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Life Cycle Assessment of a Three-Storey Terrace of Three Timber-Framed Residential Workplace Units

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Abstract: There is an urgent need to evaluate the environmental impacts of both traditional and more recent innovations in sustainable building materials. This study conducted a life cycle assessment (LCA) of a single three-storey (aboveground) terrace in Ireland composed of three timber-framed residential workplace units. The supply of raw materials, their transport to the manufacturing site, and the manufacturing processes for the materials used in the building account for 58% of the GWP during the production stage. The horizontal elements of the An Corrán building and roof account for the largest contribution (29.3%) to the GWP environmental impact. The LCA results show that the building's 469 m^2 gross internal floor area (GIFA) produced life cycle carbon emissions of 220 t CO_2e and has an embodied carbon value of 398 kg $CO_2e\ m^{-2}$ and 6.63 kg $CO_2e\ m^{-2}\ a^{-1}$ for the building's 60-year estimated cradle-to-grave life cycle. When compared to conventional (i.e., masonry) and timber-framed buildings in Europe, the An Corrán building shows that substantial GWP savings occurred during the Use Stage with a GWP footprint of 50.5 kg $CO_2e\ m^2$ compared to 375.65 and 386.6 kg $CO_2e\ m^2$ for previously reported masonry and timber-framed houses, respectively.

Keywords: construction; building; environment; GWP; sustainability

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1. Introduction

The 2022 United Nations Environment Programme (UNEP), working with the International Energy Agency (IEA) and the Global Alliance for Buildings and Construction (GABC), reported that building construction and operations were responsible for around 37% of global carbon dioxide (CO_2) emissions (i.e., 10 $GtCO_2$) [1]. They also stated that after the pandemic slowdown, the sector's operational emissions rebounded by 2% more than the previous peak in 2019, and while renewable energy growth in buildings remains modest, building sector energy intensity did not improve in 2021.

Increasing the use of sustainable materials such as wood in the construction sector is promoted by national and international organisations, e.g., the Council for Forest Research and Development (COFORD) in Ireland, the European Forest Institute (EFI), and the World Green Building Council (WGBC). Responding to the urgent actions needed to meet the targets of the Paris Agreement and subsequent developments in climate policy, organisations such as the COFORD [2], the WGBC [3], and the EFI [4] are actively engaging with construction industry stakeholders and coordinating multi-national projects involving the benchmarking of traditional building materials, e.g., concrete and steel, and recent innovations in sustainable building materials, e.g., engineered wood products such as cross-laminated timber (CLT) [5] or glue-laminated timber (GLT) [6]. The aim of these projects is to provide data to support policymakers and construction industry stakeholders in designing more sustainable solutions for future homes and businesses. In Ireland, national bodies such as the WGBC-affiliated Irish Green Building Council (IGBC) and the Wood Marketing Federation (WMF), through their "Woodspec" guides [7], also support research and innovation in the use of sustainable building materials to address the challenges of climate change over the coming decades.

Primarily due to an underdeveloped forestry sector in Ireland [8], and where some public and industry perceptions about the unsuitability of timber-based construction remain, the use of timber-framed structures and engineered wood products have not been major contributors to its residential or commercial property sectors [9,10]. Therefore, the role of wood construction within the development of the bioeconomy in Ireland is different from that in other European countries with considerably greater forest resources and longer histories of wood-based construction. Despite these challenges, there has been increasing interest and opportunities for further development of timber-based construction in Ireland. Timber-framed houses started to become more commonplace in the mid-1990s, with the building sector being a significant user of both construction timber and wood-based panels. The use of timber-framed housing methods in the Irish construction sector grew from a market share of 5% (of new house/apartment completions) in 1992 to approximately 25% of the market share in 2004 [11]. After the global financial crisis in the late 2000s, there was a significant decrease in economic activity which also severely impacted the Irish construction industry and the development of timber-framed housing in particular. According to current Sustainable Energy Authority of Ireland (SEAI) data relating to the Building Energy Rating (BER) certification programme, around 5% of the houses constructed in Ireland since 2011 used timber-framed construction methods [12].

In Ireland, the current national strategic policy on the bioeconomy acknowledges the risks posed globally and locally by climate change and the need to improve resource efficiency and transition to a low-carbon economy [13]. The Climate Action Plan also recognises the potential for economic development and the environmental and social benefits of an expanding national bioeconomy. In addition to the goals of becoming a global leader in the bioeconomy and developing a climate-resilient and environmentally sustainable economy by 2050, the national "Climate Action Plan 2019" considers mitigating the environmental impact of the Irish-built environment as an important objective [14]. The population of Ireland is expected to increase by around one million people to almost 5.7 million people by 2040, requiring at least an additional 0.5 million new homes [15]. The Irish government's "Housing for All—A new Housing Plan for Ireland" addresses the urgent need to provide new housing in Ireland. While targeting 25,000 new homes being built annually by 2023, the plan also aims to encourage innovative housing design and delivery [16]. In response to the climate emergency, the Royal Institute of the Architects of Ireland (RIAI) has also set out its specific "2030 Climate Challenge" targets for carbon emissions reductions in the construction sector [17].

Environmental product declarations (EPDs) are a standardised form of documenting and communicating the quantified environmental performance of a product [18], and within the construction sector, they can be used for comparing products to facilitate the selection of more sustainable building materials [19]. Over the last 10 years, there has been rapid global growth in the use of EPDs for the assessment and improvement of the environmental performance of construction materials [20]. All product EPDs are developed according to the ISO 14025 standard and are based on the frameworks and guidelines specified in the ISO 14040 [21] and 14044 [22] standards for the LCA methodology. More specifically, to improve the sustainability of practices, products, and materials used in the construction sector, EPDs should follow the ISO 21930 standard [19].

To date, there are relatively few published LCA studies of Irish residential buildings [23–26], and there is an urgent need to provide further LCA studies that construction industry stakeholders can reference and use as potential benchmarks for future building designs and construction projects.

The goals of this study are:

1. To provide an Irish-based case study of the environmental impacts of the 'An Corrán' building, located in the Ecovillage.

2. Evaluate the most significant building materials and life cycle stages contributing to the environmental impacts of the An Corrán building.
3. Compare the LCA results of this study to other relevant studies in the literature.

2. Materials and Methods

The Ecovillage at Cloughjordan in County Tipperary, Ireland, is the country's only ecovillage and has become one of Ireland's leading focal points for modelling sustainable development. The residents of the Ecovillage strive to both promote and demonstrate ways of achieving low-carbon living using the three pillars of ecological building standards, district heating, and its community farm food system [27]. Through ongoing projects, the Ecovillage community aim to transition to a lower-carbon future lifestyle and thereby contribute to national and international efforts to tackle climate change and offer an alternative model for housing and sustainable living [27]. The An Corrán building is a timber-framed terrace of three units combining ground-floor workplaces with residences above, with a total of 469 m^2 in gross internal floor area (GIFA), designed and constructed with sustainability as a central focus (Figure 1).

Figure 1. The An Corrán three-storey, terrace of three timber-framed residential workplace units, totalling 469 m^2 (GIFA), located in the Cloughjordan Ecovillage, Co. Tipperary, Ireland. (Source: Eoin Campbell, architect, Gaïa ecotecture).

2.1. Overview of the LCA Framework, ISO, and EN Standards

With building lifespans typically ranging from 50 to 100 years, the embodied carbon plus the operational carbon, together known as the whole life carbon [28] or total carbon footprint [29], and other environmental emissions associated with buildings occur over multiple life cycle stages [30]. Therefore, to mitigate the environmental impact of buildings, a detailed analysis of each life cycle stage is needed to better understand the potential impact of the building materials used and the energy consumed in the construction and use phases of their lifespan [31,32].

The ISO 14040 [21] and 14044 [22] standards for the life cycle assessment (LCA) methodology of environmental management define the four main phases of LCA studies (Figure 2), as follows:

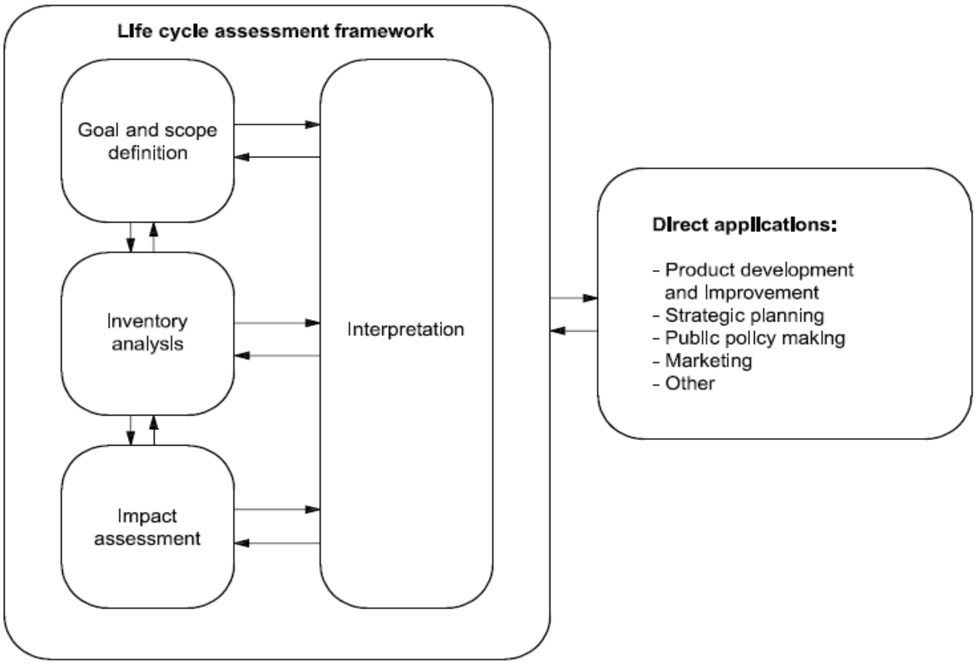

Figure 2. The four phases of a Life Cycle Assessment (LCA) study, as defined by the LCA standards (ISO 2006).

(1) Goal and scope, in which the objectives of the study are stated, the system boundary for the processes associated with a product's life cycle is defined, and a functional unit (e.g., 1 m^2 of ground floor area) for measuring the potential environmental impacts of the product is assigned.
(2) Life cycle inventory (LCI), which gathers the data on the relevant material and energy inputs, outputs, and flows within the system boundary over the product's life cycle.
(3) Life cycle impact assessment (LCIA), which uses the LCI to calculate and categorise the environmental impacts of the studied product, per the functional unit, based on the environmental sinks and sources of emissions to air, ground, and water, e.g., global warming potential (GWP), acidification, and eutrophication potentials, respectively.
(4) Interpretation, where the results of the LCA are evaluated within the context of the goals and scope of the study, opportunities for improving a product's environmental performance are identified, and conclusions and recommendations are presented.

The European EN15978 standard [32] for calculating the sustainability of a building's construction, divides the building's life cycle into 4 stages (i.e., Product, Construction, Use, and End-of-life), and 16 sub-stages to facilitate the assessment and attribution of the environmental impacts to the appropriate life cycle stage and sub-stage (Figure 3). It also helps to identify the most and least significant life cycle stages contributing to the overall environmental impacts [32].

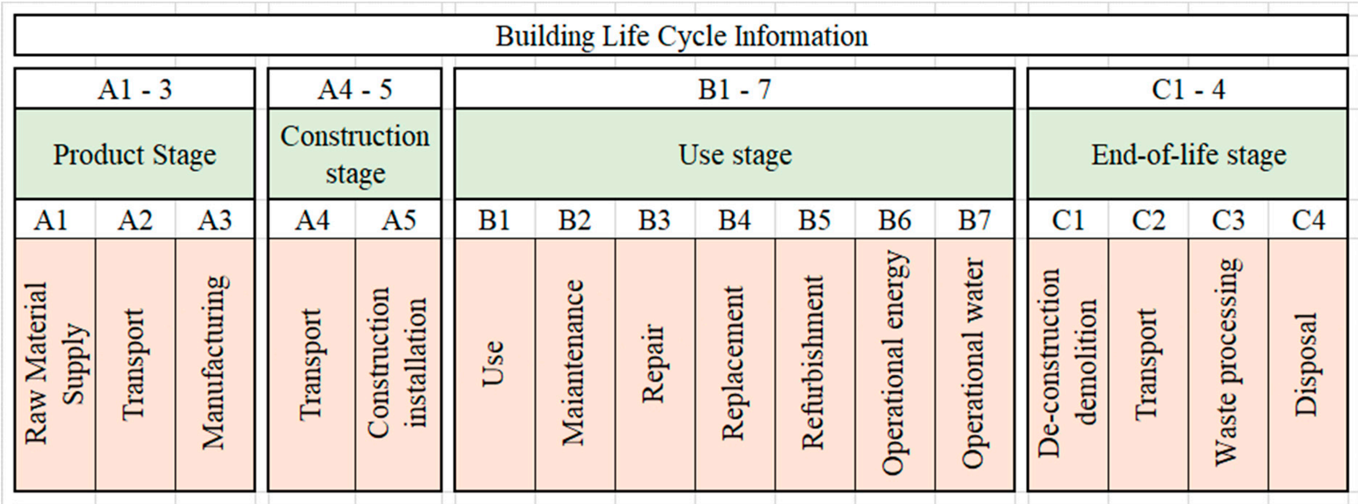

Figure 3. The 4 building life cycle stages and 16 sub-stages analysed in the case study, as designated by the European construction sustainability standard EN15978.

2.2. Overview of OCL Tools and Database

The EN15978-compliant One Click LCA (OCL) software tool [33], which is specifically designed for construction-related LCAs, was used to conduct this case study. Employing a comprehensive database of verified environmental product declarations (EPDs) for building materials, and other reference databases such as Ecoinvent (e.g., for transport-related products and processes), the OCL tool was used to develop and evaluate the LCI for the An Corrán building. There has been a 20-fold growth in the number of EPDs for construction-related products over the last 10 years [20], from approximately 500 to over 10,000. This development allows tools such as OCL access to verified LCA data for a wide range of construction materials.

The OCL tool allows for specific data entry in relation to the building area, materials used in the construction, construction site operations, annual energy and water consumption, and the life cycle calculation period. Using Bill of Quantities (BoQ) data specific to the An Corrán building, the inventory of materials used for the construction of the foundations, floor slabs, external and internal walls, ceilings, beams, and roof were compiled. Each material was uniquely identified to ensure correct allocation by building elements and to avoid duplication. The inventory of building materials and their associated quantities were then input into the OCL tool by matching them to identical products, or very similar products with EPDs in the OCL tool. The type of transport vehicle used in the A4 life cycle stage and the distance travelled for the heaviest materials, which were locally sourced within 80 km of the building site, e.g., the C25/30 ready-mix concrete, the concrete blocks for the sub-floor, the structural timber, and the windows and doors, were also specified and entered in the OCL tool. Due to the uncertainty of the manufacturing location of the other building materials supplied by Irish vendors, the OCL default was accepted for the type of transport vehicle and distances travelled to the building site.

Data specific to the An Corrán building's A5, B1, and B3 stages were not available for inclusion in the study. The data in the study for the B2 and B4–B5 stages were confined to the maintenance or replacement stages of materials such as the external windows, doors, vapour- and fire-resistant membranes, and wall insulation materials after 30 years. A service life of 60 years, which is commonly used as a study period of buildings [28], was used in this study. The B6 stage consumption of energy for heating and hot water, the B7 stage consumption of potable water, and the output of wastewater for treatment were measured for the first seven years of the An Corrán building's lifetime (i.e., from the end of its construction to the date of this study), and the mean annual value was multiplied by 60 to calculate the B6 and B7 stages for this study. Over those first seven years of the building's life cycle, it had eight occupants.

The OCL tool used the updated 2012 Centrum voor Milieukunde Leiden-Impact Assessment (CML-IA) method to apply the appropriate LCIA characterisation factors to simulate the environmental impacts of the An Corrán building over its full life cycle [34]. The database for the CML method, which was originally developed in 2001 by the University of Leiden, Netherlands, contains more than 1700 environmental flows and is required by the EN15978 standard [34].

2.3. Overview of the LCIA Impacts

The OCL software produced a comprehensive breakdown of the LCIA results for the case study building using the following six commonly reported environmental impacts:

Global Warming Potential (GWP) is usually measured in tonnes (t) or kilograms (kg) of CO_2 equivalent (CO_2e). The GWP metric is used to characterise the cumulative radiative force resulting from the pulse emission of a unit mass of a greenhouse gas (GHG), e.g., Gt CO_2 [35]. In this study, the GWP is estimated for both the embodied carbon of a building, which covers all GHG emissions during the A1–A4, B1–B5 and C1–C4 life cycle stages, and the GHG emissions associated with the lifetime consumption of operational energy and water, i.e., life cycle stages B6 and B7, respectively (Figure 4). When both the embodied and operational carbon are combined, it equates to the total carbon emissions associated with a building over its lifetime.

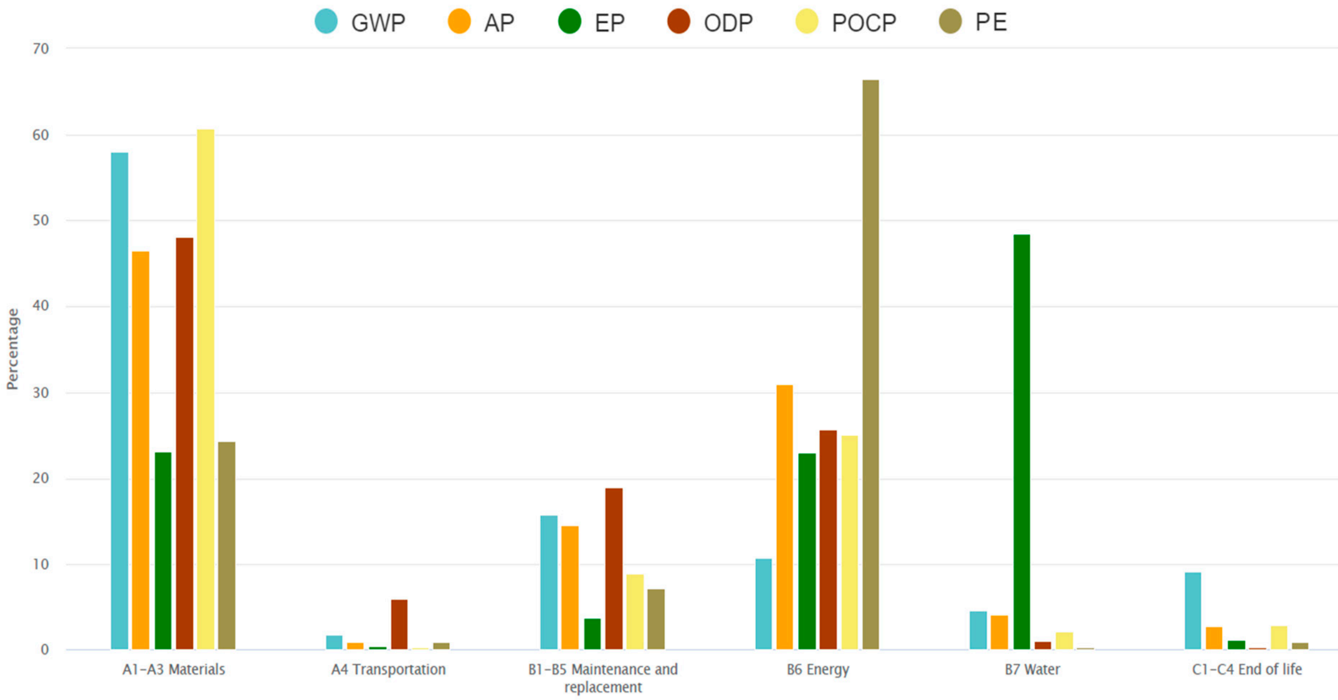

Figure 4. The LCIA results by percentage contribution of the life cycle stages to the environmental impacts of the An Corrán building. (GWP = Global Warming Potential, AP = Acidification Potential, EP = Eutrophication Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, PE = Total Primary Energy excl. raw materials).

Acidification Potential (AP) is measured in kg of sulphur dioxide equivalent (SO_2e). Emissions to the atmosphere of gases such as SO_2 and nitrogen oxides (NO_x) are causes of air pollution and acid deposition (also known as "acid rain"), which may occur local to or a considerable distance from the source of the emissions. These acidifying substances are associated with the burning of fossil fuels for energy and transport and the production of building materials such as concrete. The deposition of those substances on soil or water can alter their chemical composition and lead to ecological impacts (e.g., soil acidification) and structural damage to buildings (e.g., deterioration of reinforced concrete) [36,37].

Eutrophication Potential (EP) is used to measure the excessive release of nutrients, e.g., phosphorous or nitrogen, into the environment in kg of phosphate equivalent (PO_4e). Eutrophication of water bodies, potentially from raw material mining operations and production of building materials or uncontrolled runoff from construction sites, can drive excessive growth of phytoplankton and algae and increase water turbidity and oxygen deficiency. These environmental changes can cause undesirable alterations in the biological structure of water bodies [36,38].

Ozone Depletion Potential (ODP) measures, in kg of chlorofluorocarbon-11 equivalents (CFC11e), the damage to Earth's stratospheric ozone layer caused by CFC, hydrochlorofluorocarbon (HCHC), and halon gases. In the construction materials industry, these gases are used in the production of insulating foam-blowing agents and refrigerants. Ozone layer depletion leads to increased atmospheric penetration of carcinogenic ultraviolet (UVB) radiation, which can potentially cause damage to human, animal, and crop health [29].

Photochemical Ozone Creation Potential (POCP), also known as "Formation of ozone of lower atmosphere", is measured in kg of Ethene (C_2H_4) equivalent (Ethenee). Stratospheric ozone acts as a planetary shield against harmful UVB radiation, but ozone production via sunlight in the presence of common air pollutants such as nitrogen oxides (NOx) and volatile organic compounds (VOCs) in the lower atmosphere, causes air pollution known as "Summer smog". Common sources of NOx and VOC emissions are from the provision (e.g., diesel-powered wood harvesting and chipping machinery) and combustion processes of wood chips used for district heating and solvents used in paints and coatings, respectively. This pollution affects large cities (e.g., Los Angeles and Beijing), and is associated with crop damage and human respiratory illnesses such as asthma [29].

Total PE = Total Primary Energy (excluding raw materials) is the sum, measured in megajoules (MJ), of the use of non-renewable and renewable primary energy excluding non-renewable and renewable primary energy resources used as raw materials. Essentially, this equates to the total energy minus any embodied energy in the raw materials.

3. Results

3.1. Overview

The OCL tool groups some of the LCIA results by the life cycle stages (e.g., A1–A3, B1–B5) (Figure 4). These results show that apart from the 67% of the PE and 49% of the EP-related emissions produced by the operational energy (B6) and water usage (B7) stages of the An Corrán building's life cycle, the A1–A3 stages are responsible for the largest percentage of the other environmental impacts (i.e., GWP, AP, ODP, and POCP) (Figure 4). The supply of raw materials, their transport to the manufacturing site, and the manufacturing processes for the materials used in the building account for 58% of the GWP and 61% of the POCP-related emissions during the A1–A3 life cycle stages. The next most significant contributors to the environmental impacts are the energy supply (B6) and maintenance and material replacement phases (B1–B5) of the building's life cycle.

3.2. GWP

Further analysis of the GWP results shows that the materials used in the horizontal elements of the An Corrán building, e.g., floor slabs, ceilings, beams, and roof account for the largest contribution to the GWP environmental impact (i.e., 29.3%), equal to 64,458 kg CO_2e over the whole life cycle (Table 1). Those horizontal elements are responsible for almost twice the GWP of the next two building elements with the greatest GWP impact, i.e., the foundation/sub-surface structures and the triple-glazed windows and doors with 15.9 and 15.4%, respectively, of the whole life cycle GWP contribution.

When combined, the whole life cycle carbon (embodied + operational) of the An Corrán building's 60-year estimated service life is 220,249 kg CO_2e, or 470 kg CO_2e m^{-2}, and 7.83 kg CO_2e m^{-2} a^{-1}. The building's embodied carbon, i.e., the GWP of the total

GHG emissions minus the B6 and B7 stage GHG emissions, equals 186,450 kg CO_2e, or 398 kg CO_2e m^{-2}, and 6.63 kg CO_2e m^{-2} a^{-1} for the buildings 60-year life cycle. Due to the use of electricity from certified renewable sources (e.g., wind turbines), the water recycling measures implemented by the Ecovillage community, and the use of renewable wood chips for heating fuel, the provision of electricity and hot water, respectively, have the lowest contribution to the GWP impact category over the building's lifetime (Figure 5i).

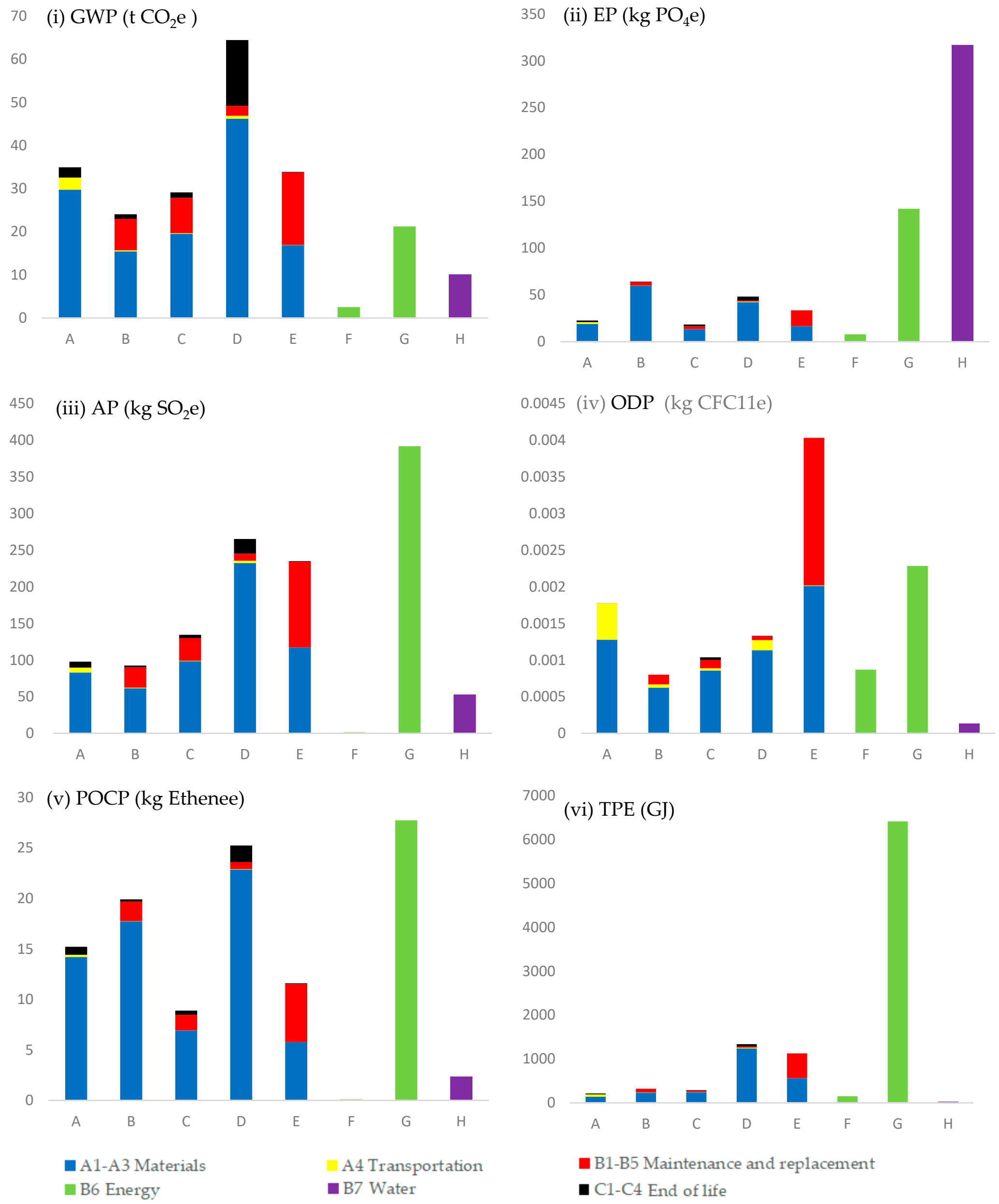

Figure 5. (**i–vi**): The contribution of the An Corrán building structures, energy, and water usage (A–H, see legend below), by life cycle stage, to the six environmental impacts that were assessed. Legend: GWP = Global Warming Potential, EP = Eutrophication Potential, AP = Acidification Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, PE = Total Primary Energy excl. raw materials, A = Foundation, sub-surface, basement, retaining walls; B = External walls and façade; C = Internal walls and non-bearing structures; D = Floor slabs, ceilings, roofing decks, beams, roof; E = Windows and doors; F = Electricity use; G = Fuels used in nearby or on-site heat suppliers; H = Total water consumption.

Table 1. The An Corrán building's GWP (kg CO_2e) environmental impact attributed to the main building material classes over each life cycle stage.

Building Material Class	Life Cycle Stages						Class Total	Class %
	A1-A3	**A4**	**B1-B5**	**B6**	**B7**	**C1-C4**		
Foundation, sub-surface, basement, retaining walls	29,733	2818	0	0	0	2383	34,933	15.9
External walls and facade	15,433	239	7319	0	0	1065	24,056	10.9
Internal walls and non-bearing structures	19,503	152	8199	0	0	1261	29,116	13.2
Floor slabs, ceilings, roofing decks, beams, roof	46,178	700	2325	0	0	15,254	64,458	29.3
Windows and doors	16,870	41	16,870	0	0	107	33,888	15.4
Electricity use	0	0	0	2467	0	0	2467	1.1
Fuels used in nearby or on-site heat suppliers	0	0	0	21,218	0	0	21,218	9.6
Total water consumption	0	0	0	0	10,114	0	10,114	4.6
Life cycle stage total kg CO_2e:	**127,718**	**3949**	**34,714**	**23,684**	**10,114**	**20,070**	**220,249**	**100**

When focusing solely on the Product Stage (A1–3) of the resources used in the building, the structural sawn timber, at 27,000 kg CO_2e or almost 21% of the total, is the single largest contributor to the GWP impact results (Table 2). That result is not surprising given the use of timber-frame construction methods and extensive use of sawn timber in the floors and roof. When combined, the first 10 listed items in Table 2 account for 73% of the total GWP impact from this stage of the building's life cycle. Various types of insulating materials and membranes, plasterboards, and wood-based products make up the other elements contributing to GWP.

Table 2. The building materials with the largest Product Stage (A1–A3) GWP (kg CO_2e, rounded) contribution and their respective percentage contribution. (NB: Only materials contributing > 1000 kg CO_2e, or >0.8%, are listed).

No.	Resource	A1–A3 (kg CO_2e)	A1–A3 (%)
1	Structural sawn timber, kiln dried, planed or machined	27,000	20.8
2	Ready-mix concrete, normal strength, generic	14,000	10.7
3	Triple glazing windows with wooden frame	12,000	9.1
4	Precast concrete blocks (CMU)	11,000	8.6
5	Plastic vapour control layer	8500	6.7
6	Triple glazed exterior wooden door & windows, aluminium elements	5200	4.1
7	Hot rolled structural steel	4500	3.5

Table 2. *Cont.*

No.	Resource	A1–A3 (kg CO_2e)	A1–A3 (%)
8	Calcium sulphate screed	4400	3.5
9	Gypsum plaster board, regular, generic	3700	2.9
10	EPS insulation	3400	2.7
11	Mortar with hemp fibre	2400	1.9
12	Gypsum plasterboard	2300	1.8
13	Hemp fibre insulation	2200	1.7
14	Polypropylene vapour membrane	1700	1.4
15	Dry mortar, adhesive for facades and tiles	1600	1.2
16	Radon and moisture membrane for site construction, PP	1500	1.2
17	OSB panels	1500	1.2
18	Reinforcement steel mesh (rebar)	1400	1.1
19	Gypsum plasterboard, with cellulose fiber	1400	1.1
20	Gypsum plaster board, moisture and fire-resistant	1300	1.0
21	Oriented strand board (OSB), generic	1300	1.0
22	Glue laminated timber (Glulam) beams	1200	1.0
23	Thin-coat renders based on organic binders, acrylic based	1200	0.9
24	Gypsum plasterboard	1200	0.9
25	Structural hollow steel sections (HSS), cold rolled, generic	1000	0.8

3.3. Comparison of the An Corrán Building GWP to Previously Reported Structures

As a timber-framed three-storey terrace of three units, the design and building regulations for the structural, fire safety, and acoustic isolation elements required in the An Corrán building are more demanding and complex than required for a detached house of two storeys. While buildings are generally not directly comparable due to their different design, size, and building materials used, it can be useful to compare them on a GIFA basis across their life cycle stages, to identify which stages are most impactful to the environment. The GWP of the An Corrán building across all construction and operational stages was assessed relative to several previously reported comparative conventional (i.e., masonry) and timber-framed buildings in Europe (Table 3). As shown, the most substantial GWP saving occurred during the Use Stage and specifically during B6 (Operational Energy), with the An Corrán build equating to a GWP footprint of 50.5 kg CO_2e m^2 compared to 375.65 and 386.6 kg CO_2e m^2 for previously reported masonry and timber-framed houses, respectively, despite the An Corrán building having a larger surface area. Similarly, the An Corrán building represents a GWP saving during the A1–3 Production Stage (272.3 kg CO_2e m^2) relative to conventional masonry builds (304 kg CO_2e m^2). However, when assessing the GWP across Use Stages B1–5, the An Corrán build represented higher $CO_2{}^e$ emissions (74 kg) relative to other Irish builds.

Table 3. Global warming potential (GWP) and embodied carbon (EC) comparison for European residential buildings.

Study #	Study Buildings	Location	GIFA (m^2)	Service Life (yr)	GWP (kg CO2e m^{-2}) by Life Cycle Stage								EC		Total EC + OC
					A1-3	A4	A-5	B1-5	B6	B7	C1-4	Lifetime (kg CO_2e)	Area (kg CO_2e m^{-2})	Annual (kg CO_2e m^{-2} a^{-1})	
1	Terrace of three × 3-storey residential workplace units (This study)	Ireland	469.0	60	272.3	8.4		74.0	50.5	21.6	42.8	186,450	398	6.63	220,249
2	(a) Masonry build 2.5-storey house	Ireland	200.5	60	304	4.3	39.2	18.4	376.5	11.9	26.9	78,756	393	6.55	156,631
	(b) Timber framed 2.5-storey house	Ireland	215.5	60	179.9	1.7	37.7	13.2	386.6	11.1	23.8	55,233	256	4.27	140,937
3	(a) Detached 2-storey house (2011 regs.)	Ireland	229.0	60									2040	8.91	122,423
	(b) Detached 2-storey house (nZEB regs.)	Ireland	229.0	60									1816	7.93	108,958
4	(a) Semi-detached 2-storey house (2011 regs.)	Ireland	117.0	60									1236	10.56	74,131
	(b) Semi-detached 2-storey house (nZEB regs.)	Ireland	117.0	60									1030	8.80	61,776
5	Semi-detached 2-storey house (Case 1)	Ireland	106.0	60	368				164,031			39,004	368	6.13	203,035
6	Medium rise (7-storey) residential building (Option 1)	Ireland	10,270.0	50	166				446.5			1,704,820	166	3.32	4,585,555
7	Residential 2-storey villa	Sweden	180.4	100	169.8	2.7	22.8	211.7	116.8	33.4	9.4	74,969	416	4.17	102,009
8	Small, medium and large scale residential (up to 4 or more storeys)	UK	469.0 *	60								221,743 ***	473 ****	7.88 **	221743 &

Study # and related citation in parentheses: 1. This study; 2. [25]; 3 and 4. [39]; 5. [23] 6. [24]; 7. [31]; 8. [28]. GIFA = Gross internal floor area. The floor area in study 7 includes a 30 m^2 garage area; for all the other studies, the GIFA is assumed to equal the heated floor area. GWP by life cycle stages and for the EC Lifetime, Area, and Annual values shown as given where data were provided by each study and used to calculate the 'Total EC + OC' values. Otherwise, other specific data relating to the EC and OC GWP, where provided in the study, were used to calculate the 'Total EC + OC' values. * Assumed GIFA value of 469 m^2 based on study 1, for calculation and comparison of GWP values for studies 1 and 8. ** Derived from the mean value of the annual GWP of studies 1, 2b, 3b, 4b, 5, and 7, and used for calculation of annual and area-based kg CO_2e for study 8. *** Derived from the LETI 60-year reference study period, the assumed GIFA of 469 m^2, and the derived mean annual GWP of 7.88 kg CO_2e m^{-2} a^{-1}. **** Derived from the lifetime GWP and assumed GIFA for study 8, to allow comparison with the LETI lifetime carbon target of 300 kg CO_2e m^{-2} for the year 2030. & Total EC + OC value derived from Annual EC × GIFA × Service life.

3.4. EP, AP and ODP

Wastewater sanitation associated with household water consumption and the fuels used for district heating are the main contributors to the EP impact, i.e., 317 and 142 kg PO_4e, respectively (Figure 5ii), with electricity usage (8 kg PO_4e) and the internal walls and non-bearing structures (19 kg PO_4e) having the least EP impact. The combustion of wood chips used as fuel for the Ecovillage district heating system is the leading contributor to the AP impact, i.e., 392 kg SO_2e (Figure 5iii), while electricity for utilities and water consumption has the lowest AP impact, i.e., 2 and 53 kg SO_2e, respectively. The combined Product (A1–A3) and Maintenance and Replacement (B1–B5) Stages of the triple-glazed windows and doors, along with the combustion of the heating fuels, are responsible for the majority of the ODP impact-related emissions, i.e., 0.0040 and 0.0023 kg CFC11e, respectively (Figure 5iv), with water consumption having the lowest ODP impact, i.e., 0.0001 kg CFC11e.

3.5. POCP and PE

The NOx and VOCs released during the combustion of the heating fuels (G) are also the main sources of the POCP impact emissions, i.e., 28 kg Ethenee, while the Product (A1–A3), and Maintenance and Replacement (B1–B5) Stages of the materials used in the floor slabs, ceilings, beams, and roof (D) account for the next largest contribution of 24 kg Ethenee (Figure 5v). The lifetime use of electricity from renewable sources (F) and total water consumption (G) are the lowest contributors to the POCP impact, with 0.11 and 2.4 kg Ethenee, respectively. Finally, the total primary energy (PE) results are dominated by the fuels used for the district heating system (G), which accounts for 6.4M MJ, or 65% of the total 9.9M MJ of PE used, with the horizontal structural elements of the building (D) being the next most significant contributor (i.e., 14%) to the whole life cycle PE results (Figure 5vi).

4. Discussion

Providing government policymakers and construction industry stakeholders with LCA-based building analysis data and benchmarks can play a key role in supporting the transition to the decarbonisation of the building sector and the growth of a vibrant low-carbon bioeconomy [14,40]. This LCA-based study was conducted to provide those stakeholders with further data by which they can assess the environmental impact of timber-framed building materials and methods. Previous Irish studies have dealt with residential two- and three-storey detached and semi-detached houses built using masonry and timber-framed construction methods, and compared the 2011 Irish building regulations with the "nearly-zero energy buildings" (nZEB) regulations, which were proposed for implementation in 2016.

The An Corrán building was built with a focus on incorporating sustainable building materials (e.g., timber frame and CLT), as substitutes for more traditional and energy-intensive materials (e.g., concrete and steel), and provides a useful benchmark for construction sector stakeholders. The An Corrán building is a bespoke design comprising three residential workplace units, each of approximately 160 m^2 in gross internal floor area (GIFA), compared to the 110 m^2 national average for a three-bedroom semi-detached residence-only building in Ireland [41]. The benchmarks published by the built environment stakeholders of the London Energy Transformation Initiative (LETI) provide embodied carbon GWP values for 'business as usual' along with 2020 and 2030 targets, on their path to net zero carbon buildings in the UK by 2050 [42]. The LETI targets for residential buildings are for a reduction in the current 'business as usual' embodied carbon of 800 kg CO_2e m^{-2} towards the 2020 target of 500 kg CO2e m^{-2}, and the 2030 target of 300 kg CO_2e m^{-2}, with estimates of between 64% and 80% of those GWP amounts attributable to the A1–A3 stages for small- and medium- to large-scale residential buildings, respectively. The 128 t CO_2e of GWP for the An Corrán building's A1–A3 stages accounted for 68% of the 186 t CO_2e embodied carbon emissions.

The An Corrán building's 398 kg CO_2e m^{-2} of embodied carbon is 64% of the RIAI 2030 target for domestic buildings of <625 kg CO_2e m^{-2} and is even less than their A1–A5 stages target of <400 kg CO_2e m^{-2}. The studied building is also less than half the LETI 'business as usual' embodied carbon GWP value and is mid-way between their 2020 and 2030 GWP targets. The much lower emissions associated with the transportation of materials to the building site (A4) and the end-of-life (C1–C4) processes reflect the use of locally sourced building materials, the Ecovillage's use of solar energy and district heating, and the recyclability of the materials chosen for the building's construction, respectively. As shown in other studies of multi-storey buildings using timber-framed construction in countries with burgeoning bioeconomies, e.g., Lithuania [43], the results of this study show that the An Corrán building represents a viable alternative to conventional construction in Ireland to achieve key international sustainability targets.

Due to inconsistent adherence to system boundaries and significant variability in the provision of data used to calculate GWPs across all life cycle stages, making comparisons across LCA studies of complex building structures is challenging [44]. Therefore, it is necessary to make comparisons as best as the available data will allow. In comparison with six other European-based studies and one set of UK targets of embodied carbon in residential buildings, providing ten datasets in total, this study had lower area-weighted EC GWP values (kg CO_2e m^{-2}) than five of the datasets considered (Table 3). Datasets 2a, 2b, and 7 provided life cycle stage data for all the stages in the EN15978 standard. Though dataset 2a provided data for stage A5, it had very similar area and annual EC GWP values, higher GWP for stages A1-A3, and a much larger B6 value, but lower GWP for stages A4, B1-B5, B7, and C1-4. The datasets for 2b and 7 had lower values for A1-A3 and A4 and much higher and lower B6 GWP values than this study, respectively. When comparing EC GWP per year of service life (kg CO_2e a^{-1}), this study also ranked lower than five others, with the exception of studies 5 and 7 (Table 3). As such, the An Corrán building compares well to other residential building types in terms of environmental impact while providing an integrated residential and workplace building.

5. Conclusions

This LCA provides a case study based on the construction of a bespoke building, designed to act as both a residence and a workplace, with sustainability in construction materials and methods as a key focus. It contributes to the building LCA literature by presenting analysis and results for the building over its lifetime, broken down by most of its life cycle stages, and across several environmental impact categories.

The results demonstrate that buildings such as An Corrán have a lower environmental impact compared to other types of residential buildings. Although not addressed here, as a combined residential and workplace building, An Corrán may also contribute to the reduction in GHG emissions associated with work-related commuting. This warrants further investigation.

There is a need for transparent and consistent methods to enable fuller and more precise comparisons between studies. The lack of location-specific EPDs for all materials, e.g., wood or masonry products used in Irish building construction and operation, limits the ability to analyse the life cycle differences of buildings due to regional differences in materials manufacture and procurement. At the national level, there is a need for support and incentives to building materials suppliers to publish and maintain digital EPDs for their products, updatable by batch for specific building projects. Furthermore, it is recommended that construction sector stakeholders drive the implementation of comprehensive recording of life cycle data for buildings to enable greater consistency and comparability in associated LCA studies.

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References

1. United Nations Environment Programme. *2022 Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector*; UNEP: Nairobi, Kenya, 2022; p. 101.
2. Council for Forest Research and Development COFORD-About Us. Available online: http://www.coford.ie/ (accessed on 25 April 2022).
3. World Green Building Council. *Bringing Embodied Carbon Upfront: Coordinated Action for the Building and Construction Sector to Tackle Embodied Carbon*; World Green Building Council: London, UK, 2019.
4. European Forest Institute (EFI) BenchValue–Benchmarking Wood Material Value Chains against Non-Renewable Value Chains by Using and Expanding Assessment Tool "ToSIA". Available online: https://efi.int/projects/benchvalue-benchmarking-wood-material-value-chains-against-non-renewable-value-chains (accessed on 2 November 2022).
5. Harte, A.M.; McPolin, D.; Sikora, K.; O'Neill, C.; O'Ceallaigh, C. Irish Timber–Characterisation, Potential and Innovation. In Proceedings of the Civil Engineering Research in Ireland Conference (CERAI), QUB, Belfast, UK, 28–29 August 2014.
6. Linkevičius, E.; Žemaitis, P.; Aleinikovas, M. Sustainability Impacts of Wood- and Concrete-Based Frame Buildings. *Sustainability* **2023**, *15*, 1560. [CrossRef]
7. COFORD. *The Wood Marketing Federation (WMF) Woodspec—A Guide to Designing, Detailing and Specifying Timber in Ireland*; National Council for Forest Research and Development (COFORD): Wexford, Ireland, 2014.
8. Department of Agriculture Food and the Marine Forests, Products and People. *Ireland's Forest Policy-A Renewed Vision*; Government of Ireland: Wexford, Ireland, 2014.
9. Department of the Environment, Heritage and Local Government. *Irish Timber Frame Housing Consortium Advantages and Disadvantages of Timber Frame Construction, Appendix 1*; Department of the Environment, Heritage and Local Government, Ireland: Dublin, Ireland, 2003.
10. Sikkema, R.; Styles, D.; Jonsson, R.; Tobin, B.; Byrne, K.A. A Market Inventory of Construction Wood for Residential Building in Europe–in the Light of the Green Deal and New Circular Economy Ambitions. *Sustain. Cities Soc.* **2023**, *90*, 104370. [CrossRef]
11. Wilson, P. *Survey of Irish Timber Frame Manufacturers*; Wood Marketing Federation: Wicklow, Ireland, 2004.
12. Sustainable Energy Authority of Ireland Building Energy Rating Certificate (BER). Available online: https://www.seai.ie/home-energy/building-energy-rating-ber/ (accessed on 25 April 2022).
13. Government of Ireland. *Department of the Taoiseach National Policy Statement on the Bioeconomy*; Government of Ireland: Dublin, Ireland, 2018.
14. Department of Communications. *Climate Action and Environment Climate Action Plan 2019 to Tackle Climate Breakdown*; Department of Communications: Dublin, Ireland , 2019.
15. Department of Housing, Planning and Local Government. *National Planning Framework, Department of Housing, Planning and Local Government Project Ireland 2040*; Department of Housing, Planning and Local Government: Dublin, Ireland, 2018.
16. Department of Housing, Local Government and Heritage Housing for All. *A New Housing Plan for Ireland*; Department of Housing, Local Government and Heritage Housing for All: Dublin, Ireland, 2021.
17. RIAI. *Royal Institute of the Architects of Ireland RIAI 2030 Climate Challenge*; RIAI: Dublin, Ireland, 2021.
18. *SO 21930:2017*; Sustainability in Buildings and Civil Engineering Works–Core Rules for Environmental Product Declarations of Construction Products and Services. ISO (International Organization for Standardization): Geneva, Switzerland, 2017.
19. *ISO 14025:2006*; Environmental Labels and Declarations-Type III Environmental Declarations-Principles and Procedures. ISO (International Organization for Standardization): Geneva, Switzerland, 2006.
20. Anderson, J. Constructionlca's 2021 Guide to EPD-Infogram. Available online: https://infogram.com/constructionlcas-2021-guide-to-epd-1h1749vwlxy7l6z (accessed on 15 March 2021).
21. *ISO 14040:2006*; Environmental Management-Life Cycle Assessment-Principles and Framework. ISO (International Organization for Standardization): Geneva, Switzerland, 2006.
22. *ISO 14044:2006*; Environmental Management-Life Cycle Assessment-Requirements and Guidelines. ISO (International Organization for Standardization): Geneva, Switzerland, 2006.
23. Goggins, J.; Moran, P.; Armstrong, A.; Hajdukiewicz, M. Lifecycle Environmental and Economic Performance of Nearly Zero Energy Buildings (NZEB) in Ireland. *Energy Build* **2016**, *116*, 622–637. [CrossRef]

24. Nolan, T.; Doyle-Kent, M. An Investigation into the Role of the Building Structure on Energy Use & CO2 Emissions over the Life Cycle of a Medium-Rise Residential Building. *IFAC-PapersOnLine* **2018**, *51*, 60–65. [CrossRef]
25. Walsh, J.; McAulliffe, B. *Study of the Embodied Carbon in Traditional Masonry Construction vs Timber Frame Construction in Housing*; Jeremy Walsh Project Management: Tralee, Ireland, 2020; p. 38.
26. Moran, P.; O'Connell, J.; Goggins, J. Sustainable Energy Efficiency Retrofits as Residenial Buildings Move towards Nearly Zero Energy Building (NZEB) Standards. *Energy Build* **2020**, *211*, 109816. [CrossRef]
27. Robbins, D.; Torney, D.; Brereton, P. *Ireland and the Climate Crisis*; Routledge: London, UK, 2020.
28. LETI. *London Energy Transformation Initiative Embodied Carbon Primer-Supplementary Guidance to the Climate Emergency Design Guide*; LETI: London, UK, 2020.
29. Anderson, J.; Thornback, J. *A Guide to Understanding the Embodied Impacts of Construction Products*; Construction Products Association: London, UK, 2012.
30. Omrany, H.; Soebarto, V.; Sharifi, E.; Soltani, A. Application of Life Cycle Energy Assessment in Residential Buildings: A Critical Review of Recent Trends. *Sustainability* **2020**, *12*, 351. [CrossRef]
31. Petrovic, B.; Myhren, J.A.; Zhang, X.; Wallhagen, M.; Eriksson, O. Life Cycle Assessment of a Wooden Single-Family House in Sweden. *Appl. Energy* **2019**, *251*, 113253. [CrossRef]
32. *EN 15978:2011*; Sustainability of Construction Works-Assessment of Environmental Performance of Buildings-Calculation Method. European Standard: Brussels, Belgium, 2011.
33. Bionova Ltd. About One Click LCA: Making Carbon Assessment & LCA Easy and Affordable. Available online: https://www.oneclicklca.com/about-one-click-lca/ (accessed on 25 April 2022).
34. VROM. *Life Cycle Assessment-An Operational Guide to the ISO Standards*; Ministry of Housing, Spatial Planning and the Environment (VROM) and Centre of Environmental Science-Leiden University (CML): Leiden, The Netherlands, 2001.
35. Levasseur, A.; Lesage, P.; Margni, M.; Deschênes, L.; Samson, R. Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments. *Environ. Sci. Technol.* **2010**, *44*, 3169–3174. [CrossRef] [PubMed]
36. Kim, T.H.; Chae, C.U. Environmental Impact Analysis of Acidification and Eutrophication Due to Emissions from the Production of Concrete. *Sustainability* **2016**, *8*, 578. [CrossRef]
37. European Environment Agency. *Europe's Environment—The Dobris Assessment-State of the Environment-31. Acidification*; European Environment Agency: Copenhagen, Denmark, 2020.
38. European Environment Agency. *Europe's Environment—The Dobris Assessment-State of the Environment-33. The Management of Freshwater*; European Environment Agency: Copenhagen, Denmark, 2020.
39. Irish TABULA National Advisory Group. *Energy Action Ireland Limited Building Typology Brochure Ireland-A Detailed Study on the Energy Performance of Typical Irish Dwellings*; Episcope: Dublin, Ireland, 2014.
40. Irish Green Building Council. *The IGBC's Submission on the National Energy and Climate Plan 2021–2030*; Irish Green Building Council: London, UK, 2019.
41. Walsh, M. *Cost Study of 3 Bedroomed Semi Detached House*; Irish Home Builders Association: Dublin, Ireland, 2012.
42. LETI. *London Energy Transformation Initiative LETI Climate Emergency Design Guide-How New Buildings Can Meet UK Climate Change Targets*; LETI: London, UK, 2020.
43. Žemaitis, P.; Linkevičius, E.; Aleinikovas, M.; Tuomasjukka, D. Sustainability Impact Assessment of Glue Laminated Timber and Concrete-Based Building Materials Production Chains—A Lithuanian Case Study. *J. Clean. Prod.* **2021**, *321*, 129005. [CrossRef]
44. Anand, C.K.; Amor, B. Recent Developments, Future Challenges and New Research Directions in LCA of Buildings: A Critical Review. *Renew. Sustain. Energy Rev.* **2017**, *67*, 408–416. [CrossRef]