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Environmental Impact Assessment of a School Building in Iceland Using LCA-Including the Effect of Long Distance Transport of Materials

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Abstract: Buildings are the key components of urban areas and society as a complex system. A life cycle assessment was applied to estimate the environmental impacts of the resources applied in the building envelope, floor slabs, and interior walls of the Vættaskóli-Engi building in Reykjavik, Iceland. The scope of this study included four modules of extraction and transportation of raw material to the manufacturing site, production of the construction materials, and transport to the building site, as described in the standard EN 15804. The total environmental effects of the school building in terms of global warming potential, ozone depletion potential, human toxicity, acidification, and eutrophication were calculated. The total global warming potential impact was equal to 255 kg of CO_2 eq/sqm, which was low compared to previous studies and was due to the limited system boundary of the current study. The effect of long-distance overseas transport of materials was noticeable in terms of acidification (25%) and eutrophication (31%) while it was negligible in other impact groups. The results also concluded that producing the cement in Iceland caused less environmental impact in all five impact categories compared to the case in which the cement was imported from Germany. The major contribution of this work is that the environmental impacts of different plans for domestic production or import of construction materials to Iceland can be precisely assessed in order to identify effective measures to move towards a sustainable built environment in Iceland, and also to provide consistent insights for stakeholders.

Keywords: buildings; construction materials; environmental impacts assessment; LCA; transportation

1. Introduction

The building and construction sectors are key sectors for sustainable development. While the building industry generates 5% to 15% of the global GDP, the built environment is responsible for one-third of the total final energy use and half of worldwide electricity consumption, as well as one-third of global carbon emissions [1,2]. According to the latest IPCC report [3], the energy use and related emissions from buildings can double or possibly even triple until 2050 as a result of several key trends, including growth in population, relocation to urban areas, changes in family size, rising levels of affluence, and behavioral changes.

Already, preventing emissions of GHGs by reducing the operational energy use in current buildings is of the utmost importance for policymakers in Europe. Thus, the main focuses of the European Performance Building Directive (EPBD) 2010/31/EU [4], and the Energy Efficiency Directive (2012/27/EU) [5] were to concentrate efforts towards better insulation, more efficient HVAC systems, and more use of sustainable energy. In the review of Chastas et al. [6], the embodied energy in residential buildings, including traditional, passive, and nearly zero energy buildings (nZEB), regardless of the drop in the total life cycle energy, the results demonstrate a growing portion of embodied energy from traditional to nZEB that could reach up to 50%. As a result of the continuous narrowing of the building regulations' requirements to reduce emission from the operation of buildings, the relative importance of embodied emissions is quickly increasing [7–9]. This is already the case for Iceland for which the operation of buildings uses almost entirely renewable energy sources. Besides, enhancement in the energy efficiency of buildings may also bring in the use of materials and energy systems that might possibly increase the embodied carbon [10,11]. Recent evidence actually depicts that it might not be so much increasing consumption which drives the growth in global emissions, but the required capital investment to accommodate rural–urban movement, that is, the construction materials [12], which currently are neglected in the majority of assessment schemes and mitigation policies.

Since the early 1990s, an increasing number of methods have been suggested to evaluate the environmental impacts of buildings. Life Cycle Assessment (LCA) is nowadays the dominant assessment method for the embodied impacts that measure the emissions, usage of natural resources, and effect on health that can be related to different products or services over their complete life cycle. It quantifies the interactions with the surroundings, whether they are inputs to the system—such as natural resources, land, and energy—or as an output of the considered system—for example emissions to air, water, and soil.

A handful of studies have shown that the relative importance of embodied energy and embodied carbon can also be high over the whole building life cycle. An investigation on the energy consumed in a low-energy building in Gothenburg, Sweden showed that the embodied energy in one family home was responsible for around 45% of the total energy needs over 50 years [13]. Rawlinson and Weight [14] suggest that the embodied energy in residential buildings is approximately equal to 10 times the annual operational energy use, while this ratio can be around 30 for complex commercial buildings in the UK. Later, the analysis by Sturgis and Roberts [15] illustrated that for some building types, up to 62% of the whole life-cycle carbon may be due to embodied carbon emissions. On the other hand, Rossi, et al. [16] used a simple tool (validated with the certified software Equer) and estimated that the embodied carbon accounts for only 10%–20% of the total carbon emissions over the life cycle of the house. To assess the mitigation capacity of alternative materials, several studies have compared the embodied energy and environmental impact of alternative materials [17–21]. For example, Utama, et al. [21] evaluated the embodied GWP impacts of using traditional clay instead of concrete in houses in Indonesia. They estimated that substitution of concrete with traditional clay could reduce the GWP impacts by 9 million tons of CO_2 eq by 2030. There are a number of studies that have concentrated on the embodied energy and the corresponding global warming potentials (GWP) (see for example [22]), but significantly fewer have included other impact categories (such as the ozone depletion potential, ODP; the acidification potential, AP; the eutrophication potential, EP; the photochemical ozone creation potential, POCP; etc.) [23,24]. Yet, they have suggested that the materials are an important source of several impacts. For example, Blengini, et al. [25] developed a detailed LCA over several impact categories including GWP, ODP, AP, EP, and POCP for a house located in Morozzo, Italy. The analysis has emphasized that, when addressing the performance of low-energy buildings, it is vital to account for the contribution of all life cycle phases and subsystems. In 2012, Passer et al. [26] analyzed the influence of five residential buildings in Austria on seven environmental indicators (AP, EP, GWP, ODP, POCP, cumulative energy demand-non-renewable, CEDnr; cumulative energy demand-renewable, CEDr). This analysis indicates that although the operation phase is the most dominant phase in all impact categories, still, the contribution of impacts may differ considerably for construction products and the operation phase in many categories.

Recently, Soust-Verdaguer et al. [27] reviewed 20 case studies primarily in order to compare system boundary definitions, sources of information, the selected life cycle phases, and estimated environmental impact categories focusing on simplification approaches (read [28] for further elaboration) and secondly, to promote further developments on LCA. Heinonen et al. [29] also recently depicted how GWP cannot be used as an indicator for the majority of the environmental impact categories in the context of the embodied emissions in the building and construction sector.

The main contributions of this study to embodied emissions literature in the building sector are two-fold: First, five impact categories are assessed in this analysis. Besides, the results for different materials in different impact categories are clarified, which has been rare. Second, this work performs a comparative analysis focusing on the impacts from the place of material production and transportation, since the vast majority of all construction materials are imported to Iceland, putting a higher emphasis on transport than normal. Iceland has a unique position, considering the fact that it has significant hydro and geothermal resources, which emphasizes the role of imported embodied emissions. The renewable energy system means also that in many cases the local production of materials would reduce the emissions significantly. Domestic building materials are essentially only various types of fill, stone wool (and cement until 2012). The renewable-based energy system is actually the main reason why there has been relatively limited consideration for directives or guidelines for energy use in buildings in comparison to the other Nordic or European countries. Recently, there has been a shift towards a broader view of sustainable buildings in Iceland. The government demanded that all new state buildings need to be certified by BREEAM or other comparable certification schemes. More recently, the Icelandic Green Building Council (IGBC) is intended to explore the potentials of executing DGNB (German Scheme) in Iceland [30,31].

The object of this study was the 20-year-old Vættaskóli-Engi school building in Reykjavik, Iceland. The environmental impact of the materials employed in the school building in terms of GWP, ODP, HT, AP, and EP were assessed with special attention to the transport of imported materials. The impact categories were selected to represent major environmental impacts. In addition, emissions from transportation to the construction site were estimated.

Section 2 presents the general framework of process LCA, while the case building and assessment method are described in Section 3. The assessment results are presented in Section 4, and Section 5 concentrates on the discussion of the results and a review of the uncertainties related to the study.

2. Research Method

The LCA approach to compute environmental effects is exemplified by the International Organization for Standardization (ISO) 14040 series. LCA is characterized as a framework which permits the formation of objective criteria and plans for the environmental impact evaluation of products (e.g., emission), considering the total life cycle (from cradle to grave) of the product. Based on ISO 14040, LCA is specified as the "collection and assessment of the inputs and outputs and the potential environmental impacts of a product or a system during its lifetime".

Eminent documents in this field are ISO 14040:2006 focusing on LCA principles and framework and ISO 14044:2006 with more emphasis on the key requirements and practical guidelines [32,33], which together form essential concepts necessary for developing a procedure to perform an LCA study.

The ISO standards allocate the LCA framework into four steps: goal and scope, inventory analysis, impact assessment and interpretation [33].

- Goal and scope outlines the envisioned application, the motivations for conducting a study, defines the methodological framework to satisfy the intended goals, outlines the boundary of the system and defines impact assessment methodology [33].
- Inventory analysis captures all inputs and all outputs that cross the selected system boundary.
- The Life Cycle Impact Assessment (LCIA) recognizes and estimates the extent and importance of the environmental impacts. Several methods are available [31], of which the most popular include:
    - The CML 2002 LCA Handbook [34], a follow-up of the CML 1992 [35] which defines he best practice for midpoint indicators, based on the ISO 14040 series of Standards.
    - Eco-indicator 99 allows the calculation of single-point eco-indicator score that can support designers in decision-making [36].

  - ○ ReCiPe [37] combines Eco-indicator 99 and CML 2002 methods by integrating midpoint and endpoint approaches in a rational scheme. All impact categories have also been updated excluding ionizing radiation [38].

- Interpretation depicts the results of the inventory analysis and/or impact assessment to reach clear, defensible conclusions.

3. Research Design

The Vættaskóli-Engi school building is located in Reykjavik, Iceland, and it was chosen because (i) it is a typical building representative of the buildings in Iceland in terms of the architecture, construction technology, and basic material use; (ii) this choice enabled us to assess the environmental effects of construction materials as near as possible to the "as built" situation.

The school building has a gross floor area of 5000 square meters. The construction of the building began in 1996 and was commissioned in 1997. The school consists of two main buildings connected with by hallway; one of the main buildings has a basement and two floor levels, the other one is on one level. Foundations, outer walls, floors slabs, and roof slabs of the main buildings are of concrete and also part of the interior walls, though some of the interior walls are of lightweight gypsum. The outer walls are insulated on the outside, partly with the rendering/insulation system and partly with ventilated aluminum cladding. The roofs are built as upside down systems on concrete slabs. The central hallway has an insulated lightweight timber structure which is cladded on the outside with aluminum sheets. Windows and doors are of aluminum, with double glazed insulation glass panes. While the general LCA methodology according to the ISO 14040:2006 standard [33] was described in Section 2, this section defines the methodology used in this study.

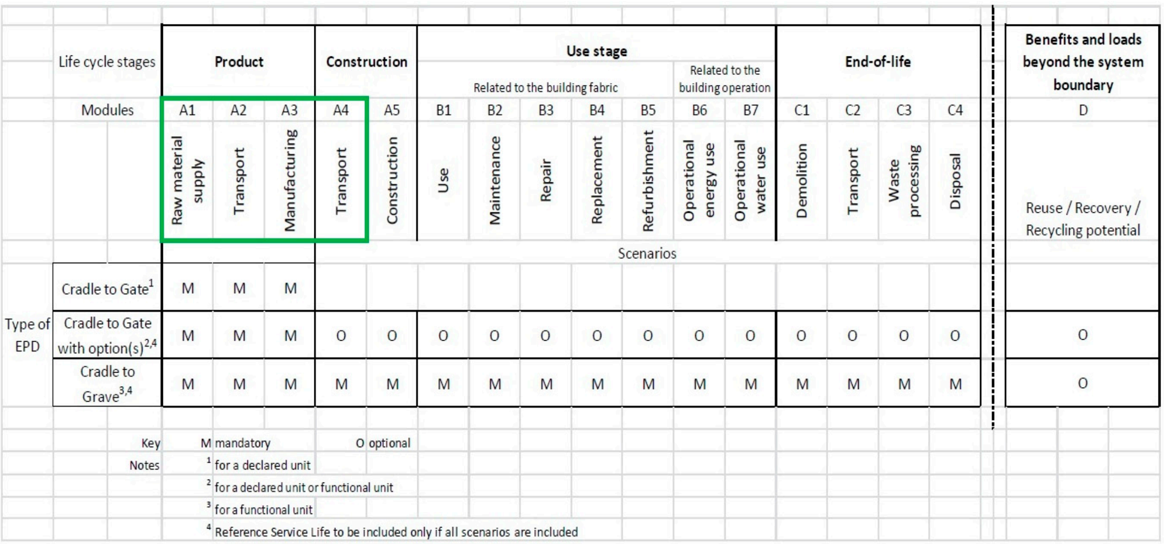
3.1. Goal and Scope Definition

The main objective of this study was to examine the environmental impacts of materials used (including the manufacturing and transportation) in the structure and envelope of the school building located in Reykjavik, Iceland. To account for major environmental concerns, a set of five impact categories were evaluated: global warming potential (GWP), ozone depletion potential (ODP), human toxicity (HT), acidification (AP), and eutrophication (EP). While there is a clear benefit from reporting the non-renewable energy use, due to lack of information regarding the use of non-renewable energies used for the production of imported materials, the impacts on non-renewable energy sources are not reported in this study. Two functional units were utilized: the entire school building and one square meter gross floor area of the school building.

The European Commission suggested the International Reference Life Cycle Data System (ILCD) as the official modelling guideline. Thus, the impact categories were assessed using the ILCD method, which is fully described in the Life Cycle Assessment handbook [39] and International Reference Life Cycle Data System (ILCD) handbook [40].

3.2. System Boundaries

Figure 1 illustrates the life cycle stages defined in the standard EN 15804 [41] and the green line shows the system boundary of this study which includes four modules of A1–A4: extraction of raw materials (A1); delivery to manufacturing site (A2); fabrication of construction materials (A3); and transportation to the construction site (A4), and thus all the embodied emissions except for from the construction site activities. The analysis covered the materials utilized in the structure and the envelope of the school building (foundation, beams and columns, floor slabs, exterior and interior walls, roofs, windows, and paint). Surface materials, fixture, fittings, stone filling material in the foundation, electrical and heating systems, and plumbing were excluded from this analysis. It should be noted that due to the scope of the study being cradle-to-grave (A1–A4), the lifespans of different materials and items are not entered in the assessment in the way they do in assessments over the whole life cycle of a building.



	Life cycle stages	Product			Construction		Use stage							End-of-life				Benefits and loads beyond the system boundary
							Related to the building fabric					Related to the building operation						
	Modules	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
		Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	Reuse / Recovery / Recycling potential
					Scenarios													
Type of EPD	Cradle to Gate[1]	M	M	M														
	Cradle to Gate with option(s)[2,4]	M	M	M	O	O	O	O	O	O	O	O	O	O	O	O	O	O
	Cradle to Grave[3,4]	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	O

Key M mandatory O optional

Notes [1] for a declared unit

[2] for a declared unit or functional unit

[3] for a functional unit

[4] Reference Service Life to be included only if all scenarios are included

Figure 1. Life cycle stages according to the standard EN 15804 and boundary setting of this study.

3.3. *Inventory*

Currently, about 95% of buildings in Iceland are built of reinforced concrete. Cement as the central component of concrete was locally produced until 2012, whereas gravel and sand are available in abundance in Iceland. Besides, stone wool insulation is produced in Iceland, while nearly 79% of the required raw materials by weight are domestic, and the needed electricity is almost entirely generated by hydropower. Other building materials such as lumber, reinforcing steel, metal claddings, structural steel, aluminum window frames, window glass, raw materials for paints, as well as electrical and plumbing materials are imported from different European countries, China, Canada, and the US.

The life-cycle inventory data for analysis were taken from various sources, including the tender documents, drawings, descriptions, and quantity estimates. Table 1 presents a list of materials within the study scope, with the details of the estimated amount and information regarding where the materials are produced. The total weight of building materials for the scope of the school building was around 1.3 tons per one square meter of gross floor area. As expected, the biggest part was due to concrete, which represents 85% of the total weight of the building.

Table 1. Inventory data for building materials used in the school based on the tender documents.

Building Materials	Quantities	Unit	Density (kg/m^3)	Export Country
Reinforcing steel	175,000.0	kg		Lithuania
Reinforcing mat	17,197.8	kg		Lithuania
Concrete	2505.0	m^3	2278	Iceland
Glued laminated timber	15.42	m^3	515	Norway
Corrugated steel cladding	2820	m^2	7850	Finland
Insulation, hard pressed stone wool	12.3	m^3	100	Iceland
Insulation, hard pressed stone wool	306.8	m^3	80	Iceland
Insulation lightweight stone wool	234.4	m^3	32	Iceland
Polyethylene, high density	575	m^2	950	Germany
Gypsum plaster board	8908.0	m^2	800	Denmark
Aluminum window	625	m^2		Germany

Table 1. *Cont.*

Building Materials	Quantities	Unit	Density (kg/m^3)	Export Country
Expanded Polystyrene	210.0	m^2	25	Germany
Extruded polystyrene	400.5	m^3	32	Germany
Underroof membrane	2670.0	m^2		Germany
Plywood board	13.4	m^3	575	Finland
Built-up asphalt	3845.0	m^2		Denmark
Concrete roofing tile	131.8	m^3	2100	Iceland
Plaster	148.6	m^3	2000	Iceland
Paint	2.1	m^3	1350	Norway

The widely used LCA program GaBi 6.0 was utilized in the study. For most materials, the processes available in GaBi were utilized, but for locally produced materials, concrete and stone wool, new inventories were done with local data. Tables 2 and 3 present the inventory data for concrete and stone wool production in Iceland, respectively.

Table 2. Inventory data and embodied energy for 1 kg concrete production in Iceland—source: [42].

Flow	Amount	Unit	Embodied Energy (MJ/kg)
Cement (CEM I 32.5)	0.1334	kg	3.4
Sand	0.3781	kg	0.0379
Gravel	0.4092	kg	0.0422
Concrete admixtures-plasticizer	0.0013	Kg	30
Water	0.0780	Kg	-
Electricity (Hydropower)	8.90×10^{-6}	MJ	8.90×10^{-6}

Icelandic stone wool is mainly made of local basalt sand and crushed sea shells (for CaO), including the insignificant volume of dust binding oil and other elements. The inventory data for the production of 1 kg of stone wool in Iceland are presented in Table 3 from [43]. Based on the collected information and similar to concrete, a separate module was developed in GaBi.

Table 3. Inventory data for 1 kg stone wool production in Iceland—source: [43].

Flow	Amount	Unit
Electricity [hydro power]	7.92	MJ
Gravel (2/32) [Minerals]	0.82	kg
Sea shell sand	0.22	kg
Olivine [Non-renewable resources]	0.10	kg
Aluminum oxide (alumina) [Inorganic intermediate products]	0.05	kg
Phenol (hydroxyl benzene) [Organic intermediate products]	0.05	kg
Three-Layer panels [Parts from renewable materials] (Package)	0.04	kg
Plastic profile [Plastics] (Package)	0.015	kg
Urea formaldehyde resin in-situ foam [Plastics]	0.008	kg
Ammonia [Inorganic intermediate products]	0.007	kg

3.4. Impact Assessment

The GaBi LCA program was used to estimate environmental impacts from construction materials. In this software, the impact factors are estimated based on models that are developed according to ILCD recommendations. In an earlier study, the authors developed two models in GaBi 6.0 for the production of concrete and stone wool in Iceland. For further information on the developed model, please read [44]. The impact factors for the rest of construction materials are obtained from GaBi's databases, except for aluminum windows, reinforcing steel, and alkyd paint where the information from the database in SimaPro was used. Both of these databases are compliant with ILCD recommendations.

Regarding environmental impacts from transportation needed from the source country to Iceland and from seaport to the construction site (the standard EN 15804 phase A4), Breiðfjörð [45] have estimated the GWP impact from containerships to be 0.0327 kg of CO_2 eq/ton·km, while the value in GaBi 6.0 is 0.0143 kg CO_2 eq/ton·km. It means that GHG emissions are more than double, which is due to the effect of heavy wind, big waves, and generally the difficulty of shipping route to Iceland. Therefore, it was decided to use the modified emission factor for the GWP impact from containership in Iceland. In order to modify the emission factors for other impact categories reported in GaBi, these factors are multiplied by the same ratio (2.28), which represents the difficulty of shipping to Iceland.

4. Results

The GHG emissions within the scope of the study of the school building were estimated at 1275 tons of CO_2 eq for the whole building, meaning 255 kg CO_2 eq/m^2 gross floor area. Overseas transportation, despite the long distances, was only responsible for around 5% of the emissions. However, the past situation of cement being locally produced reduces especially the GHGs by 14.5 kg CO_2 eq/m^2 (depending on the import assumption) in comparison to the current state of its being imported. The emissions in the other impact categories are reported below. Within some of them, transportation has a very significant impact even without cement imports, but since the impacts are not normalized, the interpretation should be carried out carefully. Of the locally produced materials, the nearly carbon-free electricity system significantly benefits rock wool, but not concrete due to the limited amount of electricity used in cement and concrete production.

4.1. Overall Environmental Impacts

Table 4 indicates the overall environmental impacts and per one square meter of gross floor area impact of construction materials utilized for the structure of the school building on GWP, ODP, HT, AP, and EP.

Table 4. The results of total environmental impacts and per one sqm gross floor area impact of the school building by impact categories.

Impacts Categories	Total Impacts	Total Impacts per One Sqm
Global warming potential (GWP)	1275 ton CO_2 eq	255 kgCO_2 eq
Ozone depletion potential (ODP)	6.80×10^{-3} kg CFC 11 eq	1.36×10^{-6} kg CFC 11 eq
Human toxicity (HT)	0.16 CTUh	3.23×10^{-5} CTUh
Acidification (AP)	4.44 kmol of H^+ eq	0.88 Mole of H^+ eq
Eutrophication (EP)	11.44 kmol of N eq	2.28 Mole of N eq

The contributions of construction materials to environmental impacts including GWP, ODP, HT, AP, and EP are compared in Figure 2. These show interesting differences, and depict how use of several materials must be concentrated to reduce the impacts through all the categories.

Concrete, reinforcing steel, and aluminum windows represent 51%, 21%, and 9% of total GWP impact from school building, respectively. It should be noted that cement is one of the main component of concrete, and it represents over 95% of total CO_2 emission from concrete. Reinforcing steel is the major contributor for ODP, HT, AP, and AP impacts, accounting for 34%, 30%, 35%, and 33% of total ODP, HT, AP, and AP impacts, respectively. Regarding the ODP impact, the contribution of concrete seems to be negligible. However, when comparing the ODP intensities between GaBi and SimaPro databases, it appears that the impact factors per 1 kg of concrete in GaBi and SimaPro are significantly different, 1.74×10^{-12} and 3.71×10^{-9}, respectively. The reasons for the difference should be studied further, however, to draw further conclusions.

Table 5 below presents the estimated environmental impacts based on the developed model for 1 kg of concrete and 1 kg of stone wool which are produced in Iceland. It should be noted that the scope of these models includes A1–A3 modules.

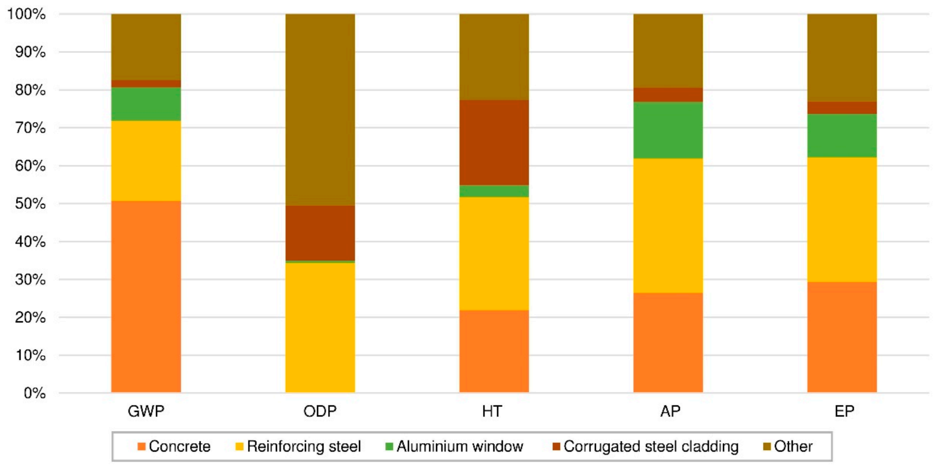


Figure 2. Total environmental impacts for modules A1–A4 by construction materials used in the school building. (The group of "Other" includes paint, plywood board, underroof membrane, glulam, stone wool, HDPE, plaster, EPS, and XPS.)

Table 5. Total environmental impacts from concrete and stone wool produced in Iceland.

	GWP (kg CO_2 eq.)	ODP (kg CFC 11 eq.)	HT (Mole of H^+ eq.)	AP (CTUh)	EP (Mole of N eq.)
1 kg of Concrete	1.13×10^{-1}	1.74×10^{-12}	6.12×10^{-9}	2.03×10^{-4}	5.74×10^{-4}
1 kg of Stone wool	4.33×10^{-1}	1.33×10^{-11}	5.34×10^{-8}	1.05×10^{-3}	3.45×10^{-3}

To validate the GWP impact estimates for stone wool, Figure 3 illustrates the comparison between the calculated GWP impact of 1 kg of stone wool produced in Iceland, with the findings for UK (obtained from [46]), Average EU (estimated by experts at Steinull company [47]), and Germany (obtained from GaBi 6.0 database [48]). According of Figure 3, the GWP impact of stone wool produced in Iceland (0.433 kg CO_2 eq) is much lower (around 41%) compared to the EU average. This difference was due to the significant use of environmentally friendly hydropower electricity in the stone wool production process in Iceland, compared to the average for the EU, UK, and Germany. The overall impact of the locally produced stone wool in the building studied was low, however. According to our estimates, stone wool accounted for 1.18%, 0.01%, 1.18%, 0.88%, and 1.20% of total GWP, ODP, HT, AP, and AP impacts, respectively.

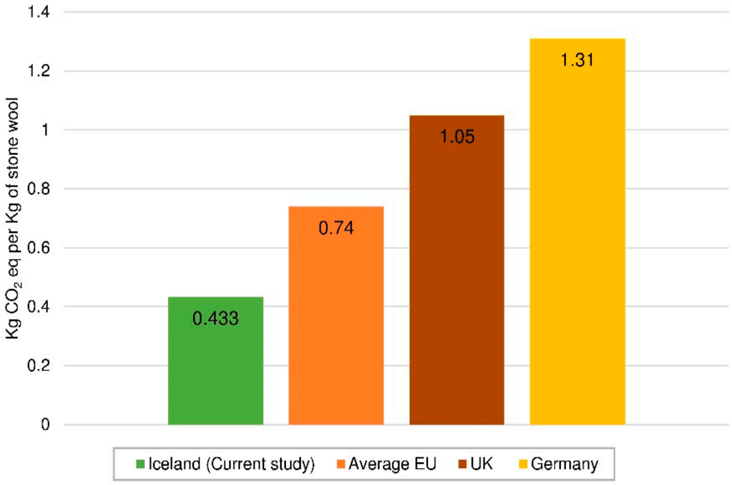


Figure 3. Comparison of GWP impact per 1 kg of stone wool.

4.2. Transportation

According to our assessment, transportation was responsible for 25% and 31% of the total AP and EP impacts, respectively, while the impact of transportation on other impact categories were relatively small (5% or less). Only a one-way trip was included as the vessel needs to be used for exports from Iceland on the route back. To better understand the benefits of domestic construction materials in Iceland and also to capture the impact of transportation on selected environmental categories, two cases were compared for concrete production. In the base case, the cement was produced in Iceland and in the second case, it was imported from Germany.

Figure 4 demonstrates that producing the cement in Iceland caused less environmental impacts in all five impact categories compared to the case in which the cement is imported from Germany. The total environmental impacts of the Vættaskóli-Engi school would increase by 5.7% and 2.5% in terms of GWP and HT, subsequently, if concrete was imported, while there would be no significant changes in terms of the ODP impact. Moreover, a substantial rise (more than 50%) was noticeable in terms of overall AP and EP. The additional impacts were all due to the transportation of cement, while other ingredients for concrete were domestic.

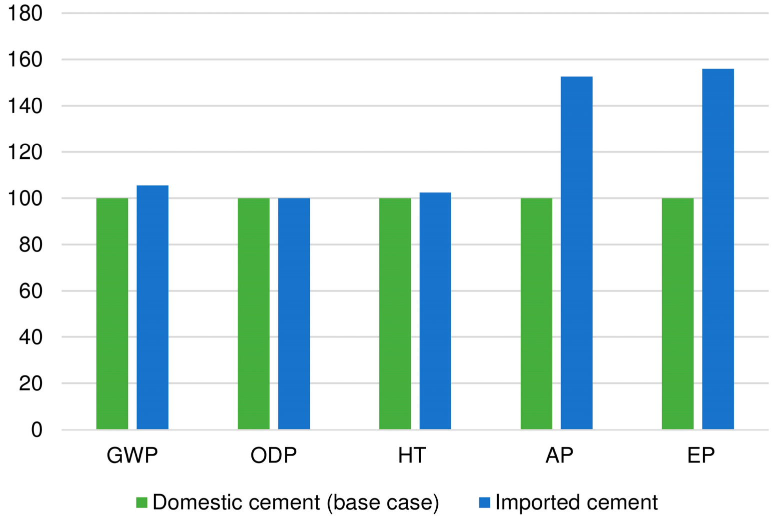


Figure 4. Normalized comparison of the total environmental impacts from two cases for concrete production; Base = 100 for cement produced in Iceland, Imported cement: cement imported from Germany.

4.3. Inter-Study Comparison of the GWP Impact Assessment

In order to compare the findings and position the study among the previous literature, the estimated GWP impact per one square meter of gross floor area from A1–A4 modules was compared with selected previous studies (Figure 5). It is challenging to compare one LCA study to another, even when a similar process LCA approach is adopted, mainly because of inherent boundary issues with LCA studies. Thus, the system boundaries of previous studies are briefly discussed here. A decision to limit the comparison analysis to the GWP category was made to bring up the main issues, which then apply very similarly to other categories. It has been depicted by Herrmann and Moltesen [49] that even the most widely utilized LCA software can lead to different outcomes, but studying this uncertainty was out of reach in this study, and the general uncertainties are still the same.

Figure 5, compares GWP impacts of the Vættaskóli-Engi school building per square meter of gross floor area with similar LCA studies. The impacts were grouped based on construction materials and modules as defined in EN 15804 [41]. As depicted by the figure, the estimated GWP per one square meter of Vættaskóli-Engi school building was about 54%–83% of the others, but similar to the impacts from "A1–A3 (Concrete)" and "A1–A3 (Steel)" together. This, to a large extent, depicts the different boundaries regarding the category "A1–A3 (Other)". The difference points out that the scope of this work is limited compared to the other case studies.

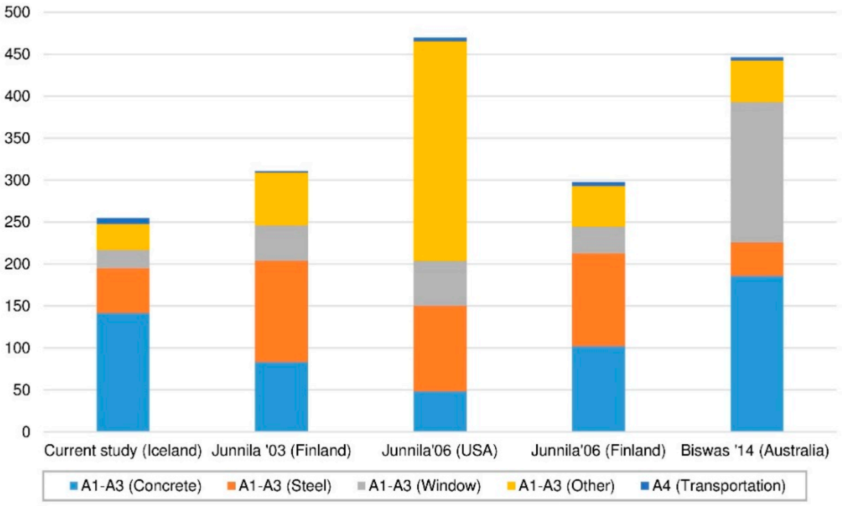


Figure 5. Compares the GWP impact of the Vættaskóli-Engi school building per square meter of gross floor area with similar LCA studies. The impacts are grouped based on construction materials and modules as defined in EN 15804.

In all cases, concrete and steel accounted for a significant share of total GWP, ranging from 10% to 56% for concrete and 9% to 39% for steel. This is also fully consistent with the finding of [29] that materials that are in terms of weight considered unimportant, those often left outside the assessment scopes, can have significant overall impact even in the GWP category, and much more so in other categories. If estimating according to the results of Heinonen et al. [29], the magnitude of the cutoffs in this study due to the boundary selection was 20%–25% in GWP. It is thus important to interpret the results correctly and to compare the overall levels of the results in different categories to studies with wider scopes. Another observation was that the contribution of steel in the GWP impact was higher than concrete in [50,51], while it was significantly lower in the Biswas' work [52] and the current study. Since the buildings assessed in [50,51] have four and five floors, and considering the dominance of steel in multi-story buildings [53], as expected, the contribution of steel on the GWP impact was higher than in the current study.

In process LCAs, such as this study, another important uncertainty perspective is brought about by the inherent truncation error related to the comprehensiveness of the processes included to the LCA databases [54,55]. The processes are almost always imperfect, truncated, and the capital requirements often fully or partially not included. According to [56], the other main LCA approach, the input-output (IO) LCA, can often lead to 10s of percentages higher calculations because of this type of an error (or bias), not affecting IO LCAs. The magnitude of the truncation error cannot be easily quantified in a particular study, but it is obvious that the highest per m^2 embodied emissions in building LCAs have been suggested in IO LCA studies [7,57,58]. This issue thus further highlights the importance of the one interpreting and using LCA results to require both LCA knowledge and knowledge about the particular study at hand.

Finally, of the aspects included in this validation analysis, several choices within an LCA about recycling rates, end of life treatment of materials, and other issues can lead to important differences. Recycling potential in the end of life can be counted as a credit even affecting the results significantly. The carbon sink capability of wooden products can be calculated as well as the carbonization of concrete, again affecting the results and making comparisons of different studies difficult without detailed knowledge about LCA and the studies to be compared.

5. Discussion and Conclusions

The purpose of this study was to measure the environmental impacts from construction materials used in the Vættaskóli-Engi school building, focusing on the influence of the source of materials (locally produced vs. imported). The contributions of the study to the building pre-use LCA literature are twofold: First, this study includes the five most widely utilized impact categories of GWP, ODP, HT, AP, and EP. Furthermore, the results are reported for different materials in the different impact categories. Thus the current study provides a point of reference on that level for future studies. The second contribution relates to two special conditions in Iceland: the high import rate of construction materials increases the importance of transport; the energy system in Iceland being fully based on renewable energy emphasizes the role of emissions embodied in the construction materials. Under these conditions, local production of materials could be a powerful measure to decrease the emissions significantly.

The scope of the study covers four pre-use phase modules of A1–A4 as designated in the standard EN 15804. Total impacts from the materials employed in the building for the selected scope of the study in terms of GWP, ODP, HT, AP, and EP were estimated to be 1275 ton CO_2 eq, 0.0068 kg CFC 11 eq, 0.16 CTUh, 4.44 kmol of H^+ eq, 11.44 kmol of N eq, respectively; which were calculated per square meter of gross floor area 255 $kgCO_2$ eq/sqm, 1.36×10^{-6} kg CFC 11 eq/sqm, 3.23×10^{-5} CTUh/sqm, 0.88 Mole of H^+ eq/sqm, and 2.28 Mole of N eq/sqm. As anticipated, concrete, reinforcing steel and aluminum windows were the main contributors and in total were responsible for 35%–81% of the overall assessed impacts. Based on the results of environmental assessment, reducing the usage of concrete and reinforcing steel would have high-yield results for the building's overall environmental impacts. The impact of transport was found to be the cause of only 5% of total GWP despite the very long transport distances, but gave a much higher impact for AP and EP. However, local production would still provide benefits in both transportation-related impacts and, due to the Icelandic low-carbon energy system, impacts currently outsourced to other countries, where the materials' production take place. Based on inter-study comparison in Figure 5, the results of this study are somewhat below those of the comparison cases, but similar in terms of concrete and steel, which corresponds to the limited system boundary of this study. Based on the estimated GWP impacts in [50,51], which have assessed multi-story buildings, and considering the dominance of steel in multi-story buildings [53], it was observed that higher use of steel in the structure of the building can significantly increase the overall GWP impacts of the building. Meanwhile, the ODP impact from concrete was found to be insignificant.

A significant difference was observed when comparing the ODP intensities between GaBi and SimaPro databases and further studies are required to draw further conclusions. Overall, the potential inconsistencies across the database information for the impacts of construction materials in different LCA tools would merit supplementary examination.

Considering the fact that most of the construction materials are imported to Iceland, a comparative analysis was done to assess the benefits of domestic construction materials in Iceland. As expected, it was concluded that producing the cement in Iceland caused less environmental impacts in all five impact categories compared to the case in which the cement is imported from Germany. If the concrete was imported, total environmental impacts of the school would rise by 5.7% and 2.5% in terms of GWP and HT, while there would be no significant differences in terms of ODP impact. Also, a considerable rise (more than 50%) in terms of overall AP and EP would be expected. The additional impacts are all due to the transportation of cement to Iceland for concrete production.

Although this examination was carefully arranged, there are uncertainties associated with this study. First of all, it should be noted that, according to the boundary of the system defined for this study, only the environmental impacts of four modules (A1–A4) as described in the standard EN 15804 are assessed of the whole life cycle. To interpret the results, it should be considered that, surface materials, electric systems, and plumbing as well as the emissions from the manufacturing work, operation and end of life are not calculated in this analysis. AS mentioned, if assessed according to the cutoff estimations of [29] for GWP impact, the cutoff is 20%–25%, but at least as important in other categories and up to 50% in HT. This draws attention to the correct interpretation of LCA results. In addition, considering the scope of the study (A1–A4), the lifespans of materials and components do not affect the assessment in the way they do in assessments over the whole life cycle of a building. Comparisons between different buildings among assessments limited to our scope could result in biased results if in some buildings materials with low initial impacts but short lifespans would dominate and in others materials with high initial impacts but long lifespans Utilization the results of a certain study should take into account the scope limitations, and even more so the utilized LCA method, as it is obvious that IO LCAs return significantly higher estimates than process LCAs [59].

Despite the recognized limitation in the developed model, this analysis has provided valuable insights regarding the embodied impacts of construction materials utilized in the structure of the school building. The identification of major contributors to each impact category is the first step to detect the most effective mitigation measure. In the following stage of this research, the data collection phase will be extended to enhance the accuracy of inventory dataset and minimize the uncertainty from imprecise input parameters.

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