Energy & Buildings 241 (2021) 110962

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Embodied emissions of buildings - A forgotten factor in green building certificates

Ali Amiri [a,*], Nargessadat Emami [b], Juudit Ottelin [a], Jaana Sorvari [c], Björn Marteinsson [b], Jukka Heinonen [b], Seppo Junnila [a]

[a] Department of Built Environment/School of Engineering, Aalto University, Espoo 00076, Finland
[b] School of Engineering and Natural Sciences/Faculty of Civil and Environmental Engineering, University of Iceland, Reykjavik 101, Iceland
[c] Finnish Environment Institute, Latokartanonkaari 11, Helsinki 00790, Finland

ARTICLE INFO

Article history:
Received 16 October 2020
Revised 3 March 2021
Accepted 23 March 2021
Available online 30 March 2021

Keywords:
LEED, Leadership in energy and environmental design
LCA, Life cycle assessment

ABSTRACT

The construction and use of buildings consume a significant proportion of global energy and natural resources. Leadership in Energy and Environmental Design (LEED) is arguably the most international green building certification system and attempts to take actions to limit energy use of buildings and construct them sustainably. While there has been a wide range of research mainly focused on energy use and emission production during the operation phase of LEED-certified buildings, research on embodied emissions is rare. The aim of this study is to evaluate the efficiency of LEED regarding initial (pre-use) embodied emissions using life cycle assessment (LCA). The study comprised several steps using a designed model. In the first step, three optional building material scenarios were defined (optimized concrete, hybrid concrete-wood, and wooden buildings) in addition to the base case concrete building located in Iceland. Second, an LCA was conducted for each scenario. Finally, the number of LEED points and the level of LEED certification was assessed for all studied scenarios. In addition, a comparison regarding embodied emissions consideration between LEED and Building Research Establishment Environmental Assessment Method (BREEAM) as mostly used green certificate was conducted in the discussion section. The LCA showed the lowest environmental impact for the wooden building followed by the hybrid concrete-wood building. In the LEED framework, wooden and hybrid scenarios obtained 14 and 8 points that were related to material selection. Among these points, only 3 (out of a total of 110 available points) were directly accredited to embodied emissions. The study recommends that the green building certificates increase the weight of sustainable construction materials since the significance of embodied emissions is substantially growing along with the current carbon neutrality goals. As most of the materials for building construction are imported into Iceland, this study is useful for locations similar to Iceland, while overall it is beneficial for the whole world regarding climate change mitigation.

1. Introduction

1.1. Background

Buildings are one of the main consumers of energy and materials [1–3]. To reduce the environmental and resource footprints of buildings, various approaches have been developed. These include thermal insulation [4,5], material choices [6,7], passive thermal storage and alternative envelope designs [8–11], local sourcing [12], and energy efficient designs [13,14]. Since the 1990s, lessons learned from such efforts have informed building codes, standards, rating systems, and green building certifications [15].

The British Building Research Establishment Environmental Assessment Method (BREEAM), created in 1990, is considered as the first one of such certification systems and mostly adopted. While the American Leadership in the Energy and Environmental Design (LEED) system created by the US Green Building Council (USGBC), was launched in 1998. Other certification systems include the Green Standard for Energy and Environmental Design (G-SEED, Korea), the Green Star (Australia) and Comprehensive Assessment System for Built Environment Efficiency (CASBEE, Japan).

LEED is one of the most internationally implemented green building certifications [16–19], aimed at reducing the energy and

* Corresponding author.
E-mail address: ali.amiri@aalto.fi (A. Amiri).

https://doi.org/10.1016/j.enbuild.2021.110962
0378-7788/

material needs of buildings. As a points-based green certification, LEED assigns 110 points in total and includes different levels: certified (40–49 points), silver (50–59 points), gold (60–79 points), and platinum (80 + points). Compared to conventional buildings, LEED-certified buildings have sale price, rental, and occupancy premiums that motivate investors to consider applying this certification to their construction project [20]. In addition, the operation costs are lower due to energy savings (such as electricity) in addition to lower maintenance costs as a result of functional testing of all energy systems before occupation [21]. There is a continuously increasing demand for the application of LEED to buildings all over the world [22].

From the very beginning of the LEED system, a common assumption was that it would reduce energy consumption of buildings and limit GHG emissions [23–25]. To confirm this assumption, the USGBC commissioned the New Buildings Institute (NBI) in 2006 to study the energy use of LEED-certified buildings. The results indicated that they consume an average of 25% to 30% less energy compared to conventional, i.e., non-certified, buildings [26,27]. Newsham et al. [27] re-analyzed the energy-consumption data for LEED-certified buildings supplied by NBI and found out that they used 18%–39% less energy per floor area compared to conventional buildings. While the results of Chen et al. [28] who studied three LEED-certified office buildings in China, indicated a 2% to 5% reduction in energy use.

To study the allocation of energy-related points in LEED certification in more detail, Scofield [26] divided the energy use of buildings in two categories: source energy (initial fuel used to produce either electricity or transportation fuel including any losses) and site energy (electricity or fuel consumed within a property). He arrived at different results to Newsham et al. [27], reporting no difference between LEED-certified and conventional buildings in terms of source energy use. Scofield [29] further examined data concerning buildings in New York City in 2011, which covered 953 office buildings of which 21 were LEED-certified. Regarding energy use and GHG emissions, LEED-certified buildings exhibited no difference compared to other buildings of the same type, time frame, and geographical and climate regions.

Most studies related to LEED have focused on energy use and emissions produced during the operation phase, which implies that LEED is an operation phase focused green certification. Previous studies have mainly used the most popular version of LEED v3 (2009), even though there are three other versions. Recently (from 2015 onwards), new studies using life cycle assessment (LCA) have been carried out to evaluate environmental impacts. Even these studies have mainly focused on emissions generated during the operation phase, while initial (pre-use) embodied emissions have seldom been the focus.

For example, Suh et al. [30] compared the reduction of adverse environmental effects of a building using LEED as green certification with other certification systems. The study covered all life cycle stages (pre-use, use, and end of life (EoL)), and applied LCA as a sustainability assessment tool. Material, services, energy, and water were considered as inputs, and waste, greenhouse gas emissions, and toxic pollutant emissions were considered as outputs. Hu et al. [31] conducted an LCA and life cycle energy assessment (LCEA) study on a school for different phases, and compared the reliability of LEED and three other green building certifications pertaining to energy use. Lessard et al. [32] evaluated both material and resources (MR) and the energy and atmosphere (EA) categories of LEED to determine how the allocated points affect the energy efficiency of a specific certified building. The study was based on six case scenarios with different levels of allocated points, which were then compared with the base case building.

Focusing on emissions generated during the operation phase and paying less attention to initial embodied emissions [33] result in several issues regarding the plans for climate change mitigation. Uncertainty about future sources of energy is one issue that affects the ratio of initial embodied emissions (pre-use phase) to operational emissions. Because methods to produce energy are continuously changing, the benefits of low-energy buildings with less operational emissions might become inflated over time [34]. According to the European Commission [35], energy produced by renewable sources in the EU increased from 8.5% to 17.5% between 2004 and 2017 and is expected to reach 20% by the end of 2020 and 32% by 2030. Another issue is that initial embodied emissions are expelled within a very short period compared to operational emissions and are evaluated by current energy production technology. Therefore, increasing initial embodied emissions would render the short-term CO_2 reduction targets of the Intergovernmental Panel on Climate Change unachievable [36–39].

1.2. Aim of the study

Given the range of environmental impacts caused by buildings and the urgent need to develop sustainable solutions to mitigate the current global climate crisis, one suggestion is to modify LEED to work towards initial embodied emissions targets in addition to energy reductions. Therefore, the aim of this study is to evaluate how effectively LEED can accommodate the urgent need for embodied emission reductions in a sustainable real estate. More specifically, we estimate how accurately the LEED points support the selection of building materials with low embodied emissions. We used LCA for the evaluation of embodied emissions and different low emission scenarios. A model was prepared that included the selection of building materials with their environmental impacts assessed by LCA, then its effect was evaluated by LEED points. Finally, the model was applied to a university building located in Iceland.

This study includes an evaluation of the environmental sustainability of building materials for housing construction in Iceland based on both LCA results and attainable number of points in the LEED system. The case environment was selected purposefully to ensure that all major building materials had to be imported to avoid a local bias in the results, whereas the operation phase was from renewable sources. However, it is worth mentioning that typically there is predefined preference of selection of building materials in different locations of the world; hence, it is recommended to use local materials. The situation is different in the case of countries that do not have adequate material resources (or have limited selection and materials) and are forced to import. Therefore, the results are valuable for other locations with the same situation as Iceland while they are beneficial globally. We will show how different decisions at the design stage affect the LEED rating, discuss the adaptability of LEED in locations where the operation phase has low importance, and demonstrate that emission loads are largely generated during the pre-use phase. Finally, we also present a general comparison of LEED with BREEAM from the viewpoint of their consideration of material selection.

2. Methods

2.1. Research design

To obtain the highest number of points attainable in LEED, a model was developed to find the optimum scenario for different material options. The majority of LEED points are allocated based on the entire building and it is not possible to evaluate the points based solely on a specific material. Therefore, a case building was used, and three scenarios (sub-section 2.3) were defined. First, an LCA study was conducted for each scenario and then the LEED

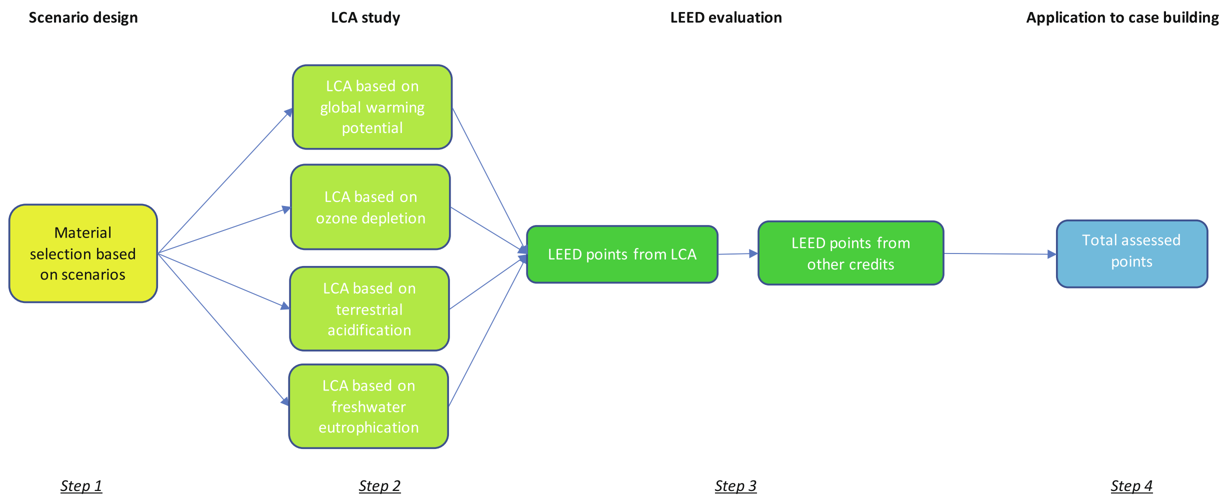


Fig. 1. LCA-LEED model.

points for each of these were evaluated (Fig. 1). Finally, each scenario was adopted to determine the LEED points for the case building and to find the preferred scenario according to LEED.

2.2. Case building

The case building is a modern educational facility at the University of Iceland in Reykjavik (Iceland), known as the building is 'Veröld – the House of Vigdís', named after the former President of Iceland Vigdís Finnbogadóttir. The construction of the building started in March 2015 and was finished in March 2017. The building houses teaching, research, and events connected to foreign languages and culture. Sustainability and environmentally-friendliness are claimed to be guiding factors in the design and construction (https://vigdis.hi.is/wp-content/uploads/2018/11/in-auguralbrochure_-_vigdis.pdf). The building was nominated for the European Union Prize for Contemporary Architecture - Mies van der Rohe Award in 2019.

The building has four floors, a gross area (GA) of 4013 m^2, and includes an underground floor, ground floor, and two above-ground floors. The underground and ground floors include a lobby, auditorium, and big classrooms, while the first and second floors include offices. The building is designed based on The Iceland Construction Authority [40], which is used for construction, fire safety, and electrical safety matters. Table 1 presents the main materials in eight sub-systems of the building. As much coverage of compo-

Table 1
Main materials in eight main building systems of Veröld building.

Building System/Sub-System	Main Material	Quantity	Unit
1. Excavation			
Facilities *			
Earth works	Excavation	23,400	m^3
Removal of existing structures and cleaning *			
Facilities *			
Earth works *			
2. Structures			
Formwork, concrete *			
Reinforcement	Reinforcing Steel	285,000	kg
Steel fasteners in concrete *			
Concrete	Concrete, 30–32 MPa	2780	m^3
Concrete elements	Concrete, 50 MPa	38	m^3
Insulation of foundation and basement slab	Polystyrene foam slab (EPS)	3387.5	kg
Steel works	Steel, low-alloyed	37,007	kg
Construction wood	Sawn wood, beam, hardwood	40	m
3. Pipes			
Sewage- and drainpipes	Polypropylene, granulate	6922	kg
Tap water system	Stainless steel	514	kg
Heating system	Polypropylene, granulate	5144	kg
Snow melting system (outdoors)	Polypropylene, granulate	1062	kg
	Stainless steel	824	kg
	Polyethylene, LDPE	800	kg
Sprinkler system	Stainless steel	4628	kg
Ventilation system	Stainless steel	12,345	kg
	Stone wool	1080	kg
Sanitary equipment	Sanitary ceramics	942	kg
4. Electrical wiring			
Electrical wiring lines	Steel	11,920	kg
	Polypropylene, granulate	1984	kg
	Aluminum	112	kg
	Copper	215	kg

(continued on next page)

Table 1 (*continued*)

Building System/Sub-System	Main Material	Quantity	Unit
Wiring	Copper	178	kg
Low voltage system	Network cable, category 5	1764	kg
Lighting system *	Lamps		
Lighting Control system *	Installation and programming		
Control system *	Sprinkler, ventilation		
Communication systems *	Sockets/outlets		
Safety systems *	Smoke detector		
5. Interior finishing			
Insulation and rendering	Polystyrene foam slab (EPS)	3841	kg
	Cement mortar, at plant	41	m^3
	Sand, at mine	62	m^3
	Concrete, 35 MPa	1.0	m^3
	Basalt	18	m^3
Light weight interior walls and claddings	Gypsum plaster board	3700	m^2
	Stone wool	3471	kg
	Saw log and veneer log-oak	5	m^3
Flooring materials	Linoleum flooring	2165	m^2
	Carpet	113	m^2
	Strip parquet	120	m^2
Ceilings	Stone wool	2093	kg
	Gypsum plaster board	284	m^2
	Saw log and veneer log-oak	3	m^3
Interior doors and windows	Door, wood-aluminum	320	m^2
	Window frame, aluminum	155	m^2
Painting	Gypsum plaster board	76	m^2
	Acrylic varnish	1669	kg
Carpeting Interior steelwork*	Saw log and veneer log-oak	0.7	m^3
	Steel		
Interior*	Cabinets		
6. Equipment *			
7. Outdoor finishing			
Painting*			
Wall claddings	Polystyrene foam slab (EPS)	26,535	kg
	Stone wool	530	kg
Roof finishing	Asphalt supporting layer	216,611	kg
	Underroof membrane	302	kg
	Concrete roof tile	2268	kg
Windows, glass, and external doors	Window frame, aluminum	519	m^2
Various	Saw log and veneer log-oak	2	m^3
8. Finishing of outdoor plot surfaces			
Finishing of outdoor plot surfaces	Asphalt supporting layer	161,563	kg
	Concrete, normal	1.4	m^3
	Prefabricated concrete ceiling	1834	m^2
Surface finishing*			
Grass and plants*			
Devices*			

* Not included in the assessment.

nents as possible was attempted to increase the validity of the results.

2.3. Scenarios

In addition to the base case, three other scenarios were designed to evaluate how material selection affects the results of LCA and LEED. In all scenarios, the U-values were the same to have equal operation energy consumption. It should be mentioned that as energy for buildings (heating and lighting) in Iceland is geothermal and hydropower is generated with low cost, the energy efficiency requirements are lower than in other countries with a similar climate.

2.3.1. Base case - Concrete building (Con)

In the base case, most building components (i.e., column and beams, structural external and internal walls, non-structural walls, and slabs) were reinforced concrete. Gypsum board was mainly used for partition walls in the first and second floors with rendering and painting. There was insulation for concrete external walls and slabs, and sound insulation was used for the auditorium.

2.3.2. Scenario 1 - Optimized concrete building (OptCon)

We studied two types of concrete: one with a high (C30) and the other with a low (C20) level of strength. In practice, this might be harder to manage in the construction phase, which would result in a lower use of cement for concrete. For this purpose, all structural walls were separated from the non-structural ones. In addition, all gypsum walls above ground floor were replaced with concrete C20 walls. The other parts remained the same as the base case (Table 2).

2.3.3. Scenario 2 - Concrete wooden building (ConWood)

Compared to OptCon, in this scenario all non-structural walls were replaced with wooden walls having an area of 785 m^2. Similarly, gypsum walls on above ground floors were replaced with wooden walls. In addition, flooring material for all floors was changed to hardwood for customer areas and parquet for private ones. Furthermore, the internal windows were replaced with wooden ones. All the alternative components in this scenario (including the non-structural wooden walls, hardwood and parquet flooring, and wooden windows) had third-party green certificates and environmental product declarations (EPDs).

Table 2
Changes in the scenarios.

Building System/Sub-System	Con	OptCon	ConWood	Wood
Structures				
Reinforcement				30% reduction[1]
Concrete	Concrete 30–32 MPa	Concrete 30–32 MPa Concrete 20 MPa	Concrete 30–32 MPa	Concrete[2] 30–32 MPa
Steel works				30% reduction
Structural walls				CLT [3] & Gypsum wall
Interior finishing				
Insulation and rendering			CLT wall Gypsum	CLT wall Gypsum
Light weight interior walls and claddings	Gypsum wall	Concrete 20 MPa	CLT wall Gypsum	CLT wall Gypsum
Flooring materials	Linoleum		Hardwood Parquet	Hardwood Parquet
Interior doors and windows	Aluminum	Aluminum	Wood	Wood
Outdoor finishing				
Windows, glass and external doors	Aluminum	Aluminum	Wood	Wood

[1] Lighter structure of wooden buildings results in 30% to 50% in foundation load [41], we adopted the lower limit, i.e., 30% reduction.
[2] Only for underground floor.
[3] Cross-Laminated Timber.

2.3.4. Scenario 3 - Wooden building (Wood)

Except for the foundation and underground floor detail, in this scenario all materials (i.e., structural and non-structural walls, internal and external windows, floors, and roof) were replaced with wood (Table 2). Cross-laminated timber (CLT) was mainly been used for the building. Similar to the ConWood building, the alternative components in this scenario had third-party green certificates and EPD.

2.4. Life cycle assessment

The aim of LCA is to capture all the direct and indirect environmental impacts related to production, transport, use, and end-of-life of a product, service, or process [42,43]. LCA has become the main method of environmental assessment in the building sector [33]. The main guidance for conducting an LCA is ISO 14040:2006 standard, which was followed in this study. However, sensitivity analysis was omitted due to added complexity and low added value with regards to the aim of this study.

There are three main approaches to LCA: process LCA, input–output LCA, and a combination of these known as hybrid LCA [44,45]. Process LCA is predominantly considered the more accurate approach for the quality of tracking the actual processes, and material and energy flows related to the production and delivery chain, use, and end-of-life of an object [33]. In contrast, input–output LCA typically operates with monetary flows and with a more comprehensive system boundary than process LCA, particularly in including capital goods and overheads [44]. Hybrid methods can thus possess both properties—high accuracy and comprehensive coverage [45–48]. However, since process LCA is still the most widely utilized approach in the building sector [33], it was chosen as the method for this study.

2.4.1. LCA tools

Two of the most widely adopted LCA software-database combinations in the building sector were utilized in the assessments: SimaPro/ecoinvent and GaBi. The software provides a user interface, an environmental information database, and options for the impact assessment method. In SimaPro, several databases are available, with ecoinvent being the most widely utilized in the building sector. GaBi includes its own building and construction sector database. Both software packages provide several impact assessment method options. We used the GaBi version 6.4.1.20 (Compilation) with the database version 6.108. In the case of SimaPro, we employed version 8.0.5.13 with the ecoinvent 3.0 database. SimaPro/ecoinvent was utilized as the primary tool, and GaBi as a backup when the match with the processes available in SimaPro/ecoinvent was unsatisfactory. Only the existing processes were used with no tailoring according to the actual life cycles of different materials. An attributional approach with no credits for the end-of-life use was selected to capture the impacts induced at the time of construction or until the beginning of the operation phase.

2.4.2. Life cycle impact assessment method

The ReCiPe Midpoint method [49] was utilized for the impact assessment due to the broadness of its indicators. ReCiPe includes 18 impact categories [50]. The Midpoint method was selected mainly because of the direct match with Leadership in Energy and Environmental Design (LEED) regarding the coverage of climate change and energy use. There is a high variation in results for different impact categories using the endpoint method or the single-score indicator, that can make the assessment challenging [51]. To assess the embodied environmental impacts of the stone wool, we used the model previously developed by Emami et al. [52].

2.4.3. Goal and scope definition

The main objective of the LCA study was to estimate the embodied environmental impacts of materials used in the case building and compare the base case to alternative low-carbon options (see section 2.3. Scenarios). All of the 18 ReCiPe impact categories were covered in this assessment: climate change (kgCO_2 eq), ozone depletion (kgCFC 11 eq), terrestrial acidification (kgSO2 eq), freshwater eutrophication (kgP eq), marine eutrophication (kg N eq), human toxicity (kg1.4 DB eq), photochemical oxidant formation (kg NMVOC), particulate matter formation (kgPM10eq), terrestrial ecotoxicity (kg 1.4DB eq), freshwater ecotoxicity (kg1.4DB eq), marine ecotoxicity (kg1.4 DB eq), ionizing radiation (kgU235 eq), agricultural land occupation (m^2a), urban land occupation (m^2a), natural land transformation (m^2), water depletion (m^3), metal depletion (kgFe eq), and fossil depletion (kg oil eq). The functional unit was 1 m^2 of gross floor area.

2.4.4. System boundaries

Pre-use life cycle stages (A1–A4) according to standard EN 15804 [53] were included in the study. These are as follows: A1 ‘raw material supply’, A2 ‘processing phase transport’, A3 ‘production of construction materials', and A4 'transportation to the construction site'. The construction (A5) and demolition phases were excluded because of their low contribution [54–56]. Further, since the operation phase is from renewable sources, it was not included in the study.

2.5. Green building certificate

Several green building certification systems exists already globally (see section 1.1). Of these, currently the number of BREEAM certificates totals 594,011 corresponding 2,313,475 registered buildings in 89 countries [57]. While these numbers are much higher than those of LEED certification, the LEED-certified buildings are spread out more internationally. In addition, countries that have similar situation to Iceland regarding material import, such as Middle East, are targeted here. In 2009, BREEAM Gulf designed for Saudi Arabia, UAE, Oman, Qatar, Bahrain and Kuwait, was launched but abandoned after two years. This might be due to the fact that the decision-makers in these countries often have gained their education in USA, and also to the efficient marketing of LEED [58]. Considering these issues, we selected LEED as a green building certificate for our evaluation. It is worth noting that the results of this study are beneficial also for the countries that are willing to replace construction materials with more environmentally friendly materials with less embodied emissions.

The fourth version of LEED (LEED v4) allocates a total of 110 points to the following categories: location and transportation (LT), sustainable sites (SS), energy and atmosphere (EA), indoor environment quality (IQ), water efficiency (WE), material and resources (MR), integrative process (IP), regional priority (RP), and innovation (IN) (Fig. 2a). Among the 110 points, 10 bonus points are allocated to the IN and RP categories. The RP category mainly focuses on sustainability issues in the location of the project. Each category comprises credits, which include some points (Fig. 2b). Regarding the impact of categories on gained points, EA can be ranked first following by IQ, LT, MR, and WE (Fig. 2c).

Among the credits in LEED, we have listed those that are affected by material selection (Table 3). To obtain the points of these credits, it is possible to select different options according to the LEED guidelines. As an example, for MR1 credit, one of the options for gaining three points is to conduct an LCA study. This study needs to consider structure and enclosure of the building and demonstrate a minimum of 10% reduction compared to the reference building justified by LEED. This reduction should be attained in at least three impact categories of the LCA study, including climate change, ozone depletion, terrestrial acidification, and freshwater eutrophication. The global warming potential should be among the three selected impacts. All the available options of credits in Table 3 (forth column) have been selected according to the scope and data availability of the current study, which can be found in the LEED guidelines.

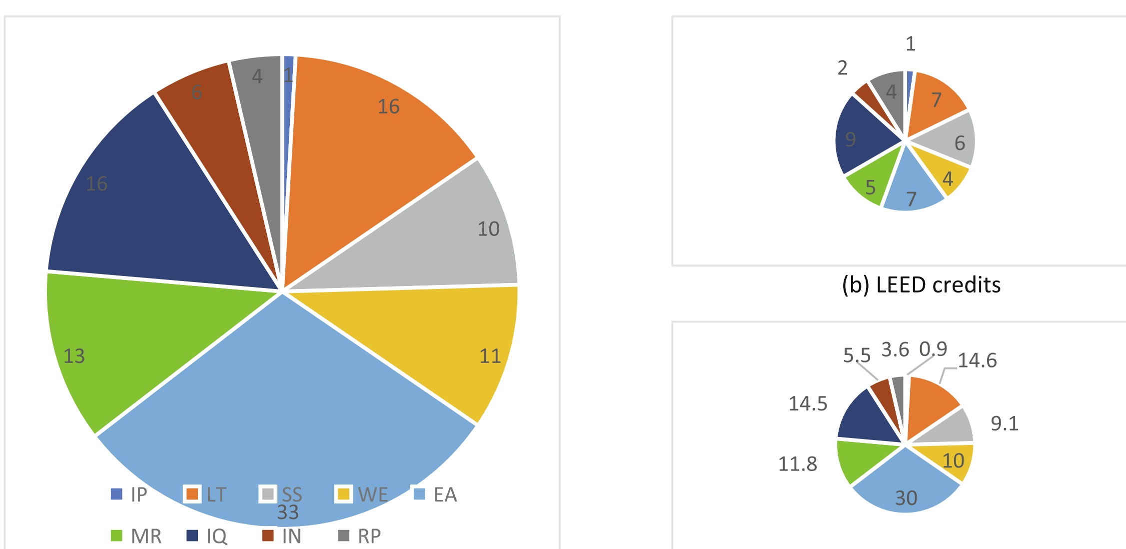
3. Results

3.1. LCA

The results show that by changing the construction material used in the structure and interior walls, the climate change impact could be decreased by 43% (from 644 to 379 kg CO_2 eq /m^2), as depicted in Table 4. The same saving can be achieved in several impact categories, including ozone depletion, terrestrial acidification, freshwater eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, natural land transformation, metal depletion, and fossil depletion.

The differences in the environmental effects between OptCon and the Con building are quite small at less than 5%. The climate change impact is reduced by approximately 15.5% in ConWood, since all nonstructural concrete walls were assumed to be replaced with wooden walls. However, the additional use of wood inadvertently increases the urban land occupation (29.9%) and agricultural land occupation (893%) compared to the Con building. The climate change impact is almost 43% lower in the Wood building as a result of extensive use of wood. Similar to ConWood, the proposed modifications negatively affected two impact categories: urban land occupation (46.7%) and agricultural land occupation (2135%).

Fig. 3 displays a comparison between the contribution of building elements to climate change, ozone depletion, terrestrial acidification, and freshwater eutrophication in three scenarios compared to the Con (base case). Due to the use of wood in outdoor and interior finishing, the climate change impact decreases by 66% and 29% in ConWood, respectively. In addition, there is a reduction of 43%,



(a) LEED points

(c) LEED points in %

Fig. 2. Distribution of LEED points and credits and between the assessment categories.

Table 3
Allocation of LEED credits in the Material and resources (MR) category.

Symbol	Credit	Points	Intent
MR_1	Building life-cycle impact reduction	5	To optimize the environmental performance of materials and products
MR_2	Building product disclosure and optimization—environmental product declarations	2	To use product and materials which are socially, environmentally, and economically preferable – Select products that their environmental life-cycle impacts have been improved and verified
MR_3	Building product disclosure and optimization—sourcing of raw materials	2	To use product and materials which are socially, environmentally, and economically preferable – Select products extracted or sourced in a responsible manner
MR_4	Building product disclosure and optimization—material ingredients	2	To use product and materials which are socially, environmentally, and economically preferable – Select products for which the chemical ingredients are inventoried with harmful substance minimization
EQ	Low-emitting materials	3	To decrease concentrations of chemical contaminants damaging human health, air quality, productivity, and the environment
IN	Innovation	5	To achieve innovative or exceptional performance in any of the credits

73%, and 60% in terms of ozone depletion, terrestrial acidification, and freshwater eutrophication in the Wood scenario compared to Con scenario. In terms of marine eutrophication, the replacement of concrete walls with wooden walls and the substitution of aluminum windows with wooden ones causes a significant increase in interior and outdoor finishing elements.

3.1.1. Contribution of transportation

Since most of construction materials are imported into Iceland, the contribution of the transportation stage to the overall environmental impacts is a potential hotspot. Thus, the environmental impacts of transportation needed from the source country to Iceland and from the seaport to the construction site (A4) were studied. Only a one-way trip was considered in the LCA as the vessel needs to be used for exports from Iceland on the route back.

According to Breiðfjörð [59], the GWP impact of containerships traveling to Iceland is 0.0327 kg CO_2 eq/ton.km (value used in this study), while the value for GWP impact from container ship in SimaPro is 0.0115 kg CO_2 eq/ton.km. The reason for the higher emission factor for Iceland compared to international shipping might include heavy winds, small cargoes, and the difficulty of the shipping route to Iceland. Thus, the emission factor for other impact categories was adjusted based on the same ratio to account for the impact of the difficult conditions of the shipping route to Iceland.

The share of transportation varies significantly across the four impact categories for different scenarios (Fig. 4). Transportation impact represents more than 15% of the total climate change impact in the Wood scenario, and between 20% and 45% of the total ozone depletion and terrestrial acidification impacts for all four scenarios. In the freshwater eutrophication category, the contribution of transportation is less than 10% in different scenarios.

Fig. 5 shows the difference in climate change impacts of the different building systems (structures, interior finishing, and outdoor finishing) and transportation in the OptCon, ConWood, and Wood scenarios compared to the base case (Con). Other building systems have been excluded because their climate change impacts did not change in the alternative scenarios.

3.2. LEED evaluation

As shown in Table 5, no difference was found in the number of LEED points for Con and OptCon scenarios. The allocation of LEED points for MR2-4 is based on using more than 20 permanently installed products in the building; therefore, the change in concrete type for OptCon has no impact on the points. The Wood scenario obtained the highest number of points while ConWood ranked second. The former scenario was the only one that attained points for the LCA credit. In addition, it succeeded to attain the points for IN as it achieved beyond the requirement needed for LEED's MR1 credit.

3.3. Application to the case building

According to the LEED guidelines, the case building received 32 points from all credits excluding the credits related to material selection (Table 6). Although the Wood scenario has six extra

Table 4
Environmental impact of the case building made from different building materials (alternative scenarios): results from LCA using the ReCipe method.

Impact Category	Unit	Con	OptCon		ConWood		Wood	
		Abs.	Abs.	%	Abs.	%	Abs.	%
Climate change	kg CO_2 eq /m^2	664.42	672.99	1.3%	562.09	−15.4%	379.16	−42.9%
Ozone depletion	kg CFC11 eq /m^2	3.21E-05	3.22E-05	0.3%	2.89E-05	−10.0%	2.33E-05	−27.3%
Terrestrial acidification	kg SO_2 eq /m^2	2.77	2.79	0.7%	2.02	−27.0%	1.55	−44.1%
Freshwater eutrophication	kg P eq /m^2	0.20	0.20	0.4%	0.17	−12.3%	0.12	−37.3%
Marine eutrophication	kg N eq /m^2	0.44	0.44	−0.1%	0.66	49.8%	0.83	86.4%
Human toxicity	kg 1.4 DB eq /m^2	294.21	295.19	0.3%	266.27	−9.5%	201.56	−31.5%
Photochemical oxidant formation	kg NMVOC /m^2	2.31	2.33	1.0%	2.04	−11.7%	1.55	−32.9%
Particulate matter formation	kg PM10 eq /m^2	1.42	1.42	0.3%	1.18	−16.7%	0.86	−39.4%
Terrestrial ecotoxicity	kg 1.4 DB eq /m^2	0.21	0.21	0.6%	0.20	−1.0%	0.12	−42.6%
Freshwater ecotoxicity	kg 1.4 DB eq /m^2	8.75	8.77	0.2%	7.60	−13.1%	5.59	−36.1%
Marine ecotoxicity	kg 1.4 DB eq /m^2	8.51	8.53	0.3%	7.44	−12.5%	5.49	−35.5%
Ionizing radiation	kg U235 eq /m^2	35.43	35.27	−0.5%	37.70	6.4%	35.27	−0.4%
Agricultural land occupation	m^2a /m^2	35.84	34.45	−3.9%	355.76	892.7%	800.81	2134.6%
Urban land occupation	m^2 /m^2	6.39	6.51	1.9%	8.30	29.9%	9.38	46.7%
Natural land transformation	m^2a /m^2	0.17	0.17	1.3%	0.16	−3.2%	0.10	−37.9%
Water depletion	m^3 /m^2	28.43	27.11	−4.6%	28.12	−1.1%	44.45	56.3%
Metal depletion	kg Fe eq /m^2	244.82	244.95	0.1%	242.77	−0.8%	156.55	−36.1%
Fossil depletion	kg oil eq /m^2	137.66	138.49	0.6%	118.58	−13.9%	90.81	−34.0%

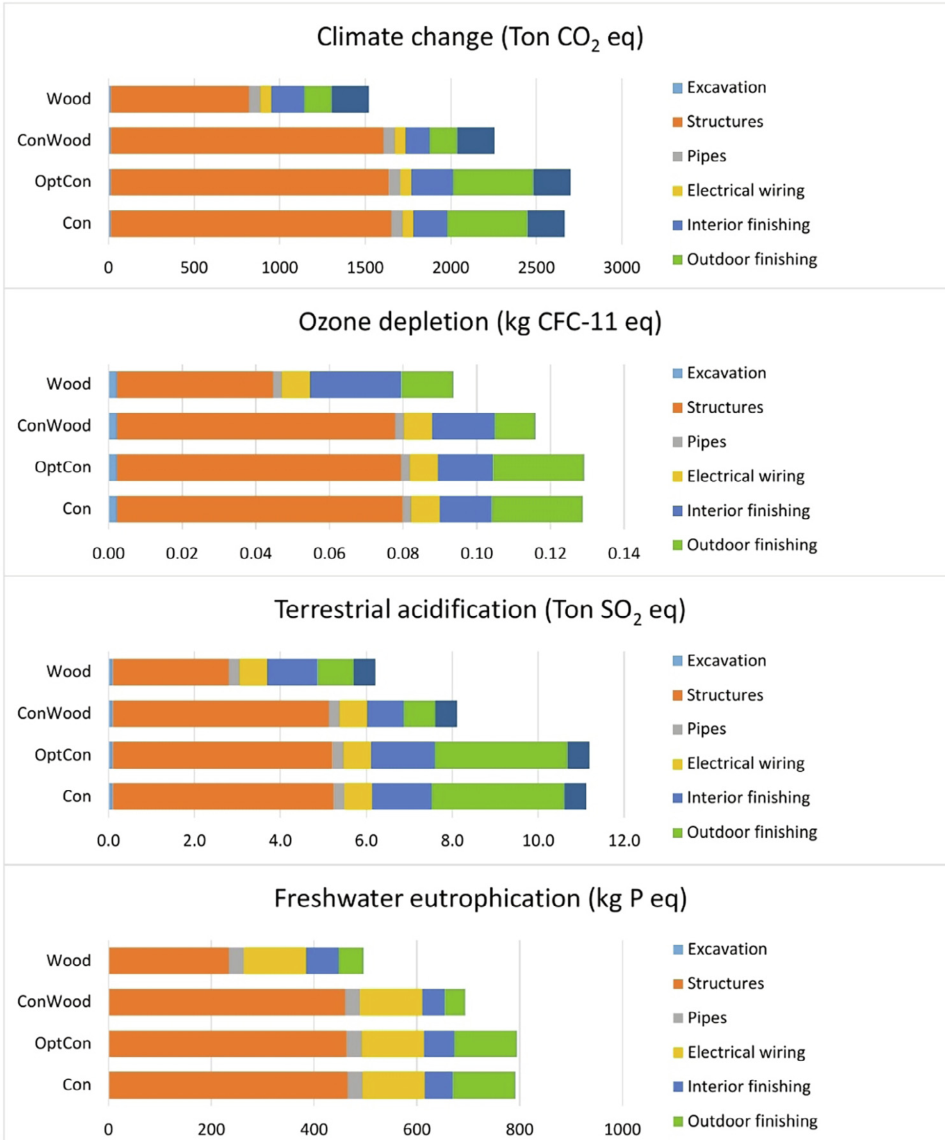


Fig. 3. Environmental impact of the case building built as per different building material scenarios.

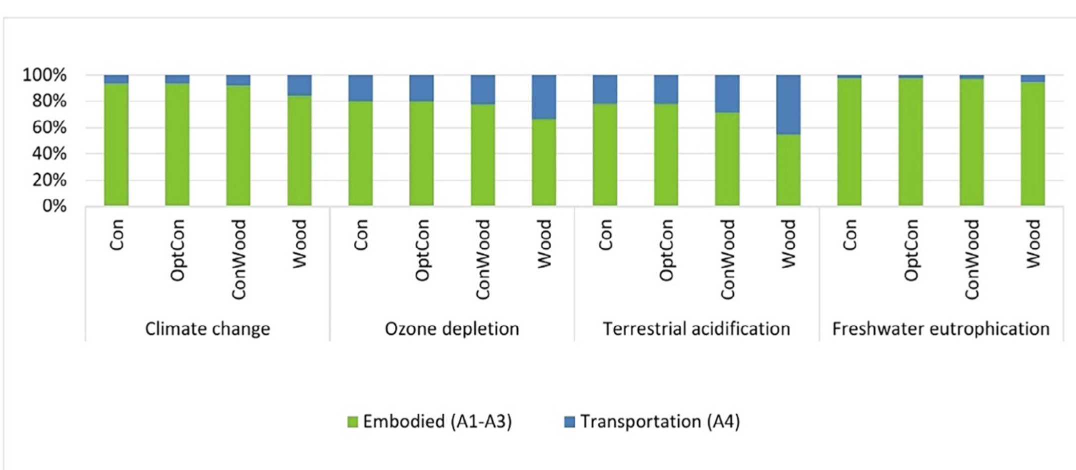


Fig. 4. The contributions of impacts arising from embodied emissions and transportation in each impact category for the studied four building material scenarios.

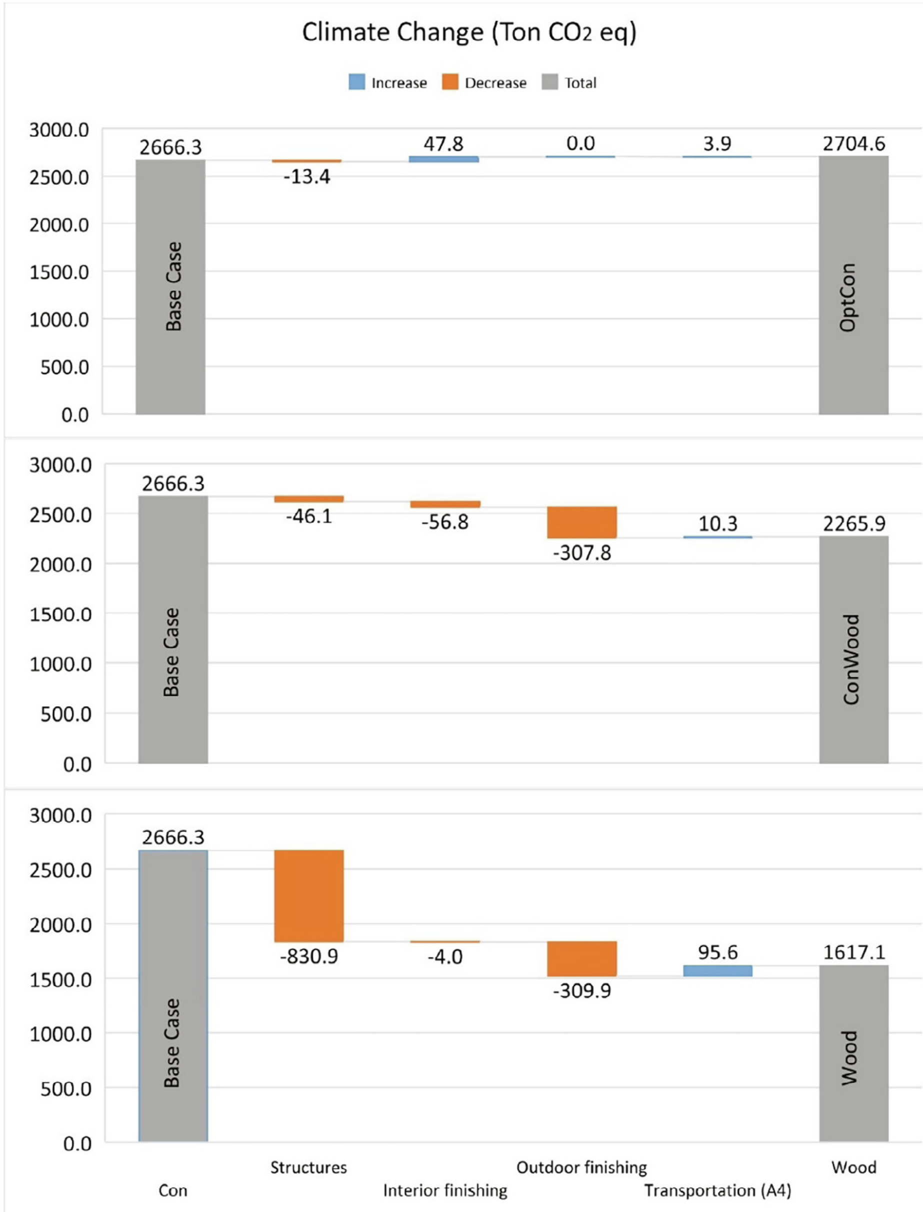


Fig. 5. The contributions of each building system in reducing the climate change impact in three scenarios compared to the base case.

Table 5
LEED points of the case building in the studied four building material scenarios.

Credits	MR_1	MR_2	MR_3	MR_4	EQ	IN	Total	Action taken
Con	0	1	1	1	2	0	5	• Used more than 20 different permanently installed products that have EPD, sourcing of raw materials, and material ingredients information ($MR_{2\text{-}4}$). • Used low-emitting materials that increase the air quality, human health, productivity, and the environment (EQ).
OptCon	0	1	1	1	2	0	5	• Used more than 20 different permanently installed products that have EPD, sourcing of raw materials, and material ingredients information ($MR_{2\text{-}4}$). • Used low-emitting materials that increase the air quality, human health, productivity, and the environment (EQ).
ConWood	0	1	2	2	3	0	8	• Used more than 20 different permanently installed products that have EPD, sourcing of raw materials, and material ingredients information ($MR_{2\text{-}4}$). • Increased amount of used wood as low-emitting material (EQ).
Wood	3	2	2	2	3	2	14	• Less environmental impact (-10%) according to building LCA study (MR_1). • Used more than 20 different permanently installed products that have EPD, sourcing of raw materials, and material ingredients information ($MR_{2\text{-}4}$). • Increased amount of used wood as low-emitting material (EQ). • Achieved triple the credit requirements (-30%) for building LCA study (IN).

Table 6
Case building's total LEED points and LEED certification level.

Scenario	Con	OptCon	ConWood	Wood
Material selection points	5	5	8	14
Other points	32	32	32	32
Total points	37	37	40	46
LEED level	–	–	Certified	Certified

points compared to ConWood, the level of LEED points in these two scenarios is the same, i.e., certified. Using wood as building material (ConWood and Wood scenarios) resulted in additional 8 and 14 points, respectively, making it possible to earn the required points for gaining a LEED certificate.

4. Discussion and conclusions

The aim of this study was to evaluate the suitability of LEED in supporting the urgently needed embodied emission reductions of buildings. More specifically, we estimated if and how well the LEED points support choosing building materials with low embodied emissions. A recently built concrete-structure university building located in Iceland, claimed to be a sustainable building, was selected as a base case (Con). Three scenarios with different building materials were defined for comparison. These three scenarios included an optimized concrete building (OptCon) with the replacement of non-structural walls with lower strength concrete; a hybrid concrete-wooden building (ConWood), in which non-structural components were changed to wood; and a wooden building (Wood) mainly constructed from wood. An LCA study was conducted for all four cases with an emphasis on four indicators: climate change, ozone depletion, terrestrial acidification, and freshwater eutrophication. This enabled the determination of a LEED certification score in each scenario. In addition, transportation emissions were evaluated to assess the possibility of using the findings globally for the challenge of climate change.

With regard to LCA, the Wood building had the lowest environmental impact, followed by the ConWood, OptCon, and Con buildings. For the Con building, the LCA resulted in an emission estimate of 664.5 kg CO_2 eq /m^2 in the case of the most important indicator (climate change). While this value is in line with the results by Dong and Ng [60], and Ng and Kwok [61], it is relatively high in comparison to previous building LCAs in general [33] and does not support the sustainable design claim (https://vigdis.hi.is/wp-content/uploads/2018/11/inauguralbrochure_-_vigdis.pdf). This is due to an excessive use of concrete as the main domestic building material. As expected, the structure of the building was the main contributor to the climate change impact. The substitution of aluminum in the windows significantly reduced the impact on all four categories. Conversely, focusing on the interior finishing, replacement of the gypsum walls with wooden walls increased the impact in all four categories.

In total, 14 (13%) of the LEED points were directly related to material selection, in which five points (5%) need substantial changes (e.g. LCA). The other points are achievable if 20 permanent materials are selected among the materials that have environmental product declarations (EPD) and information regarding material ingredients and sources (MIS). These 20 materials can be selected from any components of the building, meaning that some constructors might use the easiest and cheapest ones without any emphasis on embodied emissions. Even if the constructor is willing to use material with lower environmental impact shown by LCA, there is no possibility of achieving all the 14 points if the selected materials do not have EPD or MIS.

In BREEAM as another green building certificate, 12 (8%) points are directly related to material selection, i.e., less than in LEED. From these, five (3%) points are based on LCA. There are also some points available both in LEED and BREEAM, which can be gained if extra requirements in the category of innovation are fulfilled. These points can be interrelated with material selection.

Compared to the points allocated for energy and atmosphere category , which is mainly focused on the reduction of energy and lower emissions generated during the operation phase, the number of points allocated to embodied emissions are few in both LEED and BREEAM. Short-term climate change mitigation needs short-term plans, which are interrelated with embodied emissions. This is not just an issue related to green building certificates but also related to research, which has previously focused on energy-efficient buildings, where use stage has been optimized [62–64]. Nearly zero-energy buildings or low-energy buildings are the result of this trend. Hence, we recommend that LEED and other similar green building certificates pay more attention to the role of embodied emissions of buildings. This policy can serve as a temporary action to mitigate climate change and could be changed until a desired situation has been reached.

Even with the focus that LEED has on energy efficiency, there is doubt on the effect of LEED regarding energy efficiency in practice. The energy efficiency of LEED-certified buildings, especially in lower certification levels (i.e. certified or silver) is questionable [62]. Therefore, we suggest improving the use of more reliable environmental assessment tools such as LCA in LEED.

Generally, there are two main solutions to mitigate climate change and help the environment. One is producing less carbon, while the other is capturing carbon. Various countries have plans and incentives regarding buildings that would generate less emissions, but no motivation plan exists for buildings that can capture carbon. Also in LEED, capturing emissions by materials, such as wood during its growth, has not gained much attention. There is noticeable potential for climate change mitigation if the carbon storage of wood as a building material is fully considered. For example, the annual captured CO_2 by wood used as the main building material for European new building construction varied between 1 and 55 Mt, which is equivalent to 1%–47% of CO_2 emissions of the cement industry in Europe [65].

Among the alternative low-emission and carbon storing materials, wood can be considered a solution for climate change mitigation, not only for countries like Iceland that mainly import their construction materials, but also globally. Here, the emissions resulting from transportation remains the issue. However, based on this study, transportation emissions are low compared to other emissions, making this solution viable.

It should be mentioned that using forest and wood harvesting is only reasonable if the forest is managed sustainably and its value as a habitat for biota is considered by avoiding monoculture plantations. Otherwise, using wood for construction will result in the depletion of forest resources and a loss of biodiversity, which is an even worse option from the viewpoint of climate change. It is widely assumed that buildings have a life cycle of 50 years. Using wood in buildings saves biomass, which will also continue to increase at each round of 50 years. The best way to benefit from this saving is to reuse wood after the demolition of wooden buildings, or it could be used as renewable fuel. According to results published by IPCC [66], direct or indirect replacement of fossil fuels by biomass using wood instead of energy-intensive materials is a more efficient method of CO_2 reduction than leaving the forest untouched.

Declaration of Competing Interest

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

Acknowledgments

This research was funded by the Ministry of the Environment of Finland, CarbonSinkCity grant (310283). The views expressed by the authors do not necessarily reflect those of the funder.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2021.110962.

References

[1] S.I. Junnila, Empirical comparison of process and economic input-output life cycle assessment in service industries, Environ. Sci. Technol. 40 (2006) 7070–7076.
[2] H. Schandl, M. Fischer-Kowalski, J. West, S. Giljum, M. Dittrich, N. Eisenmenger, A. Geschke, M. Lieber, H. Wieland, A. Schaffartzik, Global material flows and resource productivity: forty years of evidence, J. Ind. Ecol. 22 (2018) 827–838.
[3] H. Hong, S. Wang, Z.Z. Wu, Implementing sustainable management in construction industry, Advanced Materials Research. Trans Tech Publ (2011) 85–88.
[4] K. Çomaklı, B. Yüksel, Environmental impact of thermal insulation thickness in buildings, Appl. Therm. Eng. 24 (2004) 933–940.
[5] A.M. Papadopoulos, E. Giama, Environmental performance evaluation of thermal insulation materials and its impact on the building, Build. Environ. 42 (2007) 2178–2187.
[6] C. Thormark, The effect of material choice on the total energy need and recycling potential of a building, Build. Environ. 41 (2006) 1019–1026.
[7] M.J. González, J.G. Navarro, Assessment of the decrease of CO2 emissions in the construction field through the selection of materials: practical case study of three houses of low environmental impact, Build. Environ. 41 (2006) 902–909.
[8] G.P. Henze, C. Felsmann, G. Knabe, Evaluation of optimal control for active and passive building thermal storage, Int. J. Therm. Sci. 43 (2004) 173–183.
[9] G.P. Henze, D.E. Kalz, S. Liu, C. Felsmann, Experimental analysis of model-based predictive optimal control for active and passive building thermal storage inventory, HVAC&R Res. 11 (2005) 189–213.
[10] S.B. Sadineni, S. Madala, R.F. Boehm, Passive building energy savings: a review of building envelope components, Renew. Sustain. Energy Rev. 15 (2011) 3617–3631.
[11] H. Sozer, Improving energy efficiency through the design of the building envelope, Build. Environ. 45 (2010) 2581–2593.
[12] J.C. Morel, A. Mesbah, M. Oggero, P. Walker, Building houses with local materials: means to drastically reduce the environmental impact of construction, Build. Environ. 36 (2001) 1119–1126.
[13] C.J. Kibert, Sustainable construction: green building design and delivery, John Wiley & Sons (2016).
[14] N. Lin, F. Liu, Green low carbon design in the application of energy-saving building, Advanced Materials Research. Trans Tech Publ (2012) 2878–2881.
[15] J. Yudelson, The green building revolution, Island Press (2010).
[16] M.L. Nilson, Quantifying the cost impacts of LEED-NC gold construction in New York city. Senior Honor thesis, Dept. of Civil and Environmental Engineering, Lafayette College, Easton, PA, 2005.
[17] D. Pearce, Is the construction sector sustainable?: definitions and reflections, Build Res. Inf. 34 (2006) 201–207.
[18] J. Jeong, T. Hong, C. Ji, J. Kim, M. Lee, K. Jeong, Development of an evaluation process for green and non-green buildings focused on energy performance of G-SEED and LEED, Build. Environ. 105 (2016) 172–184.
[19] G. Donghwan, K.H. Yong, K. Hyoungsub, LEED, its efficacy in regional context: finding a relationship between regional measurements and urban temperature, Energy Build. 86 (2015) 687–691.
[20] N. Leskinen, J. Vimpari, S. Junnila, A review of the impact of green building certification on the cash flows and values of commercial properties, Sustainability 12 (2020) 2729.
[21] G.S. Vyas, K.N. Jha, What does it cost to convert a non-rated building into a green building?, Sustainable Cities Soc. 36 (2018) 107–115.
[22] A. Amiri, J. Ottelin, J. Sorvari, S. Junnila, Economic and Technical Considerations in Pursuing Green Building Certification: A Case Study from Iran (2020).
[23] M. Michael, L. Zhang, X. Xia, An optimal model for a building retrofit with LEED standard as reference protocol, Energy Build. 139 (2017) 22–30.
[24] H. Feng, K. Hewage, Energy saving performance of green vegetation on LEED certified buildings, Energy Build. 75 (2014) 281–289.
[25] J. Jeong, T. Hong, C. Ji, J. Kim, M. Lee, K. Jeong, Development of an evaluation process for green and non-green buildings focused on energy performance of G-SEED and LEED, Build. Environ. 105 (2016) 172–184.
[26] J.H. Scofield, Do LEED-certified buildings save energy? Not really..., Energy Build. 41 (2009) 1386–1390.
[27] G.R. Newsham, S. Mancini, B.J. Birt, Do LEED-certified buildings save energy? Yes, but..., Energy Build. 41 (2009) 897–905.
[28] H. Chen, W.L. Lee, X. Wang, Energy assessment of office buildings in China using China building energy codes and LEED 2.2, Energy Build. 86 (2015) 514–524.
[29] J.H. Scofield, Efficacy of LEED-certification in reducing energy consumption and greenhouse gas emission for large New York City office buildings, Energy Build. 67 (2013) 517–524.
[30] S. Suh, S. Tomar, M. Leighton, J. Kneifel, Environmental performance of green building code and certification systems, Environ. Sci. Technol. 48 (2014) 2551–2560.
[31] M. Hu, P. Cunningham, S. Gilloran, Sustainable design rating system comparison using a life-cycle methodology, Build. Environ. 126 (2017) 410–421.
[32] Y. Lessard, C. Anand, P. Blanchet, C. Frenette, B. Amor, LEED v4: where are we now? Critical assessment through the LCA of an office building using a low impact energy consumption mix, J. Ind. Ecol. 22 (2018) 1105–1116.
[33] A. Säynäjoki, J. Heinonen, S. Junnila, A. Horvath, Can life-cycle assessment produce reliable policy guidelines in the building sector?, Environ. Res. Lett. 12 (2017).
[34] A. Säynäjoki, J. Heinonen, S. Junnila, Carbon footprint assessment of a residential development project, Int. J. Environ. Sci. Dev. 2 (2011) 116.
[35] 35. European Commission, Available online: https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2.html (Accessed on 14.10. 2019).
[36] A. Dodoo, L. Gustavsson, R. Sathre, Carbon implications of end-of-life management of building materials, Resour. Conserv. Recycl. 53 (2009) 276–286.
[37] B.V. Reddy, K.S. Jagadish, Embodied energy of common and alternative building materials and technologies, Energy Build. 35 (2003) 129–137.
[38] C. Thormark, The effect of material choice on the total energy need and recycling potential of a building, Build. Environ. 41 (2006) 1019–1026.
[39] G. Verbeeck, H. Hens, Life cycle optimization of extremely low energy dwellings, J. Build. Phys. 31 (2007) 143–177.
[40] Iceland Construction Authority, Available online: http://www.mannvirkjastofnun.is/english/iceland-construction-authority/ (Accessed on 24 April 2020).
[41] C. Bengtsson, Challenges in timber construction, 2009.
[42] W. Klopffer, Life cycle assessment-from the beginning to the current state, Environ. Sci. Pollut. Res. 4 (1997) 223–228.
[43] R. Crawford, Life cycle assessment in the built environment, Routledge (2011).
[44] S. Suh, M. Lenzen, G.J. Treloar, H. Hondo, A. Horvath, G. Huppes, O. Jolliet, U. Klann, W. Krewitt, Y. Moriguchi, System boundary selection in life-cycle inventories using hybrid approaches, Environ. Sci. Technol. 38 (2004) 657–664.
[45] R.H. Crawford, P. Bontinck, A. Stephan, T. Wiedmann, M. Yu, Hybrid life cycle inventory methods–a review, J. Clean. Prod. 172 (2018) 1273–1288.
[46] Y. Yang, R. Heijungs, M. Brandão, Hybrid life cycle assessment (LCA) does not necessarily yield more accurate results than process-based LCA, J. Clean. Prod. 150 (2017) 237–242.
[47] A. Stephan, R.H. Crawford, P. Bontinck, A model for streamlining and automating path exchange hybrid life cycle assessment, Int. J. Life Cycle Assess. 24 (2019) 237–252.
[48] G. Majeau-Bettez, A.H. Strømman, E.G. Hertwich, Evaluation of process-and input–output-based life cycle inventory data with regard to truncation and aggregation issues, Environ. Sci. Technol. 45 (2011) 10170–10177.
[49] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, R. Van Zelm, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, Ministry of VROM.ReCiPe, The Hague, 2009.
[50] Y.H. Dong, S.T. Ng, Comparing the midpoint and endpoint approaches based on ReCiPe—a study of commercial buildings in Hong Kong, Int. J. Life Cycle Assess. 19 (2014) 1409–1423.
[51] H. Dahlbo, S. Koskela, H. Pihkola, M. Nors, M. Federley, J. Seppälä, Comparison of different normalised LCIA results and their feasibility in communication, Int. J. Life Cycle Assess. 18 (2013) 850–860.
[52] N. Emami, B. Marteinsson, J. Heinonen, Environmental impact assessment of a School building in Iceland using LCA-including the effect of long distance transport of materials, Buildings 6 (2016) 46.
[53] Council, U.G.B. EN 15804: 2012þA1 Sustainability of Construction Works. Environmental Product Declarations. Core Rules for the Product Category of Construction Products, 2012.
[54] P. Zhong, Study of building life-cycle energy use and relevant environmental impacts, Sichuan University (in Chinese) (2005).
[55] R. Fay, G. Treloar, U. Iyer-Raniga, Life-cycle energy analysis of buildings: a case study, Build. Res. Inf. 28 (2000) 31–41.

[56] W. Songqing, W. Wei, Z. Xu, Calculation and analysis on energy consumption of residential buildings in severe cold region based on life cycle theory, Build. Sci. (2008) 58–61.
[57] BREEAM, Available online: https://www.breeam.com/ (Accessed on 21 February 2021).
[58] L. Mark, LEED outstrips BREEAM across the globe – including Europe, 2013.
[59] K. Breiðfjörð, No title. Byggingarefni á Íslandi.Uppruni, flutningar til landsins ásamt kolefnisspori timburs, 2011.
[60] Y.H. Dong, S.T. Ng, A life cycle assessment model for evaluating the environmental impacts of building construction in Hong Kong, Build. Environ. 89 (2015) 183–191.
[61] T.K. Ng, S.M. Kwok, Carbon emission estimation—a design verification tool for new public housing developments in Hong Kong, in: Proceedings of the HKU-HKHA International Conference, Hong Kong, China, 2013, pp. 2–3.
[62] A. Amiri, J. Ottelin, J. Sorvari, Are LEED-certified buildings energy-efficient in practice?, Sustainability 11 (2019) 1672.
[63] O. Ortiz, F. Castells, G. Sonnemann, Sustainability in the construction industry: a review of recent developments based on LCA, Constr. Build. Mater. 23 (2009) 28–39.
[64] A. Passer, H. Kreiner, P. Maydl, Assessment of the environmental performance of buildings: a critical evaluation of the influence of technical building equipment on residential buildings, Int. J. Life Cycle Assess. 17 (2012) 1116–1130.
[65] A. Amiri, J. Ottelin, J. Sorvari, S. Junnila, Cities as carbon sinks-classification of wooden buildings, Environ. Res. Lett. (2020).
[66] Intergovernmental Panel of Climate Change, (IPCC) Climate Change 1995. The Science of Climate Change, Contribution of Working Group II to the Second Assessment Report of the IPCC, 1996.