Improving Energy Consumption in Building Products using Life Cycle Assessment and Energy Analysis

Reza Norouzalizadeh Ghoochani, Mahyar Habibi Rad

Abstract: Modern building products have the potentials to save energy and improve environmental impacts in comparison to conventional products. However, in order to reduce of the energy and environmental impacts of any building product, its materials and energy consumption must be evaluated over its entire life cycle. This study analyzed the energy consumption associated with the total life cycle of the building products. It reviewed the literatures and information provided in existing life cycle assessment studies and reports to develop a comprehensive analysis of the life cycle energy for the building products. The analysis comprised three main phases: manufacturing, transportation, and operation. The results confirmed that the life cycle energy analysis could assign the useful metrics for equal comparison the products types and reduced uncertainty throughout quantifying the energy consumption and environmental impacts of the entire life cycle of the building products. Moreover, the life cycle energy analysis provided the facility of continuing improvements to efficiency and operating lifetime of the building products.

Keywords: Life cycle energy analysis; building materials and products

I. INTRODUCTION

Buildings have an important role in use of worldwide energy. Buildings are the largest energy-consuming sector in the world, and account for over one-third of total final energy consumption and an equally important source of carbon dioxide emissions [1]. The building sectors have substantial affects over consumption of natural resources and related environmental impacts. A building uses energy throughout its life from construction to demolition. The demand for energy in buildings in their life cycle is divided two parts: Energy for construction, operation, renovation, and demolition and energy for production of materials used in construction and technical installations [2].

The life cycle assessment (LCA) methods have been used to assess product development processes and environmental evaluation of products in the industries for many years [3, 4]. The LCA studies have focused on the quantification of used energy and materials, and wastes released into the environment throughout the life cycle [5]. Moreover, the LCA has been applied to the building sectors for recent years [6, 7].

The LCA was developed as an environmental assessment tool for green building design in the building sectors [8], due to the LCA applies a comprehensive approach to environmental evaluation.

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Reza Norouzalizadeh Ghoochani, Department of Civil Engineering, Islamic Azad University, U.A.E. Branch, Dubai, United Arab Emirates.

Mahyar Habibi Rad, Department of Civil Engineering, K.N. Toosi University of Technology, Tehran, Iran.

Into building construction and helps to decision makers to select environmentally preferable products, as well as to evaluate and optimize construction processes [9]. With the current push toward sustainable construction, the LCA gained importance as an objective method to evaluate the environmental impact of construction practices [10]. The LCA was used as a powerful tool for the evaluation of environmental impacts of buildings. It had the potential to make a strong contribution to the goal of sustainable development [11]. It brings the benefits to review sustainability initiatives throughout the entire life cycle of the building, including the design, detailing, delivery and deconstruction phases [12].

In addition to the LCA, there were other approaches to assess the environmental impacts of buildings. The life cycle energy analysis (LCEA) was an approach to account all energy inputs to a product, not only energy inputs during manufacturing, but also all energy inputs needed to produce components, materials and services during the manufacturing process [13].

The review of studies showed that the LCA was used for low energy buildings that were designed and constructed using low energy products. There were very few studies on the LCEA and quantifying the energy consumption and environmental impacts of the entire life cycle of the building products. This has provided the basis for this study. The rest of the paper is organized as follows: The next section overviews in brief the necessity of solving the problem. Section 3 presents definitions and general information of the LCA. Section 4 demonstrates the LCEA and the proposed procedure. Section 5 highlights the features of applying the LCEA through the proposed procedure and discusses the results. Section 6 concludes.

II. Energy intensive building products in Iran

The energy consumption in building sector is almost 40% and to produce the building products is 5% of the total energy of final energy consumption. Thus, the production of building materials and products accounts for 25% of the total energy embedded in the buildings sector in Iran [14]. However, the useful lifetime most of building products is too short and estimated to be less than 35 years in Iran. There is a lack of accurate and standard method to assess properly energy consumption and environmental impacts of building products.

III. Life cycle assessment

The LCA was defined as a method to analyze systematically environmental impacts of a product, process, or system over their entire life cycle, including raw material

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extraction, manufacturing, transportation and distribution, use, reuse, maintenance, and end-of-life (EOL) disposal and recycling [15, 16, 17].

The International Organization for Standardization (ISO) presented an environmental management standard in the 1990s as a part of its 14,000 standards series, with the 14040 series focusing on establishing methodologies for LCA [18]. A major figure of the ISO standard was included four distinct analytical phases for conducting LCA analyses: defining the goal, scope and boundary, creating and analysis the life cycle inventory, assessing the life cycle impact and finally interpreting the results (Figure 1).

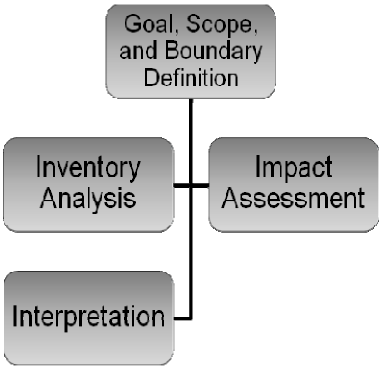

Figure 1. The LCA phases based on ISO 14040.

The ISO 14040 defined LCA as a technique for assessing the environmental aspects and potential impacts associated with a product, by compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts; and interpreting the results of the inventory analysis and impact assessment phases [11]. The LCA characterized and quantified the inputs, outputs, and environmental impacts of a specific product or system at each life cycle stage [18]. The similar approaches consist of the four-stage frameworks were presented by other international organizations [10]. The International reference life cycle data system (ILCD) presented the handbook and the data network to provide the governments and the businesses with a basis for assuring quality and consistency of life cycle data, methods and assessments [19]. Some of useful definitions of LCA was summarized in table 1.

Table 1. Definitions of LCA based on ISO 14040.

Acronym	Concept	Definition
LCA	Life cycle assessment	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of the product system throughout its life cycle
LCI	Life cycle inventory analysis	Phase of life cycle assessment involving data collection and calculations to quantify of inputs and outputs for the product system throughout its life cycle
LCIA	Life cycle impact assessment	Phase of life cycle assessment in order to recognizing and evaluating the magnitude and significance of the potential environmental impacts for the product system throughout the life cycle of the products
-	Life cycle interpretation	Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations
LCEA	life cycle energy analysis	In order to demonstrate energy saving potential, as well as the importance in continued improvements to efficiency and lifetime, life cycle energy estimates are provided for future products.

3.1. Defining the goal, scope and boundary of LCA

Defining the goal of the LCA study was depended on establishing the purpose and audience and describing the intended use of the results. Potential goals might include determining the energy saving and environmental impacts in life cycle of the products or process, identifying opportunities to improve the existing system, or comparing different systems and their potential impacts.

The scope determined which product system or process should be analyzed, the unit processes evaluated, functional unit, system boundaries, allocation procedures, impact categories, data requirements, limitations, and quality criteria for inventory data. Definitions for these terms were provided in the ISO 14040 guidelines [18].

3.2. Inventory Analysis

The phase of life cycle inventory (LCI) analysis involved data collection and calculation procedures to compilation and quantifies relevant inputs and outputs of the product system(s). Data for each unit process within the product systems boundary often included energy, raw material, products, co-products, and waste and emissions to air, water,

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and soil. The LCI then involved determining the energy consumption required to complete this unit process.

The general life cycle phases of a product or system were grouped into four main phases. These included raw materials extract and processing, manufacturing and assembly, installation and operation, and end-of-life. Transportation was often included between each phase. The LCI dealt with the collection and synthesis of information on materials and energy flows in various phases of the products life cycle (Figure 2).

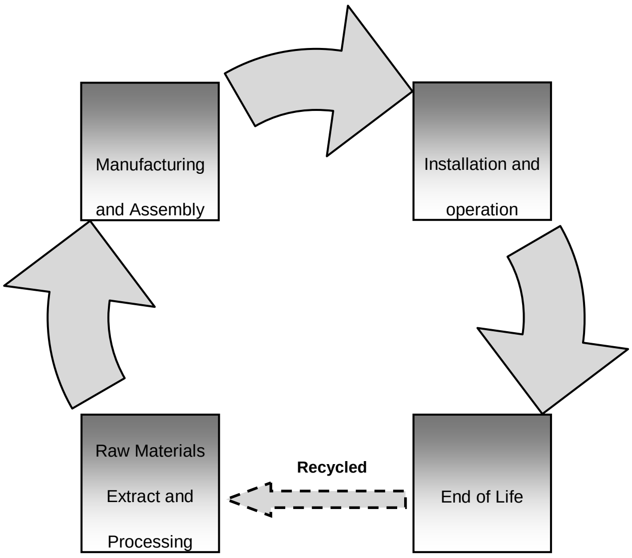

Figure 2. Life cycle of a product.

3.3. Impact Assessment

The energy consumption, environmental impacts such as emissions, and other waste products at each life cycle phase were the results from the LCI analysis. The LCI results focused on quantifying the different environmental flows of the product system. The impacts were the downstream effects of the flows, such as the health effects caused by the inhalation of emissions and so on. A life cycle impact assessment (LCIA) could be conducted using these results.

In the LCIA, the environmental impacts of various material and energy flows were assigned to different categories including global warming potential (GWP), natural resources depletion, ozone depletion, photochemical ozone formation, eutrophication, acidification, human toxicity, aquatic toxicity and land use.

3.4. Interpretation

The final phase of life cycle assessment was interpretation of results from both LCI and LCIA. This dealt with drawing conclusions and making recommendations from the inventory analysis, and or impact assessment, or both. Within this phase, several steps to complete the LCA were identified and discussed. These steps were included identification of the significant issues, evaluation the completeness, sensitivity, and consistency of the data, and drawing conclusions and recommendations.

IV. Life Cycle Energy Analysis

Energy consumption was an important component of any LCA study. The majority of data collected for energy assessment of building materials and products were provided from the information in existing LCA studies and reports. Several studies focused on the environmental evaluation of buildings. The efforts of these studies were mostly to enable selection of materials and products by identifying sources of the most significant environmental impacts [6]. Some of LCA based studies was summarized and referred to table 2.

Table 2. Selected LCA studies on building materials and products.

Study	Materials and products	Use	Results
Jonsson et al. (1997) [20]	linoleum, vinyl, solid wood	floor	solid wood was low impact
Mroueh et al. (2001) [21]	bitumen and cement	varies	the most energy consuming through LCA
Junnila and Horvath, (2003) [22]	Steel, concrete, paint	-	steel and concrete were high impact
Guggemos and Horvath, (2005) [23]	Steel, concrete	frame	concrete was low impact than steel
Asif et al. (2007) [24]	wood, aluminum, glass, concrete and ceramic tiles	varies	concrete was high impact
Kofoworola and Gheewala, (2008) [25]	Varies	varies	steel and concrete were high impact
Asdrubali (2009) [26]	thermal and sound insulating materials	varies	impact on lifetime of building

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Douglas and A. Noy, (2011) [27]	new and traditional materials	varies	survey on alternatives
Zabalza et al. (2011) [28]	Bricks, tiles, Insulation materials, Cement, concrete, Wood products, Other	varies	steel was highly energy intensive
Asdrubali et al. (2012) [29]	natural and recycled	varies	survey on acoustical properties
Thiel et al. (2013) [30]	concrete, steel, other	structure	concrete and steel had the largest environmental impacts
Ximenes and Grant (2013) [31]	wood, acoustic insulation, other	floor and sub-floor	wood was low impact

The following procedure was proposed by this study in order to standardize the information provided within the LCEA for the building materials and products:

4.1. Performance and functional unit

It was necessary to determine the functional unit as a metric for equal comparison of energy consumption impacts across the types of the products. The functional unit was defined through LCEA as a quantified measure of performance that served as the basis for comparison when considering the environmental impacts of multiple product types or systems.

Moreover, it could be considered several assumptions to increase the efficiency or output of a typical product as long as some of the features remained constant. While a typical product provides the output less than the desired output value, the LCEA estimates should multiplied by the number of products needed to reach this equivalence.

4.2. Manufacturing Phase

Some of the most difficult and important life cycle phases to characterize were raw material extract and processing, and manufacturing and assembly. These phases could be energy and or emissions intensive; hence, it was difficult to estimate energy and environmental impacts through these phases without providing the information from manufactures.

The manufacturing phase was presented as a product result due to involving in how the LCA studies presented data for this phase and the difficultly in determining the boundaries between material processing and manufacturing.

The LCA studies that considered the impacts other than energy consumption either provided data on global warming potential or disassembled components and their associated masses. Assuming that global warming potential was entirely the result of carbon dioxide (CO2) emissions converted to energy consumption using assumptions on the metric tons of carbon dioxide per unit of energy production.

The majority of the LCA studies focused on the manufacturing of some of products due to concern that the energy consumption during the process might outweigh the energy savings during the installation and operation phase. Determining the manufacturing energy consumption for some of conventional products was fairly straightforward since the majority of previously conducted LCA achieved the studies on these products. However, most of them did not clearly specify which unit processes were included within their manufacturing analysis. It was likely that some estimates were incomplete and only represented energy consumption from material extraction and processing or manufacturing and assembly.

The manufacturing energy consumption for a typical product was usually assumed to be sum of the energy (thermal, electrical, and….) associated with manufacturing the bulk materials plus the energy associated with the manufacture of a single package multiplied by the number of packages of this product.

4.3. Transportation Phase

It was ideal to define the energy impacts associated with transporting a typical product between each life cycle phase. However, traditionally transportation was only considered between the manufacturing and installation phase.

To calculate the energy use due to the transportation phase, first the original manufacturing for each product was characterized. Then, based on the distance of transport, and type of transportation vehicle, and the estimated capacity of that vehicle (in terms of number of products able to be transported), the total transportation energy use, on a per product basis, was calculated. Lastly, the transportation energy was then converted using the functional unit assumptions.

4.4. Installation and Operation phase

The Installation and operation phase of a typical product was associated with the consumption of energy to produce the desirable output throughout its life cycle. The existing LCA studies were utilized for the analysis including estimates for the energy consumption from the types of this product they considered. Using the performance characteristics, the primary energy consumption for each type was calculated per functional unit.

V. Results and Discussion

Until recently, only operating energy was considered to gauge the energy consumption in the buildings. However, due to increasing the advantages of energy efficient equipment and appliances, associated with more advanced and effective insulation materials, the potential for curbing operating energy has increased and as a result, the current

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emphasis has shifted to include embodied energy in building materials and products [32].

The LCA and LCEA could be used as tools to evaluate energy and raw material consumption, and environmental impacts such as CO2 emissions, and other pollutants and wastes related to the entire life cycle of the products or systems applied in buildings. However, there was still the high uncertainty, but the LCEA allowed using information of the existing LCA studies and reports to reduce uncertainty throughout quantifying the energy consumption and environmental impacts.

The data from the previous studies provided for both quantitative and qualitative analysis enabling the development of a comprehensive LCA literature review. While many of the existing LCA studies considered similar products, the goals, scope and boundaries defined for each vary. The greatest variance in assumptions was seen in life cycle phases included, as well as the level of disaggregation provided within each study. In light of these gaps, only three major life cycle phases was considered by this study: manufacturing, transportation, and operation.

5.1. Performance and functional unit

Considering several assumptions throughout the LCEA helped to describe the energy consumption of the products more detailed and accurate than those analyzed in the LCA studies. Moreover, it was possible to describe the life cycle energy consumption of a typical product with higher output performance than those analyzed in the existing LCA studies.

Each of the previous LCA studies considered an array of the products each having different specifications. The LCA studies had the advantages of covering performance over the whole product life and therefore could provide the most comprehensive evaluation [33]. While assessing life cycle energy consumption, it was important that the products be compared on an equivalent basis. The advantage considering of the functional unit through LCEA was that the energy consumption values could be all normalized, thus the different lifetimes of the typical products caused their energy consumption to differ. Moreover, the total desired output was provided using the LCEA estimates for a typical product multiplied by the number of products needed to reach this equivalence.

The functional units employed varied among the studies examined. For example, some of studies considered the consumed energy per usable area and the lifetime of building as the functional unit [34, 22]. However, in order to demonstrate energy saving potential for building products, as well as the importance in continued improvements to efficiency and lifetime, some of important specifications associated with energy consumption in the buildings was proposed for the construction materials and products most used currently in the building sector in Iran (table 3). Each of specifications could be considered as the functional unit to compare the products types. The specific weights and the thermal conductivities were provided from [35] and [36] respectively. The reference of the thermal and electric embodied energy was the standards of ISIRI [37]. The study of Douglas and A. Noy was utilized for the lifetimes [27].

Table 3. Some of building materials and products in Iran.

Material or product	Use	Specific weight, kg/m3	Thermal conductivity, w/c.m	Thermal energy, GJ/t	Electric energy, kWh/t	Lifetime, years
Iron	varies	8770	72	1.0	110	50
Steel	varies	7780	52	0.6	500	50
Cement	Concrete structures	400-2400	0.15-1.75	0.7-1.2	90-135	30-50
Brick	Concrete structures	1000-1900	0.46-0.8	1.9-2	48	20-40
Ply hardwood	varies	800-1000	0.29	2.14	1-2	10
Ply softwood	varies	600-750	0.23	1.9	1-2	6
Ply chips wood	varies	N/A	0.15	0.7	3-5	6
Glass	varies	2700	1.25	1.9	95-110	20-40
Aluminum	varies	2700	203	N/A	13.5	N/A
Chalk	bleaching	1600	0.7	0.9-1	12.0	6
Tile	Covering, facing	-	0.7	2.5-6.9	0.03-0.1	20
Lime	facing	1700	0.9	3.78	N/A	3

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PVC	coating	20-50	0.03-0.035	1.5	254	10-20
Polyester	coating	20-50	0.035-0.04	1.1	114	10-20
Wool stone and glass	coating	20-30	0.04-0.045	N/A	N/A	20-30
Natural stone	Covering, facing	800-3000	2.3-3.0	N/A	N/A	20
Asphalt	Roof covering	1700-2100	0.5-0.7	N/A	N/A	6

Note: kg/m3: kilogram/cubic meter; w/c.m: Watt/meter-Kelvin; GJ/t: Gigajoule/tone; kWh/t: kilowatt hour/tone

The results indicated that the contribution from steel, iron, cement and glass to primary energy demand through manufacturing phase were much than other materials and products needed in the building constructions. However, these materials had the highest lifetime whole life of a building and did not need to be replaced. Moreover, Aluminum, Iron and Steel were the thermal conductors, so could pass thermal energy and caused the energy loss through operation phase in buildings. Wood products were effective thermal insulators and used far less energy to produce than brick, cement or steel. Steel and Iron products needed more insulation to achieve the same thermal performance as wood products.

5.2. Manufacturing Phase

The LCA considered by [22] was included the phases of building materials manufacturing, construction process, use of the building, maintenance, and demolition. The result of this study showed that the most of the impacts related to buildings were associated with materials manufacturing phase. Particularly manufacturing maintenance of steel, concrete and paint were identified as the most significant aspects. However, determining embodied energy and environmental impacts through materials manufacturing was complex and time consuming [38], due to there was a lack of accepted method available to compute embodied energy accurately and consistently and wide inevitable variations in measurements caused the results to differ [39].

The results indicated that the efficiency improvements throughout the LCEA would decrease the energy consumption and environmental impacts of the products and thus potentially decrease the manufacturing energy consumption of the bulk materials and packing of the products.

Considering the energy associated with packages was useful to gauge of the manufacturing energy consumption of the typical products. The packages had incorporate equivalent die areas, thus a typical product that used fewer packages had lower embodied energy consumption compared to other product that used more packages. However, there was great uncertainty due to difference in the assumed number of packages implicated for manufacturing energy use and it depended on the number of packages needed to provide the desired output.

Moreover, the manufacturing energy consumption of a single package was not correlated to the efficiency of a typical product, as long as total die area remain constant. Thus, a package of a lower efficiency product might have the same embodied energy consumption as a higher efficiency product. The advantage of LCEA was that it allowed for the package manufacturing energy estimates from the existing LCA studies to be utilized in characterizing packages, which might have higher efficiencies. Therefore, based on expected increases in product and package efficiencies, it was projected that the average number of packages required to produce the desired output of a typical product would decrease.

Furthermore, the manufacturing energy consumption of the bulk materials to produce a typical product remained constant while the level of desired output did not change. However, changes in the desired output might affect the energy management and caused to a change in design and material use of the product. The LCEA allowed evaluating the typical product that had more average desired output according to the previous LCA studies to calculate the embodied energy of the bulk materials.

5.3. Transportation Phase

The study of [21] showed that the application of LCA could useful to minimize the environmental loads, resource consumption and applied strategies such as recycling and reusing of building materials. Moreover, the production and transport of the materials produced the most significant environmental burdens. Production of the bitumen and cement, crushing of materials and transport of materials were the most energy consuming through the life cycle of the construction.

The results indicated that traditionally the energy impacts of the transportation were defined as the energy associated with transporting a packaged product from the manufacturing facility to the retailers, thus the energy impacts through the transport to and storage in distribution centers before being shipped to the retailers or consumers were not considered.

Moreover, some of the studies analyzed including energy estimates for the transportation phase; all indicated that the contribution from transport was relatively insignificant representing less than one percent of total life cycle consumption. A few studies considered coefficients for transport stage from production plant to building site [28]. However, these studies offered limited data describing how these transportation energy use estimates were derived, and hence provided no way to standardize these estimates for use in the future studies. Therefore, an independent transportation profile was developed for each type of a typical product under accurately analyzing throughout the LCEA.

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5.4. Installation and Operation phase

Some of studies such as [20] emphasized on necessity to assess use phase and end-of-life phase impacts to develop a more comprehensive understanding. The LCA phases considered by [34] was included: manufacturing, transport, erection, occupation, renovation, demolition and removal phase The occupation phase was accounted for about 70–90% of total environmental impact of a building [40], so this study emphasized to choose the building materials and products which had less environmental impact during the occupation phase. Hence, it was important to identify the most used materials and products in the buildings that had the greatest effect on a building's environmental impacts in order to target specific areas to minimize environmental impacts in future construction [30].

Measuring operating energy of buildings was easy and less complicated than determining embodied energy through manufacturing building products [38]. Designing of low energy buildings was achieved by reducing energy of operation phase using energy management technologies. However, reduction this energy was generally associated with decrease in embodied energy issued of energy intensive building materials and products considered in LCEA [10].

The efforts of LCEA studies identified life cycle phases with the highest environmental impacts and provided a basis for overall building system assessment. Most of these studies were related to energy consumption and environmental impacts throughout operation phase of building products [41]. The LCEA application for evaluation of energy consumption and environmental impacts of construction processes and buildings systems involved more than the simple aggregation of individual product and material assessments [7].

The LCEA results confirmed that the energy consumption and environmental impacts of buildings through installation and operation phase could be significantly reduced by better building products aspect of insulation and useful lifetime.

The potential energy from future reuse or recycling of disposed end-of-life materials was not considered by this study.

VI. Conclusions

The production of the building materials and products accounts for over one-fourth of the total energy embedded and an equally carbon dioxide emissions in the building sector in Iran. The environmental impacts of buildings are gradually increasing due to use of energy intensive materials and products. Therefore, there is a necessity to improve the performance of buildings in terms of both embodied and operating energy in order to reduce energy consumption. The embodied energy through manufacturing of building materials and products may outweigh the energy savings during the installation and operation phase.

The results indicated that the “operation” phase represented the most energy intensive life cycle phase, accounting for 70-90 percent of total life cycle energy on average. This was followed by the manufacturing and transport phases. Hence, high performance buildings that use less energy through operation phase, the embodied energy required to raw materials extract and processing, manufacturing and assembly, transportation, and installation building materials and products may make up as much as 30% of the overall life cycle energy consumption.

The LCA framework was flexible to achieve to a broad range of possible outcomes. Hence, the energy results could be presented throughout the existing LCA studies and reports for a wide variety of conditions.

The functional units employed varied among the studies examined, hence some of the important specifications associated with energy consumption was proposed by this study as quantified measures of performance for the construction materials and products most used in the building sectors. These measures could be useful to target specific areas for minimizing energy consumption and environmental impacts in future constructions.

The results indicated that concrete and steel, the majority used for the excavation, foundations and structural parts of buildings, represented the highest environmental impacts. The contribution from steel, iron, cement and glass to primary energy demand through manufacturing phase were much than other materials and products needed in the building constructions. However, these materials had the highest lifetime whole life of building and did not need to be replaced. Wood products were effective thermal insulators and had a lower embodied energy than brick, concrete or steel.

The improvement performance for the building products that was provided through LCEA could be applied as good standards for comparison and show the potential and importance of continuing improvements to efficiency and operating lifetime of the building products.

The most of the uncertainty in life cycle energy consumption was on calculating the embodied energy of conventional products and the manufacturing of the product packages. The recommendations to utilize LCEA and reduce uncertainty throughout the energy calculations could be useful to improve the understanding of the impacts of building materials and products, linking their embodied and operating energy directly to the environmental impacts targets.

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Author Contributions

Reza Norouzalizadeh Ghoochani and Mahyar Habibi Rad conceived and designed the study, analyzed the information, and wrote the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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