azapagic, A., 2014. Life cycle sustainability assessment of UK electricity scenarios to 2070. Energy Sustain. Dev. 23, 194–211. https://doi.org/10.1016/J.ESD.2014.09.008

Stephan, A., Crawford, R.H., de Myttenaere, K., 2013. A comprehensive assessment of the life cycle energy demand of passive houses. Appl. Energy 112, 23–34. https://doi.org/10.1016/j.apenergy.2013.05.076

Su, S., Li, X., Zhu, Y., Lin, B., 2017. Dynamic LCA framework for environmental impact assessment of buildings. Energy Build. 149, 310–320. https://doi.org/10.1016/J.ENBUILD.2017.05.042

Symons, K., Moncaster, A., Symons, D., 2013. An Application of the CEN/TC350 standards to an Energy and Carbon LCA of timber used in construction, and the effect of end-of-life scenarios. Aust. Life Cycle Assess. Soc. Conf. Sydney, Aust.

Terreal Solution PV3-1 S, 2017. PV system-EPD Ecopassport. pep-ecopassport.org. URL http://www.pep-ecopassport.org/ (accessed 9.11.22).

UK Government's National Calculation Methodology, 2021. Standard Assessment Procedure. Dep. Business, Energy Ind. Strateg. URL https://www.gov.uk/guidance/standard-assessment-procedure (accessed 12.25.21).

UKGBC, 2021. Renewable Energy Procurement & Carbon Offsetting - Guidance for Net Zero Carbon Buildings. UK Green Build. Counc. London, UK. URL https://www.ukgbc.org/ukgbc-work/renewable-energy-procurement-carbon-offsetting-guidance-for-net-zero-carbon-buildings/ (accessed 9.20.22).

UKGBC, 2019. Net Zero Carbon Buildings: A Framework Definition. UK Green Build. Counc. london. URL https://www.ukgbc.org/ukgbc-work/net-zero-carbon-buildings-a-framework-definition/ (accessed 9.10.22).

Valencia-Barba, Y.E., Gómez-Soberón, J.M., Gómez-Soberón, M.C., 2023. Dynamic life cycle assessment of the recurring embodied emissions from interior walls: Cradle to grave assessment. J. Build. Eng. 65, 105794. https://doi.org/10.1016/J.JOBE.2022.105794

Wang, J., Song, C., Yuan, R., 2021. CO2 emissions from electricity generation in China during 1997–2040: The roles of energy transition and thermal power generation efficiency. Sci. Total Environ. 773, 145026. https://doi.org/10.1016/J.SCITOTENV.2021.145026

Wang, Yan, Pan, Z., Zhang, W., Borhani, T.N., Li, R., Zhang, Z., 2022. Life cycle assessment of combustion-based electricity generation technologies integrated with carbon capture and storage: A review. Environ. Res. 207, 112219. https://doi.org/10.1016/J.ENVRES.2021.112219

Wang, Yongzhen, Wang, J., He, W., 2022. Development of efficient, flexible and affordable heat pumps for supporting heat and power decarbonisation in the UK and beyond: Review and perspectives. Renew. Sustain. Energy Rev. 154, 111747. https://doi.org/10.1016/j.rser.2021.111747

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Wiik, M.K., Fufa, S.M., Kristjansdottir, T., Andresen, I., 2018. Lessons learnt from embodied GHG emission calculations in zero emission buildings (ZEBs) from the Norwegian ZEB research centre. Energy Build. 165, 25–34. https://doi.org/10.1016/J.ENBUILD.2018.01.025

Wood for Good, 2023. Wood for Good Lifecycle Database. BRE. URL https://woodforgood.com/lifecycle-database/ (accessed 3.15.23).

Wood for Good, 2017. Environmental Product Declaration: 1m3 of kiln dried planed or machined sawn timber used as structural timber. BRE. URL https://woodforgood.com/assets/Downloads/EPD/BREGENEPD000124.pdf (accessed 9.20.22).

World bank, 2018. Electric power transmission and distribution losses. IEA Stat. URL https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS (accessed 9.27.22).

WRAP, 2008. Net Waste Tool - Guide to Reference Data. WRAP's Built Environ. Program. URL https://wrap.org.uk/wraps-built-environment-programme (accessed 9.15.22).

Wu, W., Skye, H.M., Domanski, P.A., 2018. Selecting HVAC systems to achieve comfortable and cost-effective residential net-zero energy buildings. Appl. Energy 212, 577–591. https://doi.org/10.1016/J.APENERGY.2017.12.046

Zhang, T., Wang, M., Yang, H., 2018. A Review of the Energy Performance and Life-Cycle Assessment of Building-Integrated Photovoltaic (BIPV) Systems. Energies 2018, Vol. 11, Page 3157 11, 3157. https://doi.org/10.3390/EN11113157

Zhang, Z., Malik, M.Z., Khan, A., Ali, N., Malik, S., Bilal, M., 2022. Environmental impacts of hazardous waste, and management strategies to reconcile circular economy and eco-sustainability. Sci. Total Environ. 807, 150856. https://doi.org/10.1016/J.SCITOTENV.2021.150856

Zhao, G., Baker, J., 2022. Effects on environmental impacts of introducing electric vehicle batteries as storage - A case study of the United Kingdom. Energy Strateg. Rev. 40, 100819. https://doi.org/10.1016/J.ESR.2022.100819

Zhou, Z., Feng, L., Zhang, S., Wang, C., Chen, G., Du, T., Li, Y., Zuo, J., 2016. The operational performance of "net zero energy building": A study in China. Appl. Energy 177, 716–728. https://doi.org/10.1016/J.APENERGY.2016.05.093

Chapter VII

APPENDIX

V. APPENDIX

V.1 List of publications

Click on the icons below to go to the author's profiles.

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V.1.1 Research articles

[1]. Masoud Norouzi, Assed N. Haddad, Laureano Jiménez, Siamak Hoseinzadeh, Dieter Boer, "Carbon footprint of low-energy buildings in the United Kingdom: Effects of mitigating technological pathways and decarbonization strategies", *Science of The Total Environment*, April 2023, Volume 882. Area: Environmental Engineering (#7 of 173/Q1) / Environmental Science, pollution (#8 of 144/Q1). DOI: 10.1016/j.scitotenv.2023.163490. Impact Factor: 10.754. Status: Published.

[2]. Youssef Elomari, Masoud Norouzi, Marc Marín-Genescà, Alberto Fernández, Dieter Boer, "Integration of Solar Photovoltaic Systems into Power Networks: A Scientific Evolution Analysis", *Sustainability*, July 2022, Volume 9249. Area: Sustainability (Q1). DOI: 10.3390/su14159249. Impact Factor: 4.089. Status: Published.

[3]. Masoud Norouzi, Shane Colclough, Laureano Jiménez, Jordi Gavaldà, Dieter Boer, "Low-energy buildings in combination with grid decarbonization, life cycle assessment of passive house buildings in Northern Ireland", *Energy and Buildings*, February 2022, Volume 261. Area: Building and Construction (#9 of 211/Q1), Civil and Structural Engineering (#10 of 326/Q1). DOI: 10.1016/j.enbuild.2022.111936. Impact Factor: 7.201. Status: Published.

[4]. Mohamed Hany Abokersh, Masoud Norouzi, Dieter Boer, Luisa F. Cabeza, Gemma Casa, Cristina Prieto, Laureano Jiménez, Manel Vallès, "A Framework for Sustainable Evaluation of Thermal Energy Storage in Circular Economy", *Renewable Energy*, May 2021, Volume 175. Area: Renewable Energy, sustainability, and environment (#21 of 215/Q1). DOI: 10.1016/j.renene.2021.04.136. Impact Factor: 8.634. Status: Published.

[5]. Masoud Norouzi, Marta Chàfer, Luisa F. Cabeza, Laureano Jiménez, Dieter Boer, "Circular economy in the building and construction sector: A scientific evolution analysis", *Journal of Building Engineering*, May 2021, Volume 44. Area: Engineering, Architecture (#3 of 149/Q1) / Building and Construction (#32 of 211/Q1). DOI: 10.1016/j.jobe.2021.102704. Impact Factor: 7.144. Status: Published.

V.2 Scientific conferences participations

V.2.1 Oral communications

[1]. M Norouzi, JG Farías, AN Haddad, L Jiménez, D Boer, "A prospective life-cycle carbon assessment of low-energy buildings in the United Kingdom: effect of electricity decarbonisation", *3rd International Centre for Sustainable Development of Energy, Water and Environment Systems (3rd LA SDEWES conference)*, July 2022.

[2]. M Norouzi, S Colclough, L Jiménez, D Boer, "Comparative life cycle assessment of energy-efficient buildings in Ireland's rural area", *XII National and III International Engineering Thermodynamics Congress (CNIT 12)*, June 2022.

[3]. M Norouzi, D Boer, DA Vasco, "Environmental impact of the preliminary life cycle of a thermally refurbished home", *ACVCHILE22*, August 2022.

V.2.2 Poster presentations

[1]. M Norouzi, L Jiménez, D Boer, "A Whole Life Carbon (WLC) assessment of timber-frame buildings and strategies for decarbonization", *Project DecaTES*, March 2023.

[2]. M Norouzi, S Colclough, L Jiménez, D Boer, "Low-Energy Buildings in Combination with a Grid Decarbonization, Life Cycle Assessment of Passive House Buildings in Northern Ireland", *URV doctoral day*, May 2022.

[3]. M Norouzi, L Jiménez, D Boer, "Life Cycle Assessment of Passive House Buildings", *Internal workshop of RedTES*, November 2021.

[4]. M Norouzi, L Jiménez, D Boer, "LCA of a multi-scenario case study of a low energy buildings", *Internal workshop of RedTES*, October 2020.

[5]. M Norouzi, L Jiménez, D Boer, "Circular Economy in Building/Construction Industry: A Bibliometric Analysis", *National plan MATCE*, September 2019.

V.3 Master thesis co-supervision

Title: "The influence of windows in the design of a residential building: life cycle assessment and circular economy considerations", F Norouzi, Supervisors: D Boer, S Kariminia, M Norouzi, Master of Architecture Engineering – Energy, Azad University of NajafAbad (2019-2020).

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