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Comparative Life Cycle Analysis of Low Energy-consuming Materials, Case Studies: Concrete, Brick, Wood, System Boundary: Cradle to Gate

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A B S T R A C T

Recent researches all across the world emphasize the threat of the increasing consumption of energy. The undeniable role of energy consumption in all stages of the life cycle of materials, including extraction, factory manufacturing, and transportation has revealed the necessity of using sustainable methods to have lower energy consumed. The whole energy of all different steps of the life cycle is called "embodied energy" and the process of assessing this embodied energy input is called "life cycle assessment" (LCA). Despite the great importance of LCA, the quantitative test of such a hypothesis has been less of a concern for previous researchers in our country Iran, and due to the lack of organized information from industrial units, such a study has also faced the difficulties of data collection. In this regard, this paper evaluates the amount of embodied energy consumption of building materials at different stages of their life cycle. To reach this goal this research evaluates the initial energy quantitatively (including different stages). More precisely, the present study, based on life cycle assessment system, quantitatively evaluates and compares energy input in different stages of cradle to gate scope, in 3 case studies: Concrete, wood, and brick. The results finally show that per ton of concrete produced 110 (kw.h) electrical energy, 35 (ton) of gas, 170 (Mj) of human Energy, and 495 (g) of Gasoline is consumed, while these quantities for per ton of Brick are 35(kw.h), 18.2 (ton), 72 (Mj) and 250 (g) and For one ton of timber produced are 900 (Kw.h), no Gas used, 170 (Mj) and 495 (g).

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INTRODUCTION

One of the vital issues facing the world today is less environmental pollution, less energy consumption, and minimize carbon emissions. Sustainable design in architecture emphasizes three principles: fuel-saving, design based on the life cycle, and design for humanity [1]. Construction itself is not an environmental-friendly process [2] but there are solutions to mitigate this procedure. One of the main approaches is green materials with the least harmful environmental effects extraction, processing, transfer to the site, and utilization in the construction of buildings. These materials should be also efficient in the lifetime of the building. The selection of the building materials has a potential impact on the health of the environment and the health of residents. This choice is always influenced by different factors depending on different conditions (from the micro-scale of the same project to regional, national, and even global policies and restrictions). In recent decades, sustainable architecture and subsequently sustainable design has been raised in response to the conflict between the construction industry and the environment. The sustainable design intends to meet future needs. In the case of buildings, sustainable design refers to resource efficiency, minimal energy consumption, flexibility, and longevity. Although, it does not include the operation time of the building, includes all the steps before operation from extraction to transfer, as mentioned. With a more comprehensive view when

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talking about a building, sustainable development will be affected by all stages of design, construction, equipment, and destruction or reuse. A building is coproduced by materials and compounds which interact with each other. In this comprehensive view of energy consumption, and estimating the correct amount of environmental impact of the building and the materials which are used, the concept of "embodied energy" is introduced as an effective tool. Embodied energy in the construction industry is the sum of the energy used to construct a building [3]. Each building material possesses its latent energy. As a consequence, knowing the embodied energy of each material is very effective in the selection of the type of material to be used in the building. Some of the factors and technologies that are used to achieve a material with more desirable energy consumption are speed and rehabilitation of existing buildings, construction waste management, reducing the disposal of this waste, design with standard dimensions (in such a way that building materials can be reassembled and used elsewhere after its useful life), procurement of building with different functions, design with the potential for residents' reconstruction [4], use of recycled materials, products with maximum recycling capacity, products with a natural base, products that prevent pollution, products that reduce heating and cooling load [5]. Parameters that are frequently raised in building sustainability issues, fall into the realm of "usage phase energy." But in the field of energy, "embodied energy" is so important but unfortunately, its importance is ignored. The construction or reconstruction of today's buildings should be carried out in the perspective that fossil fuels will not be as abundant, cheap, and reliable sources as were in the past. On the other hand, utilizing renewable energy needs costly facilities and equipment. Accordingly, the determination of the correct strategy and decision and an appropriate energy plan for the building is vital to minimize the demand for fossil fuels and costly equipment, in the production, extraction, and operation phases.

Various energy sources consume different kinds of primary energy and cause corresponding environmental impacts [6]. Life cycle assessment (LCA), which uses a cradle to grave approach, is the most reliable method to access the environmental impact of a product process [7]. Some recent studies have stated that Manufacturing cement is the most energy-consuming industries in the world. It is used about 10-15% of industrial energy use. Generally, energy attains 35-45% of production cost in the cement industry [8], Besides this hypothesis seems to need more quantitative investigations. The demand for durable and sustainable concrete is increasing in the construction industry [9], Not only in concrete but also other building materials this issue is considerably considered recently. The present study tries to evaluate the total sum of energy in some stages of the life cycle (extraction-processing and transportation) by providing a quantitative approach. This procedure facilitates analogy and decision making for experts and decision-makers in this field. This holistic aspect as well as providing accurate quantitative data is the first innovation of the forthcoming research compared to previous researches. For this purpose, to increase the accuracy of the comparison between different stages of extraction, processing, and site transportation, the three case studies of high-consumption materials in the northwest of the country, which are as concrete, brick, and wood are considered. Restricting research on these materials is the second innovation of research. Having a correct, up-to-date, and accurate idea of the embodied energy which are the most practical widely used architectural materials in the northwest of the country and the city of Tabriz will be a facilitator to use them in the construction industry and benefit from greener and more sustainable materials. It is worth mentioning that directing the research path towards the executive process of production of each of these materials requires a step-by-step field study in the location of each factory and sites located in the area, considering the entire transportation system, all employed and human power in the production line and considering different energy inputs such as electricity, gas, and gasoline in factories and transportation.

LITERATURE REVIEW

To ensure the necessity of this investigation in Iran, the energy consumption of some countries is briefly mentioned. In Europe, 40% of energy consumption and 36% of co_2 annual emissions are related to construction. Such a large contribution has made storage and energy saving in buildings, an impressive strategy to deal with economic problems and global warming [10]. The intensity of energy consumption in Iran is 9 times greater than that of Japan and Norway, 7 times more than that of developed European countries, 3 times greater than that of Saudi Arabia, and 4 times more than that of Turkey and the world average. Iran, with a population of one percent of the world, consumes more than 4 percent of the world's natural gas. About 40 percent of the country's total gas consumption is consumed by houses. Studies conducted by the Energy Efficiency Organization of Iran (Satba) demonstrate 31% of electricity consumption in households [11]. According to the National Building Regulations Office of Iran, if the consumption process continues in the same way, by 2040 Iran will definitely become a major importer of energy. To identify appropriate approaches to reduce the energy consumption of buildings, energy flow, and its consumption in different stages of the building life cycle and subsequently, building materials, should be competently investigated. A building consumes energy throughout its life from construction to demolition [12]. Building materials in the construction industry have consumed more than half of natural resources by weight so far. The process of construction and demolition produces four times more waste than household waste, which is equivalent to more than one ton per person. The environmental effects of the extraction, processing, transportation, and ultimately the resulting waste of these materials will lead to the emission of greenhouse gases, poisoning, destruction of natural habitats, and erosion of resources [13].

The construction industry consumes the most natural resources, especially through the extraction of construction materials from the earth. Building materials not only use non-renewable natural resources during the process from extraction to destruction, but they will also create a chain of environmental impacts. These impacts will include various environmental aspects on a local and global scale. The most important of them are "air and water pollution, ozone depletion, extinction of plant and animal species, and the release of toxic gases". Environmental impacts, extraction, processing, and transfer of these materials and their waste disposal cause emissions of greenhouse gases and toxic substances, destruction of ecosystems, and natural resources [13].

It can be concluded that building materials will have an impact on the natural and artificial environment during their life cycle. Each material according to its specific characteristics can cause:

a) A reduction in energy consumption
b) Use of environmental energy
c) Less environmental impact
d) Fewer carbon emissions according to product processing and manufacturing, (Including extraction of raw materials and their transfer, processing of products, and Construction on site) and form of use and exploitation [14].

Among all stages of the life cycle, the three stages illustrated in Figure 1 are in more immediate interaction with the pre-construction industry and are a priority over the other stages. On the other hand, comprehensive and complete coverage of all stages (design, planning, demolition, and recycling phases) is very extensive and requires a lot of research, so in this study, three stages mentioned (Factory input, Manufacturing, and transportation to the site) will be investigated and analyzed. In this way, the amount of needed energy consumption in its various forms, including electrical energy, types of fuels, human resources, etc. will be thoroughly considered. Finally, a comparative comparison between the total embodied energies of the studied materials will be carried out.

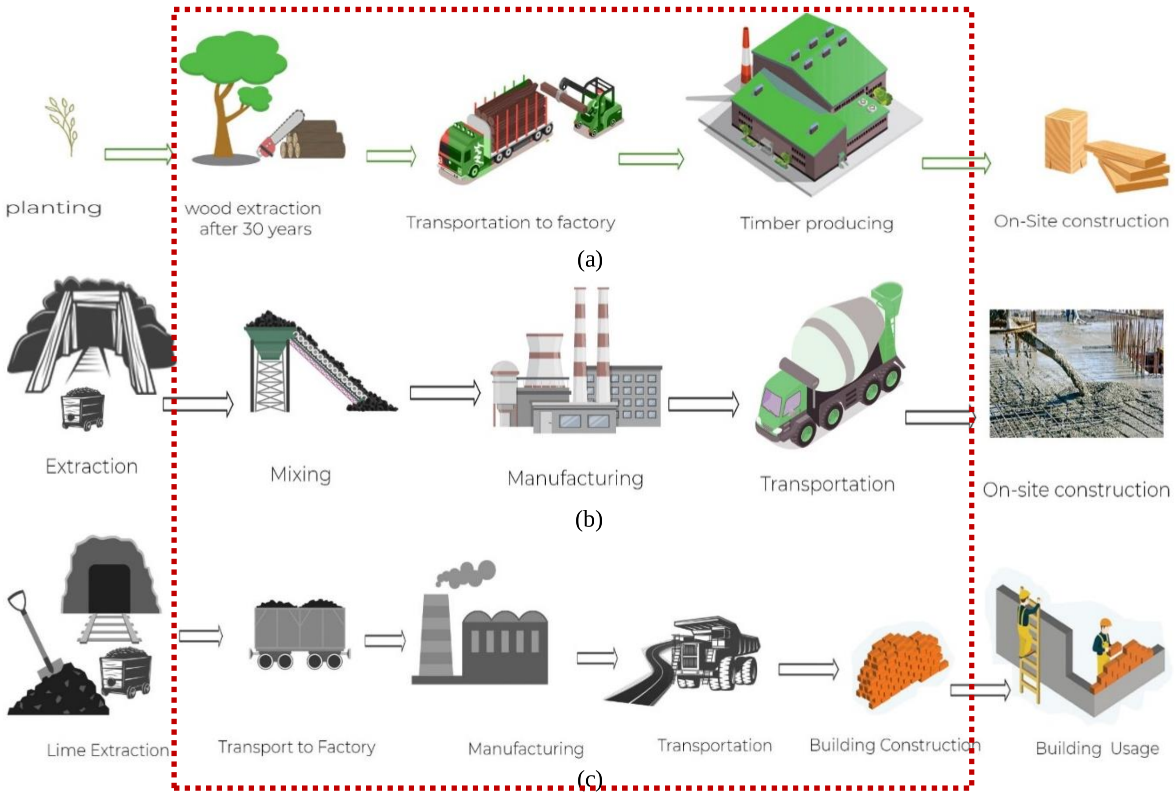

Figure 1. (a) The factory to gate boundary of LCA of wood, (b) The factory to gate boundary of LCA of concrete, (c) The factory to gate boundary of LCA of brick

MATERIALS AND METHODS

As briefly explained earlier, this research is based on a quantitative approach. In this regard, to evaluate the environmental sustainability of different phases of the material life cycle, which are: factory operations, and processing, transportation, are taking into account respectively. This measurement is done in a model called life cycle assessment (LCA). The LCA is a systematic analytical method that helps to identify, evaluate, and minimize the environmental impacts of a specific processor's competing processes. It uses material and energy balances to quantify emissions, resource consumption, and energy use [15]. The LCA is an accurate, new, and appropriate way to measure the environmental impact of a building. This measurement can be done both on the scale of the whole process of construction (WPC), as a whole and can target each building material and component combination (BMCC) separately. Our research would be in the second category as it is monitoring single materials which are concrete, wood, and brick.

According to the Society of Environmental Toxicology and Chemistry (SETAC) definition, LCA is a method of determining the environmental impact of activities by calculating the amount of used material and energy on one hand, and measuring the emissions to the environment, on the other hand, helps identify, prioritize and evaluate the opportunities to improve environmental conditions. In this tool, the building has a continuous nature and includes various stages including production and transportation of materials, construction, operation, repair, and demolition. Therefore, in this method, the amount of environmental effects must be calculated at all stages of the life cycle [16]. In general, there are two methods for assessing the environmental factors of materials in the life cycle. These methods are called process-based" and economic "input-output". Major construction projects are evaluated by the first method, "process-oriented [17]. In this method, according to the project implementation process, different parts are defined for its life cycle. Afterward, their input and output materials are identified and calculated to determine the extent of environmental impact for each sector [18]. The LCA used in this research has been done according to ISO 14040 standard in the form of four stages of goal and scope definition, inventory analysis, impact assessment, and interpretation [17]. In the first phase, i.e. the phase of defining the objectives and scope, the products and operations that needs to be evaluated are defined, later on, the functional unit (in this study, the relevant industrial unit) is selected and the desired level for evaluation is determined [19]. So as it is shown graphically in Figure 1 it is limited to 3 stages of factory energy input, factory human energy analysis, and transportation energy.

It is worth mentioning that in this method, the basis is the calculation of the amount that has been extracted from field studies. Following the research assumptions, the values appropriate to these assumptions have been selected and based on that, the results of this step have been estimated. For all three materials, 3 random factories which produce a considerable cement of the area have been selected and primary information of the number of staff, the input of gas and consumption of electricity have been derived from the Human, Safety, and Environment (HSE) center of each factory. The factories selected are Sofian, Orumieh, and Arta factories. It is assumed that the concrete is produced at the concrete station and transported to the construction site by a mixer. The amount of fuel consumed with heavy types of machinery (trucks, mixers, trains) is estimated according to the standard of transport services [20]. By determining the distance traveled, the fuel consumption of the trucks and trains can be calculated. Fuel consumption is the function/result of distance traveled and fuel efficiency derived from Table 1.The Number of people working in each factory is also determined from field study then according to the equations of World Health Organization (WHO) the standard is transferred to MJ of energy [21] which is shown in Figure 2. To identify the details of the machines required for each stage, such as capacity, horsepower, weight, and other items, the information is collected from the manufacturing factories as well as the field information gathered from the base of each of the on-site and factories.

Calculation of factory energy input

It is a remarkable issue to mention that In Iran according to the abundancy of gas, some other fossil fuel sources of energy as petroleum and coal are not used in most industries (and thus are not considered in analysis) whilst in our neighbor countries as Turkey petroleum and coke are the main energy source in cement factories. The amount of gas used in idustrial units are shown in Figure 3 and the amount of electricity is illustrated in Figure 4.

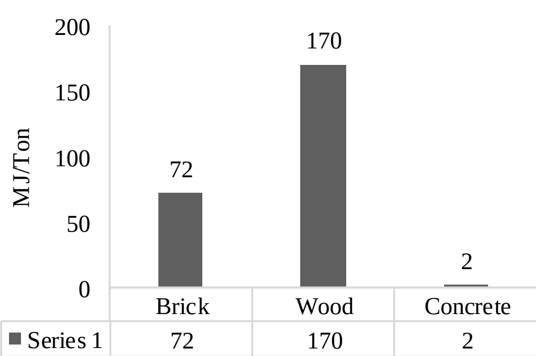

Figure 2. Human energy consumption for each ton of materials

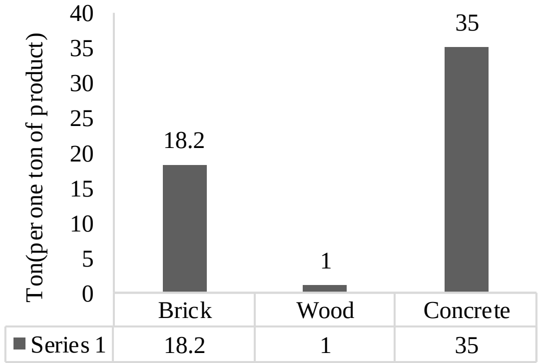

Figure 3. Natural gas energy input

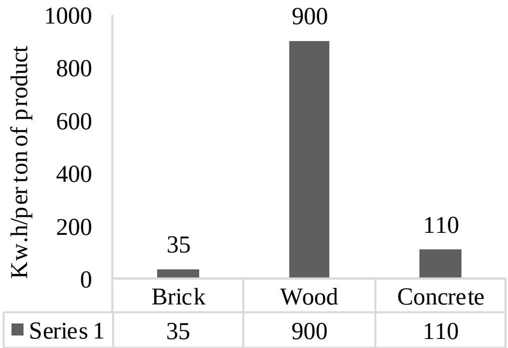

Figure 4. Electrical energy input

Calculation of transportation energy requirements
Unfortunately in our country Iran, due to some unjustified policies in the energy section and also low price of fuel energy most of transportations is road-transportations via trucks, truck mixers and heavy types of machinery than trains. Energy consumption in road transitions is 6 times more than rail transitions (Figure 5).

The average fuel consumption of different vehicles (rail transportation/road transportation) are derived from the standard of transport services as shown in Table 1 and the transportation calculations are based on its presenting data [20].

Total energy consumed in our case studies (concrete-wood-brick) according to the data collected considering the number of trucks and distances they are delivering materials, from field studies illustrated in Figure 6.

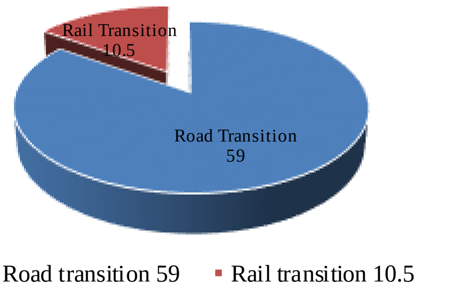

Figure 5. Ratio of fuel consumption in rail/road transportation (Retrieved from : https://www.mrud.ir/)

Calculation of human energy requirements in factory
Energy requirements were calculated from the factorial estimates of physical activity level (PAL) described in the preceding section. They were converted into energy units (i.e. Joules and calories) by multiplying the PAL value by the Basal Metabolic Rate (BMR) formulas (Men BMR = 66.4730 + (13.7516 x weight in kg) + (5.0033 x height in cm) – (6.7550 x age in years) Women BMR = 655.0955 + (9.5634 x weight in kg) + (1.8496 x height in cm) – (4.6756 x age in years)). To express requirements as energy units per kilogram of body weight, they were divided by the weight used in the equations to predict BMR. Table 2 summarizes the average energy requirement of a male population 30 to 60 years of age with a moderately active [21].

BMR (calculated with the predictive equation: 5.45 MJ/day (1 302 kcal/day). PAL (mid-point of the moderately active lifestyle: 1.85.

Energy requirement: 5.45 × 1.85 = 10.08 MJ/day (2 410 kcal/day), or 10.08/55 = 183 kJ/kg/day (44 kcal/kg/day). 1.13 Factory Labour Ratio would be multiplied so the final number is 11.4 MJ/day.

RESULTS AND DECISIONS

Comparison of life cycle energy of wood, brick, and concrete as building materials in different stages of their life cycle includes three calculations:
1. Factory processing,
2. Human energy consumption, and
3. Transportations which in a wholistic view is known as cradle to gate is the subject of this research.

Table 1. Energy consumption per VKM for road and rail transportations [20]

Transition type	Road						Rail	
Vehicle Capacity (g/vkm)	3.5-20t average	20-28t average	>28t average	3.5-20t full	20-28t full	>28t full	4000t average	8000t full
Fuel Consumption	1.8E+02	2.5E+02	2.8E+02	2.0E+02	3..0E+02	3.6E+02	18.0E+02	21.6E+02

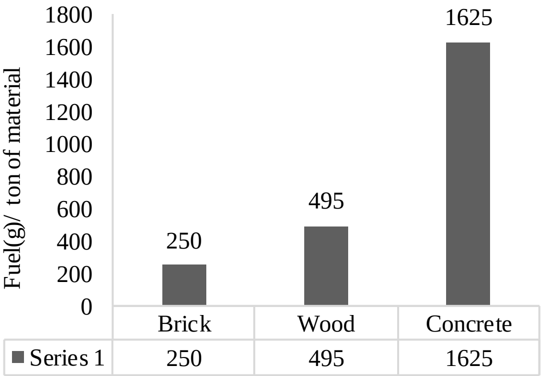

Figure 6. Fuel Used for each ton of materials

The data extracted from the field study in the form of the number of each equipment as well as the number of users, type of activity and distances traveled, are converted into energy units by the methods and formulas mentioned above and thus per specific volume unit from each of the materials, the embodied energy of the cradle to its gate is obtained. To reduce errors and obtain more accurate information from mines and factories from each of the cases of wood, concrete, and brick, three production units in the region (East and West Azerbaijan provinces) have been selected. It is possible to define a guide with each of the collected data sets. The guide is linked to a page containing classified information that is categorized according to standard classifications related to factory and transportation operations.

The case studies for each material are selected from the Azerbaijan region to give a more precise and reliable result. As is shown in Figure 7 the total sum of energy input in 3 different stages of each material is given.

Besides all the energy consumption issues mentioned above, air pollution is also a growing problem because of rising urban populations, unchecked urban and industrial expansion, as well as the phenomena, surge in the number and use of motor vehicles [22]. By considering CO_2

Table 2. Human energy indicator [21]

Mean weight	BMR/Kg[a]	Daily energy requirement according to BMR factor (or PAL) and body weight indicated																								Height(m) for BMI values		
		1.45*BMR				1.60*BMR				1.75*BMR				1.90*BMR				2.05*BMR				2.20*BMR						
Kg	Kj	MJ	KJ/Kg	K cal	K cal/Kg	MJ	KJ/Kg	K cal	K cal/Kg	MJ	KJ/Kg	K cal	K cal/Kg	MJ	KJ/Kg	K cal	K cal/Kg	MJ	KJ/Kg	K cal	K cal/Kg	MJ	KJ/Kg	K cal	K cal/Kg	24.9	21	18.5
50	121	8.8	175	2/100	42	9.7	195	2/300	46	10.6	210	2/550	51	11.5	230	2/750	55	12.4	250	2/950	59	13.3	265	3/200	64	1.42	1.54	1.64
55	114	9.1	165	2/200	40	10.1	185	2/400	44	11	200	2/650	48	12	215	2/850	52	12.9	235	3/100	56	13.8	250	3/300	60	1.49	1.62	1.72
60	109	9.5	160	2/250	38	10.5	175	2/500	42	11.4	190	2/750	46	12.4	205	2/950	49	13.4	225	3/200	53	14.4	240	3/450	57	1.55	1.69	1.8
65	104	9.8	150	2/350	36	10.8	165	2/600	40	11.9	180	2/850	44	12.9	200	3/100	47	13.9	215	3/300	51	14.9	230	3/550	55	1.62	1.76	1.87
70	100	10.2	145	2/450	35	11.2	160	2/700	38	12.3	175	2/950	42	13.3	190	3/200	45	14.4	205	3/450	49	15.4	220	3/700	53	1.68	1.83	1.95
75	97	10.5	140	2/500	34	11.6	155	2/750	37	12.7	170	3/050	40	13.8	185	3/300	44	14.9	200	3/550	47	16	215	3/800	51	1.74	1.89	2.01
80	94	10.9	135	2/600	32	12	150	2/850	36	13.1	165	3/150	39	14.2	180	3/400	43	15.4	190	3/650	46	16.5	205	3/950	49	1.79	1.95	2.08
85	91	11.2	130	2/700	32	12.4	145	2/950	35	13.5	160	3/250	38	14.7	175	3/500	41	15.9	185	3/800	45	17	200	4/050	48	1.85	2.01	2.14
90	89	11.6	130	2/750	31	12.8	140	3/050	34	14	155	3/350	37	15.1	170	3/600	40	16.3	180	3/900	43	17.5	195	4/200	47	1.9	2.07	2.21

equivalent to each of the types of energy in Figure 7 we would have total embodied CO_2 of concrete, brick, and wood in the considered boundary. According to statistics of the environmental protection agency, usage of 1 kw.h of electricity would emit 0.707 Kgs of CO_2 into the atmosphere[1]. Using 1 thm[2] of natural gas emits 5.3 Kgs of CO_2 into the atmosphere. 1 ton of natural gas is about 492 thm of natural gas[3]. Also, 1 gallon of gasoline usage would emit 8.9 Kgs of CO_2 to the earth[4]. The weight of each gallon of gasoline is 3217 grams. Finally, for human energy, each man working averagely emits 900 grams of CO_2 per day which means each MJ of human energy stands for 60 grams of CO_2 emission [23]. So All ecological footprint in the form of CO_2 emission is shown in Figure 8.

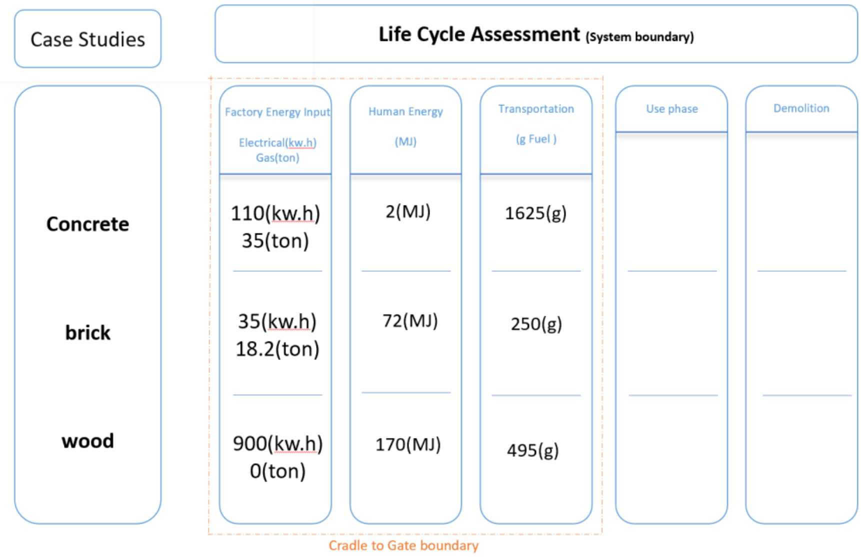

Figure 7. The total embodied energy in system boundary (Retrieved from https://www.soufiancement.com, https://urmiacement.com, https://www.espandar.com)

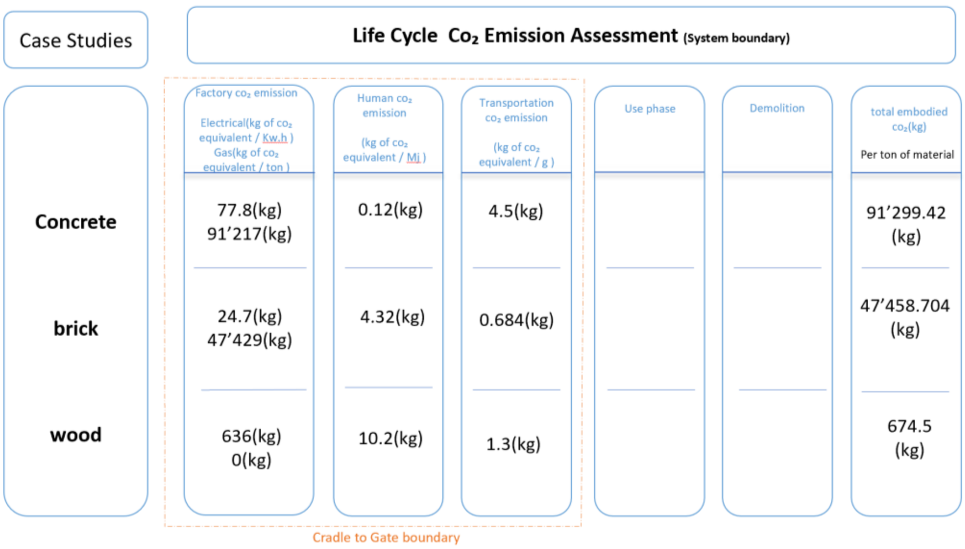

Figure 8. The total embodied CO_2 in system boundary

[1] Retrieved from https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator
[2] Therm which is a non-SI unit of heat energy
[3] Retrieved from https://www.unitjuggler.com/convert-energy-from-MtLNG-to-thm.html
[4] Retrieved from https://micpohling.wordpress.com/2007/03/27/math-how-much-CO$_2$-is-emitted-by-human-on-earth-annually/

FINDINGS

The energy required for the mentioned executive methods includes the embodied energy of concrete, brick, and wood, and the energy used to realize the operations of each from the beginning of factory operations to the beginning of the construction process, which has been evaluated in separate stages. As it is shown in Figure 2, Despite the general belief that wood is always greener and more sustainable than concrete or brick but the exact and quantitative results of this research show that in different stages of the life cycle such as human energy consumptions it is not. The human energy per capita of wood produced is 2.5 times more than brick and 85 times more than cement and concrete. The reason relies on the small populated wood cutting factories (less than 12 people), middle populated brick factories (less than 70 people) and high populated cement factories (usually more than 500 people) which causes that optimization of production line decreases and as a result human energy per capita increases. Also in the aspect of transportation energy as brick factories are so close to the city Tabriz (Average of 20 kilometers) the sum of transportation energy is less than wood and concrete. But in comparison of wood with concrete, Although wood resources are further, as 80% of its transportation is via trains so the final number of fuel consumed is one-fourth of concrete. Looking to the findings more wholistic concrete stands in the 1st place of embodied energy which is 110 kW.h of Electrical, 35 ton of gas, 2 MJ of human energy and 1.6 kg of Gasoline, while brick stands in the second place with 35 kW.h of electrical energy, 18.2 tonnes of natural gas, 72 MJ of human energy and 0.25 kg of gasoline and finally wood has the least embodied energy with 900 kW.h of electrical energy, no natural gas used, 170 MJ of human energy and 0.5 kg of gasoline. Equivalent embodied carbon for each of the case studies is 91 tonnes CO_2 per ton of concrete, 48 ton CO_2 per ton of brick and 0.68 ton of CO_2 per ton of wood is emitted into the atmosphere. So as it revealed in this research being low-embodied energy is up to different factors that they may not be considered at first and so it is always a variable factor and varies according to the different environmental conditions such as distances, types of vehicles, the scale of the factory. Therefore, its optimization conducted in the production line, types of fuels consumed in each region and country. It is hoped that with further studies in the field of LCA we can have a better perspective of which material is greener and low-embodied energy for which city and as a result helps us make better decisions in this field.

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Persian Abstract

چکیده

تحقیقات اخیر در سراسر جهان بر تهدید افزایش مصرف انرژی تأکید دارند. نقش انکارناپذیر مصرف انرژی در تمام مراحل چرخه عمر مواد، از جمله استخراج ، ساخت کارخانه و حمل و نقل، ضرورت استفاده از روش‌های پایدار برای مصرف انرژی کمتر را نشان داده است. کل انرژی تمام مراحل مختلف چرخه زندگی "انرژی تجسم یافته" و روند ارزیابی این ورودی انرژی تجسم یافته "ارزیابی چرخه زندگی" (LCA) نامیده می‌شود. علی رغم اهمیت زیاد LCA، آزمون کمی چنین این فرضیه کمتر مورد توجه محققان قبلی کشورمان بوده است، و به دلیل کمبود اطلاعات سازمان یافته از واحدهای صنعتی، چنین مطالعه‌ای با مشکلات جمع‌آوری داده‌ها نیز روبرو بوده است. در این راستا، این مقاله میزان مجسم‌سازی را و مصرف انرژی مصالح ساختمانی در مراحل مختلف چرخه زندگی آن‌ها ارزیابی می‌کند. برای رسیدن به این هدف، این تحقیق انرژی اولیه را از نظر کمی ارزیابی می‌کند (از جمله مراحل مختلف). به طور دقیق‌تر مطالعه حاضر، بر اساس سیستم ارزیابی چرخه زندگی، انرژی ورودی را در مراحل مختلف گهواره تا دروازه، ارزیابی و مقایسه می‌کند؛ در ۳ مطالعه موردی: بتن، چوب و آجر. نتایج در نهایت نشان می‌دهد که در هر تن بتن ۱۱۰ انرژی الکتریکی کیلووات تولید می‌شود، ۳۵ (تن) گاز، ۱۷۰ (MJ) انرژی انسانی و ۴۹۵ (گرم) بنزین مصرف می‌شود، در حالی که این مقادیر برای هر تن آجر ۳۵ (کیلووات ساعت)، ۱۸/۲ (تن)، ۷۲ (MJ) و ۲۵۰ (g) است، و برای یک تن چوب تولید شده ۹۰۰ (کیلووات ساعت)، بدون گاز استفاده شده، ۱۷۰ (MJ) و ۴۹۵ (گرم) است.