EMBODIED ENERGY ASSESSMENT OF THREE TYPES OF IRANIAN CLAY BRICKS AND COMPARISON OF THE EMBODIED ENERGY OF FIVE EXTERIOR WALL CONFIGURATIONS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

AISAN GHARBI OSKOUEI

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
BUILDING SCIENCE IN ARCHITECTURE

AUGUST 2022

Approval of the thesis:

EMBODIED ENERGY ASSESSMENT OF THREE TYPES OF IRANIAN CLAY BRICKS AND COMPARISON OF THE EMBODIED ENERGY OF FIVE EXTERIOR WALL CONFIGURATIONS

submitted by **AISAN GHARBI OSKOUEI** in partial fulfillment of the requirements for the degree of **Master of Science in Building Science in Architecture, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences** __________________

Prof. Dr. Fatma Cana Bilsel
Head of the Department, **Architecture** __________________

Prof. Dr. Soofia Tahira Elias-Ozkan
Supervisor, **Architecture, METU** __________________

Examining Committee Members:

Asst. Prof. Dr. Bekir Özer Ay
Architecture, METU __________________

Prof. Dr. Soofia Tahira Elias-Ozkan
Architecture, METU __________________

Asst. Prof. Dr. Güzide Atasoy Özcan
Civil Engineering, METU __________________

Assoc. Prof. Dr. Arzuhan Burcu Gültekin
Civil Engineering, Gazi University __________________

Assoc. Prof. Dr. Yağmur Topraklı
Architecture, Gazi University __________________

Date: 25.08.2022

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name Last name : Aisan Gharbi Oskouei

Signature :

ABSTRACT

EMBODIED ENERGY ASSESSMENT OF THREE TYPES OF IRANIAN CLAY BRICKS AND COMPARISON OF THE EMBODIED ENERGY OF FIVE EXTERIOR WALL CONFIGURATIONS

Gharbi Oskouei, Aisan
Master of Science, Building Science in Architecture
Supervisor: Prof. Dr. Soofia Tahira Elias-Ozkan

August 2022, 133 pages

Environmental considerations and future sustainability are among the significant factors that have been considered in the present century. In the company of various influencing factors, the building and construction side has a momentous role in this regard due to its large contribution in consuming resources and energy, in addition to the release of detrimental greenhouse gases. The embodied energy of different alternative materials that are more commonly used in the construction of exterior walls and other related materials in Tehran the capital of Iran will be compared and analyzed from their cradle to gate based on an international database called ICE. For materials that their embodied energy is not evaluated in this database, various articles that include them have been reviewed, and among them, the number that has been mentioned in most of the articles has been selected, or a number as the average of all available data. A comparison will be made among these materials based on the measurements and results and will indicate that the application of which structural systems and materials have the most and the least negative impact on the environment from their embodied energy point of view. To achieve reliable results and comparable to global examples, the most authoritative database formed at the University of Bath in UK has been used. In addition to these analogies, which are based on available global data, the whole production chain of three types of one of the most widely used materials in Iranian construction, namely brick, has been fully studied based on site surveys. All required local data are collected through observation and interviews and integrated into international data to bring the results closer to Iran. Pre-use phase of the materials are assessed in this research based on LCA method which comprises checking the type and amount of fuel used in the transportation of raw materials from the source to the factory as well as within the site, required energy for the manufacture of new materials, and energy expenditure of the labors. These assessments allow materials to be compared and prioritized based on their initial energy, so that materials can be selected wisely to achieve a more sustainable construction. The results of this study show that the embodied energy of the studied materials, which includes refractory brick, red clay brick, and hollow clay brick are 8.344 MJ/Kg, 1.209 MJ/Kg, and 1.766 MJ/Kg respectively. Also, the results obtained from a comparative study between different alternative materials for the construction of external walls based on their embodied energy, relying on the ICE database, showed that the amount of embodied energy of Iran's hollow clay brick, generic clay brick, concrete block, AAC block, and drywall system are equal to 6,105 MJ, 15,271.53 MJ, 5,134.30 MJ, 10,439.13 MJ, and 14,248.06 MJ, respectively.

Keywords: Embodied Energy, Cradle-to-gate LCA, Iranian Brick, Wall Construction Materials

ÖZ

İRAN'DA ÜRETİLEN ÜÇ TİP KİL TUĞLASININ VE BEŞ FARKLI DIŞ DUVAR SİSTEMİNİN GÖMÜLÜ ENERJİ DEĞERLENDİRMESİ VE KARŞILAŞTIRMASI

Gharbi Oskouei, Aisan
Yüksek Lisans, Yapı Bilimleri, Mimarlık
Tez Yöneticisi: Prof. Dr. Soofia Tahira Elias-Ozkan

Ağustos 2022, 133 sayfa

Günümüzde çevresel değerlendirmeler ve gelecekteki sürdürülebilirlik, bu yüzyılda dikkate alınan önemli faktörler arasındadır. Yapı ve inşaat sektörü zararlı sera gazlarının salınımına ek olarak, kaynak ve enerji tüketimine büyük katkısı nedeniyle bu faktörleri etkileyen, önemli bir role sahiptir. Bu çalışmada, İran'ın başkenti Tahran'da genellikle dış duvar sisteminde kullanılan malzemelerin gömülü enerjisi 'ICE' adli uluslararası bir veri tabanına dayalı olarak ham madde eldesinden fabrikadan çıkıp, kullanıma hazır olduğu aşamaya kadar karşılaştırılacak ve analiz edilecektir. Bu veri tabanında gömülü enerjisi değerlendirilmeyen malzemeleri içeren çeşitli makaleler gözden geçirilmiş ve her bir malzemeye dair araştırma ve makalelerde belirtilen değerlerin ortalaması olarak bir değer seçilmiştir. Bu malzemeler arasında ölçüm sonuçlarına dayalı olarak bir karşılaştırma yapılacak ve hangi yapısal sistemin ve malzemelerin uygulamasının gömülü enerji açısından çevreye en çok ve en az olumsuz etkisi olduğu değerlendirilecektir. Çalışmada güvenilir sonuçlar elde etmek ve çalışmayi küresel örneklerle karşılaştırılabilir hale getirmek için İngiltere'deki Bath üniversitesi'nde oluşturulan en yetkili ve kapsamlı veri tabanı kullanılmıştır. Mevcut küresel verilere dayanan bu karşılaştırmalara ek olarak, İran'ın inşaat sektöründe en yaygın kullanılan malzemelerden biri olan tuğlanın üç farklı tipinin tüm üretim zinciri saha araştırmalarına dayalı olarak yerinde incelenmiştir. Bu amaçla gerekli tüm yerel veriler gözlem ve görüşmeler aracılığıyla toplanmış, uluslararası verilere entegre edilmiş ve bu verilerden elde edilen sonuçlar İran'daki yerel özellikler dikkate alınarak uygun hale getirilmiştir. Malzemelerin kullanım öncesi aşamasını, ham maddelerin kaynaktan fabrikaya ve saha içinde taşınmasında kullanılan yakıt türü ve miktarını, üretim ve üretimdeki işçiler için gerekli enerji harcamalarının kontrol edilmesini içeren yaşam döngüsü (LCA) yöntemine dayalı olarak değerlendirilmiştir. Bu değerlendirmeler, malzemelerin başlangıçtaki enerjilerine göre karşılaştırılmasına ve önceliklendirilmesine olanak tanır, böylece daha sürdürülebilir bir yapı elde etmek için malzemeler akıllıca seçilebilir. Bu çalışmanın sonuçları, refrakter tuğla, kırmızı kil tuğla ve içi boş kil tuğla içeren incelenen malzemelerin gömülü enerjisinin sırasıyla 8.344 MJ/Kg, 1.209 MJ/Kg ve 1.766 MJ/Kg olduğunu göstermektedir. Ayrıca, ICE veri tabanına dayalı olarak, dış duvarların inşası için farklı alternatif malzemeler arasında somutlaştırılmış enerjilerine dayalı olarak yapılan karşılaştırmalı bir çalışmadan elde edilen sonuçlar, İran'ın içi boş kil tuğla, jenerik kil tuğla, çimento blok, AAC blok ve alçıpan sistemi gömülü enerji miktarlari sırasıyla 6.105 MJ, 15.271.53 MJ, 5.134.30 MJ, 10.439.13 MJ ve 14,248.06 MJ'ye eşittir.

Anahtar Kelimeler: Somutlaştırılmış Enerji, Beşikten Kapıya LCA, İran Tuğlası, Duvar İnşaat Malzemeleri

To my beloved family,

ACKNOWLEDGMENTS

I would like to express my deepest appreciation to my supervisor Prof. Dr. Soofia Tahira Elias-Ozkan for her dedicated endless support and guidance. Her constant support and guidance to me during all the steps encouraged me and made me eager to continue on my path.

I would like to extend my gratitude to Mr. Abdolhasani, the manager and owner of Agorr brick production company who, helped me in collecting information and explaining all the details of my factory.

Finally, I am grateful to my friends and family who always supported, helped, and believed in me. And I am always grateful for the endless love and support of my mother Forouzan, my father Mohammad Reza, and my brother Kian, who stood by me in all stages.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

ABBREVIATIONS

AAC	Autoclaved Aerated Concrete
BoM	Bills of Materials
CED	Cumulative Energy Demand
DE	Demolition Energy
EE	Embodied Energy
EPD	Environmental Product Declaration
GHG	Green House Gasses
I-O	Input –Output
ISO	International Standards Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
OE	Operational Energy
SETAC	Society of Environmental Toxicology and Chemistry

CHAPTER 1

INTRODUCTION

The argument, objectives, methodology, and disposition of the research are the topics that are included within the Introduction section to begin describing the steps and operations performed during this research.

1.1 Argument

Buildings have always been one of humanity's most pressing needs in every era and that has been the driving force behind the ongoing trend in the construction industry. The indisputable role of the construction industry in environmental impacts is a subject that needs much attention. Improving the quality of buildings has always been an important issue to be considered. In fact, it is essential to improve the quality of life of people without jeopardizing the quality of life on earth. Implementation of sustainable construction can help achieve this goal.

As the population grows, the need for buildings increases and this could be a starting point for environmental degradation through the diffusion of CO2 and the excessive use of natural resources such as energy, materials, and water. The trend of increasing carbon dioxide emissions over time is illustrated in Figure 1.1. Based on the data obtained from United Nations Environment Program (UNEP, 2019), this industry accounts for 40% of global energy consumption and it produces one-third of the world's green house gasses (GHG). Also, about 60% of the world's electricity is consumed in the operational phase of buildings.

Each building is composed of a set of energies that are consumed during its life cycle which are: Embodied Energy (EE), Operational Energy (OE), and Energy for Demolition (DE). Each of these energies has a share in the total energy consumed by a building from cradle-to-grave. Since the supply of energy requires the use of the aforementioned natural resources, these consumed energies can cause negative and destructive impacts on the environment.

Embodied energy is usually defined and known as an energy which has been consumed to produce a material. So, it can be assigned to the stages of extraction, transportation, and manufacture. As it is obvious each of these stages requires energy to be executed. Since these energies are not always accounted for, less attention has been paid to them as contributing to the EE of buildings or products.

By implementing methods to decrease the operational energy, the need to pay attention to embodied energy increases. To reach a completely sustainable building, considerations should be given to all energies that have a role in the total required energy of a building.

It is not possible to achieve all of the environmental effects of a building by considering its embodied or operational energy individually but evaluating each of them alone will help us gain a better perception of the life cycle embodied energy (LCEE) of the building.

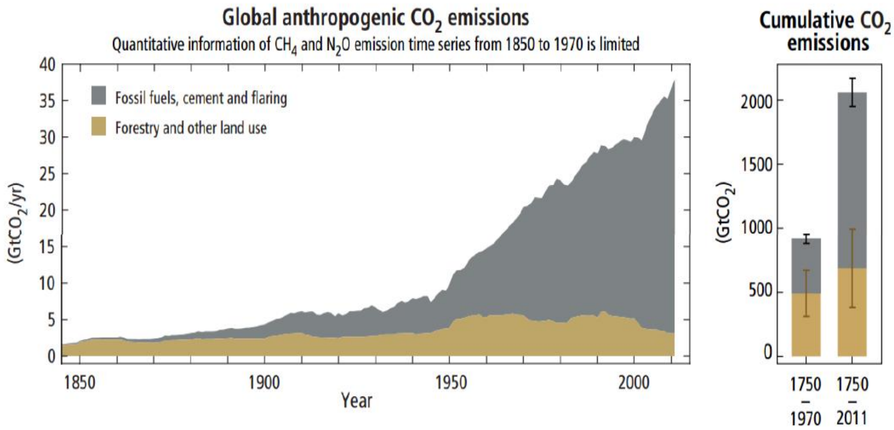

Figure 1.1. Global increase in CO2 emissions in Gton CO2 /year due to the burning of fossil fuels and their flaming (IPCC, 2014)

Although many studies have been done in different countries around the world, the embodied energy is still an issue which is novel in the construction industry of Iran.

Studies in the field of consumed operational energy have been conducted to an acceptable degree and satisfactorily, and this has led to the need to focus more on embodied energy.

Therefore, embodied energy consumption at the national level is deserving of studying as a way to recognize fields where energy efficiency strategies can be proposed (Dixit, Fernández-Solís, Lavy, & Culp, 2010).

Accordingly, this research was focussed on the embodied energy of construction materials used in residential buildings in Iran, i.e. different types of bricks; and pursuant to the obtained data for each of the selected bricks types, comparisons were made among them through a LCEE analysis.

1.2 Aim and Objectives

- The primary aim was to comprehend the general concept of Embodied Energy and the importance of its role in the life cycle of a building, through a thorough literature review.
- The secondary aim was to identify the conventional materials in the construction of exterior walls with the least and most Embodied Energy, in Iran.
- Hence, the main objective of this study was to investigate the energy consumed in the brick production cycle, which is one of the most widely used materials in residential construction, in Iran.
- The secondary objective was to perform a Life cycle assessment (LCA) in order to calculate the Embodied Energy of different bricks; and
- To make a comparison between the exterior wall options prior to construction according to their EE.

In order to reach these objectives the following research questions were posed in this study:

- How is brick being produced in Iran; what is the technology for each type of brick?
- What type and amount of energy is consumed in the brick production cycle in the Iranian construction industry?
- What are the factors that should be used to calculate the embodied energy of different bricks?.
- How do different wall materials compare in terms of their embodied energies?

With the obtained results, it will be possible to create a database for 3 most commonly used types of bricks in Iran which can later be expanded.

1.3 Procedure

This study was conducted in 3 stages. In order to understand the production chain of bricks in Iran, site visitis were made to the factories and data was obtained which was local and reliable. All the data were collected through interviews with skilled people present in the factory. Three types of bricks , including refractory, red clay brick, and hollow clay brick, which have the most demand in construction in Iran were selected to investigate their embodied energies. All the operations and stages that played a role in making bricks in the factory have been analyzed in terms of fuel, electricity, and gas consumption, and also manpower, and the energy resulting from each has been included in the calculations for the final energy used for the bricks production.

The data that are used through this is study are collected not only from people working in the factory but also from ICE database, which is one of the most reliable databases in the field of EE.

Most common materials in the construction of the exterior walls in Iran, including hollow clay brick, generic clay brick, concrete block, AAC block, and drywall system, were selected to compare their embodied energy by calculationg them as part of a test wall that is 10 meter by 2.7 meters. These materials were compared by calculating their embodied energy within a standard wall and the details are presented in material and method chapter. The EE coefficients of these materials are calculated by relying on the Ice database. In their calculations, not only the role of masonry materials but also the structures related to each type of wall are considered.

1.4 Disposition

This dissertation consists of five chapters. The first part of which is introduction and is devoted to explaining the intended purposes of selecting this topic as the case study. This section covers the sub-sections that include argument and aim and objectives of this thesis, each of which includes the relevant description.

The second part examines backgrounds and previous studies that are related to the field of study. The first part of this literature survey deals more specifically with the issue of environmental impacts resulting from the construction of building materials. In the second part, the whole topic of embodied energy is explained in more detail. In the third part the required information to study this energy, which is suggested by other articles and studies, is described. The fourth section includes figures provided by other countries in their energy calculations for building materials. Fifth subsection describes possible and available methods for evaluating energy in the construction life cycle and in the sixth part of this chapter, the characteristics of each of the life cycle assessment methods are examined and interpreted.

The third chapter introduces the adopted material and methods in collecting field data and objective surveys and observations performed to obtain the required information.

The results of this field survey and observations are presented in fourth chapter.

Chapter five discusses the study performed and compares and categorizes the results obtained to give a general conclusion about the embodied energy of different materials and also interprets the results obtained for the studied Iranian bricks.

CHAPTER 2

LITERATURE REVIEW

This section is devoted to information collected from the articles studied. Each title is dedicated to the concept of the intended topic, and related data are presented. Under each title, different ideas, perspectives, and experiences of various researchers in the same field are briefly stated.

2.1 Environmental Impacts of Building Materials

Based on the statistics compiled from the United Nations Environment Program, (UNEP, 2019), the construction sector in developed countries is causing a large percentage of the impacts on the environment. In European countries, almost 40% of the total environmental burdens lie with the construction and construction sector. Also, 40 percent of primary energy in British buildings is consumed both at construction and at occupation times. These environmental effects can occur at all stage of the life of a building.

The construction industry can impact on the environment from three crucial points of view. These impacts can be categorized into energy which is consumed during the manufacturing, utilization, and end of life of a product, global warming potential which is generally measured in units of CO_2 emissions, and water consumption (Bribián, Capilla, & Usón, 2011).

As an example, the percentage of resource use and environmental impacts in the US construction industry is illustrated in Figure 2.1.

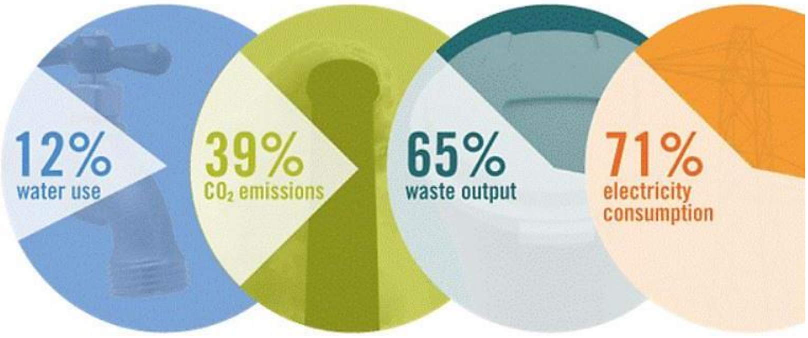

Figure 2.1. Environmental impacts of building in the US (Western Village, 2013)

In summary, the ecological effect is dedicated to issues like the emissions of gases to the environment and resource consumption and interpositions such as land occupation which are the outcomes of the production of material and products and can occur during the extraction of resources, their production, use and end-of-life phase. These effects can be categorized into climate change, ozone depletion, acidification, and eutrophication, which can be harmful to the health of the ecosystem and all living species. Therefore, in addition to the prevalent flows of monitoring practices there is a need to be provocative and to provide different intuitions to mitigate such effects.

Of all these impacts, energy consumption accounts for the most significant percentage, which could be energy used to manufacture building materials or energy consumed for the rest of the building's life. Hence, more focus is going to be provided on embodied energy, which is less than the operational energy that is in the spotlight.

2.2 Embodied Energy

The three leading stages of a building can be classified into pre-use, use, and after-use phases (Dumani, 2009)**.** The pre-use stage which is affected by the material processes from raw material extraction through construction to site implementation, is accountable for the embodied primary energy.

The use phase which contributes to the utilization of operational energy for lighting, heating, ventilation, and the use of machines and devices; and the repetitive use of embodied energy for maintenance, repair, or replacement of materials.

The post-use is a stage that consists of reusing, recycling, and disposal operations that are performed at the end-of-life of the buildings.

The consumption of energy during the whole life of a building can be divided into four categories:

- The primary and initial energy is energy which is spent on the creation of a building and has been consumed during the derivation, processing, production, transfer, and fabrication of materials.
- The recurring embodied energy is energy which is spent on maintenance, repair, renovation, or replacement of materials throughout the entire life of a building.
- Operational energy is energy, which is spent on the ventilation, lighting, heating, cooling, and providing energy to all existing electrical equipmentutilized in buildings.
- Demolition energy: The energy that is spent on destruction and the buildings' disposal (Ezema, Fagbenle, & Olotuah, 2015).

As a general definition, the life cycle embodied energy of the cradle-to- grave term of a building is the sum of the primary energy, the recurring energy, and the energy of disposal (Ezema *et al.,* 2015).

Achieving sustainability in the process of designing a building can be the motive for engineers, architects, and other practitioners to expanding knowledge in order to help them in having a smart choice of the material for their designs.

In terms of energy consumption, the importance of different stages in the life cycle of a building is variable and changes over time, as the environmental impact of embodied energy increases. Accordingly, the embodied energy component is growing in importance, and more emphasis is needed on it in order to handle the

emissions of GHGs and maximize the decrease of environmental impacts from the construction industry (Dumani, 2009).
As described by Holtzhausen (2007), non-renewable energy that is consumed in the production and manufacture of materials and that plays a vital role in the selection of advisable materials is known as Embodied Energy. The role of this factor in life cycle assessment of a construction is undeniable and pertinent to the sustainability of environment.

Embodied energy is the intrinsic energy of a building correlated with the materials of construction, construction processes, and its durability (Ezema *et al.*, 2015).
As buildings are designed with more sensible ideas and methods and are more efficient in terms of operational energy, the embodied energy of the building and the materials used in the construction, operation, and maintenance of the building also need to be carefully examined (Holtzhausen, 2007).

Sometimes just focusing on the operational energy and ignoring the type of utilized materials will lead to an increase in embodied energy, and the efforts to achieve sustainable building become useless, and they happen to increase it. For instance installation of overhangs which are made of concrete, metal, or other materials to the southern façade in order to have reduction in heat accumulation or overuse of insulation materials to reduce temperature transfer, and other strategies can be the cause of an increase in the embodied energy (Azari & Abbasabadi, 2018).
In buildings that are built with a low energy consumption strategy, the contribution of embodied energy can vary between 9 to 46 percent (Bribián *et al.*, 2011). In order to achieve a better performance in a building with low energy consumption, attention to the embodied energy must be in parallel with the functional energy (Birgisdottir *et al.*, 2017).

In some studies of buildings that do not require energy for heating or cooling, or are even designed as zero-energy and their required energy is provided from renewable sources and passively, the embodied energy has been reported to be notably high (Khasreen, Banfill, & Menzies, 2009).

Environmental impacts linked with embodied energy such as resource depletion, emissions of noxious gases, biodiversity conservation, and degradation of the environment are incorporated in embodied energy metering.

Embodied energy can be cited as a sign of carbon footprint or greenhouse gas emissions and can be used as an indicator of sustainability of the environment since it can be beneficial for the mitigation of the adverse effects (Dixit, Fernández-Solís, Lavy, & Culp, 2012), (Alwan & Jones, 2014),(Ezema *et al.,* 2015).

According to CSIRO (Scientific and Industrial Research Organization), an Australian organization, the energy consumed for the production of building materials is very relevant and influential on the emission of CO_2. Approximately, the consumption of every GJ of embodied energy can produce 0.098 tons of CO_2.

Giga Joules (GJ) or Mega Joules (MJ) per unit of weight (Kilogram or ton) or area (m^2), are the units that embodied energy is declared in.

Due to the variety of factors and complexities, various sources are required in order to calculate the embodied energy. The embodied energy of materials is influenced by factors such as geographic location, the technology used in the production process, and production methods (Holtzhausen, 2007).

As it is described by Stephan and Crawford (2016), the floor area in our constructions affects the embodied energy and also the value of the cycle of life.

As an example, to illustrate the importance of building's scale, we can cite a study that compared the embodied energy of a traditional brick house with a contemporary home made of concrete, cement, and burnt brick. The result of the experiment showed that the use of bricks reduced the total embodied energy per 100 m^2 of the constructed area by 245 GJ, indicating the importance of material selection in overall energy content (Shukla, Tiwari, & Sodha, 2009).

It is also demonstrated by Rauf and Crawford (2015) that another factor that affects the embodied energy is the service life of the materials, and it means a period in which a material stays in an utilizable condition.

The production process must be understood in order to calculate embodied energy, the processes of different products by modeling their production plan, from raw material extraction to production. The difference in the estimation and evaluation of the embodied energy originates from the difference in the scope definition as well as in the technology of production and transportation of materials. In addition to the ISO framework, some literature refers to standard protocols for estimating embodied energy, and sometimes such challenges encompass a wide range of embodied energy metrics in terms of material use and transportation (Dixit *et al.*, 2012).

2.3 Categories of Embodied Energy

Initial embodied energy and Recurring embodied energy are the two main components that make up the embodied energy. These two categories are explained further in th following sections.

2.3.1 Initial Embodied Energy

The initial EE can be atributed to the building material, the building component, or the entire building. This includes energy required for extraction of raw material, manufacturing of the building components, and construction of the building including the energy expended by the workers and trasportation.

The energy that is nonrenewable and consumed since the attainment of raw materials till their processing and construction is described as the initial embodied energy. The utilized resources, the sort of selected building materials and the building's nature can be considered as the influencing factors of initial embodied energy.

According to several articles that have been reviewed, the commonly used equations for calculating initial embodied energy (EE_i) are as follow (Ramesh, Prakash, & Shukla, 2010):

$$EE_i = E_M + E_C$$

Where,

EE_i: Initial embodied energy of the building;

EE_M: Energy for building material manufacturing; and

E_C: Energy used for building construction

Also based on the Ramesh, Prakash, & Shukla (2010), it has been stated that the production energy can be calculated with the following equations:

$E_M = \sum m_i M_i$

Where,

E_M: Energy required for material manufacturing;

m_i: Quantity of building material required to produce a building; and

M_i: Energy content of material per unit quantity

2.3.2 Recurring Embodied Energy

A nonrenewable energy which is spent on maintenance, repair, renovation or replacement of materials throughout the whole life of the buildings is known as recurring energy. Durability and conservation of materials utilized in a building are the factors which affect the recurring embodied energy.

According to the reviews literatures, recurring embodied energy calculation can be done using the following equations (Ramesh *et al.,* 2010):

$EE_r = \sum m_i M_i [(L_b/L_{mi})-1]$

Where,

EE_r: Recurring embodied energy of the building;

M_i: Quantity of building material required to produce a building;

M_i: Energy content of material per unit quantity;

L_b: Life span of the building;

L_{mi}: Life span of the building material.

2.4 Data and Information for EE Assessment

The availability and access to data for building materials and construction products are crucial to evaluate the Embodied Energy and embodied GHGs (EEG) of a building (Birgisdottir *et al.*, 2017), (Chae C., Kim S., 2016). This information should be reliable and comparable so as to allow for useful comparisons to be drawn between different products and materials.

Table 2.1 Minimum requirements for EEG-database for construction products (Seo, Foliente, & Ren, 2018)

Item	Description
Materiality	Should cover the most significant construction materials and building technologies
Consistency	Analysis of all construction materials follows the same modeling principles, apply the same system boundaries.
Transparency	This transparency enables the user to independently check the data quality of the underlying data.
Timeliness	The age of a dataset provided in a database is determining its quality.
Reliability	The data used to establish a dataset sourced from reliable information sources.
Quality control	Datasets offered in a database should undergo an independent and external verification or critical review.

The field survey, in which data is gathered by assessing energy related parameters directly from processes of factories or building sites, is the most common method used at every level of building parts as it is illustarted in Figure 2.2.

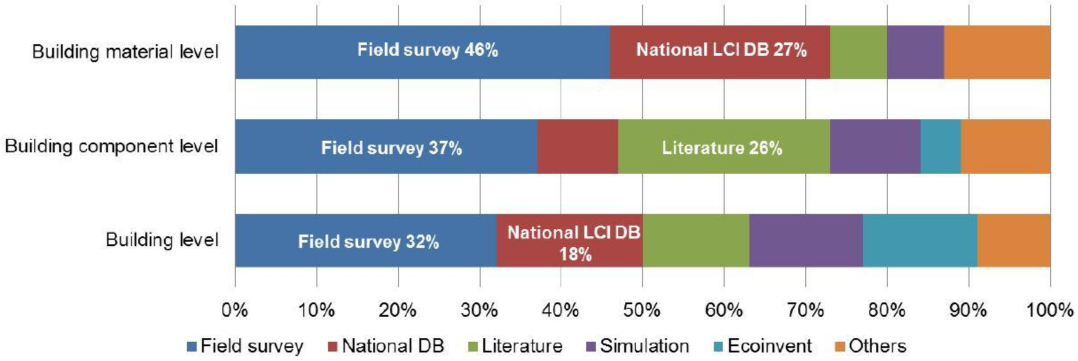

Figure 2.2. Common LCI database source in different level of building parts (Chae C., Kim S., 2016)

2.5 Calculated Values of Embodied Energy in Different Countries

In this section, several examples of studies in different regions of the world on the embodied energy field and its importance will be discussed in order to better comprehend the role of this embodied energy in the construction industry.

- In an Australian study conducted in 2007, the total intensity of embodied energy visualized for residential buildings ranged from 9570 MJ/m^2 to 14630 MJ/m^2. Also, in this study, the initial embodied energy accounts for between 62 to 63 percent of the total energy of a building, while the recurring embodied energy element was in the range of 38%. And total embodied energy contributes about 17 to 24 percentage of the whole life cycle energy (Pullen *et al.,* 2006).
- In another study in Australia, the researchers have estimated the amount of operational energy as 40% of the total energy in the life cycle; however, the primary and recurrent embodied energy accounts for 37 and 22 percent of the entire cycle energy, respectively. The results are indicative of the importance of embodied energy as an essential element in the energy profile of a building (Crawford, 2014).
- Another study was conducted by Crawford and it showed that 63% of the original energy is deemed as the primary energy, while the energy embedded in the repetition represents 37% of the total energy, demonstrating the stability in the embodied energy aspect of the Australian studies (Stephan & Crawford, 2016).
- In a study carried out in Malaysia, the amount of primary embodied energy varied between 4120 MJ/m^2 and 5380 MJ/m^2 based on the difference between the materials applied. The presented statistics demonstrate the undeniable importance of this component of the total lifecycle energy (Mari, 2007).
- The intensity of embodied energy in a Brazilian study is reported as 7200MJ/m^2, and also the recurring energy intensity is about half of that value.

In this study, walls account for about 57 percent of the embodied energy (Paulsen & Sposto, 2013).

– In some cases, operational energy exceeds embodied energy; for instance, in a study conducted on a residential building in India, of the total energy of the building, 89% represents the operational energy share and 11% as the embodied energy share (Ramesh, Prakash, & Kumar Shukla, 2013).

All the examples cited above point to the increasing importance of embodied energy in the overall energy use. Table 2.2 summarizes the results of evaluations of the embodied energy in further research conducted by Dixit (2013).

Table 2.2 Obtained embodied energy of materials from sources present in the literature (Dixit, 2013)

	Energy Values in GJ/m^2
Study	Materials Embodied Energy
Adalberth (1997b)	3.00
Sattler & Sperb (2000)	1.21
Chen et al. (2001)	4.48
Chulsukon et al. (2002)	3.04
Thormark (2002)	5.17
Scheuer et al. (2003)	5.40
Almeida et al. (2005)	7.59
Thormark (2006)	3.85
Johnson (2006)	0.77
Nassen et al. (2007)	3.10
Thormark (2007)	3.85
Kim (2008)	3.84
John et al. (2008)	2.98
Fridley et al. (2008)	8.64
Utama & Gheewala (2009)	0.88
Shiu et al. (2009)	3.11
Sobotka & Rolak (2009)	0.74
Vukotic et al. (2010)	2.49
Leckner & Zmeureanu (2011)	3.30
Ramesh et al. (2013)	6.94

2.6 Factors Involved in Calculating EE of Materials

Different factors are involved in the production of building materials in a factory, each of which has a fundamental role in the production process. All the operations performed during the production of any building product consume energy, and for this reason, they are considered in the embodied energy calculations of different materials. Among these factors, we can mention the transportation of raw materials, electricity consumption of machines, manpower, and other factors affecting the amount of embodied energy of materials.

2.6.1 Energy Expended by Workers

Load of work is a momentous issue to be figured out to consider the health of the workers and also to fit the work according to the physique of each person (Saber *et al*., 2014). Relying on the information obtained from the mentioned research, which is considered in a steel production factory in Iran, and the average age of the workers working there is about 30.84, the energy consumption of male workers is approximately 2.81±0.809 has been obtained.

In the table below, the results obtained from this research are shown in relation to the estimation of energy consumption based on heart rate while doing work in the studied workers. This Table B is shown in the original language of the reference article in the appendix and the English translation of this table by the author is shown in Table 2.1.

Table 2.3 The energy consumption estimation table based on the heart rate while doing work in the studied workers *(Saber et al., 2014),* translated into English (by author)

Energy consumption (Kcal/min)				Heart rate while doing work (bpm)	
Maximum	Minimum	Standard deviation	Average		
4.56	1.1	0.734	2.65	n=67	Light work (90>)
4.9	1.94	0.706	2.9	n=26	Medium work (90-109)
5.64	2.67	1.07	4.11	n=7	Heavy work (110-129)
-	-	-	-	n=0	Very heavy work (130-149)
-	-	-	-	n=0	Extremely heavy work (150-170)

A significant feature of health and safety in occupations is called energy cost (EC). In order to obtain a general guideline regarding the energy expenditure during work, which is consumed in the unit of the number of calories consumed in a certain period of time, preliminary studies are needed. considering the growing outbreak of features related to the work aspects, determining energy cost is counted as a major and significant issue in the safety and health matter of occupations. The negative effects of some work on individual health can be mentioned as stress, fatigue, and some diseases that are the result of high metabolism on the body. In the long run, these effects can lead to a decrease in the health of employees and their efficiency. Among the many surveyed jobs that are considered as hard work, after agriculture, which ranks first in the difficulty of work, construction and manufacturing industry are placed in the second and third categories, respectively (Poulianiti *et al.*, 2018).

According to the results obtained from (Poulianiti *et al.*, 2018), each male worker in the construction industry burns about 4.9 ± 1.6 kcal/min to work in this field. This amount for a male worker who works in a manufacturing plant is equal to 3.8 ± 1.1 kcal/min for men and about 3.0 ± 1.3 kcal/min for women.

2.7 LCA methodology for energy use evaluation in buildings

To establish sustainable design in construction industry, evaluating the degree of sustainability of the building plays an important role. Procedures are needed to inquire environmental factors and focus on the reciprocal relations between the construction industry and related activities and its life cycle environmental impacts. Life Cycle Assessment (LCA) is the most commonly used method among the various ways that are available to obtain data and present the results. It is crucial to examine the current method of housing, especially concerning the materials applied and the construction processes, to identify associated energy reduction possibilities. This approach can be made by applying the Life Cycle Assessment Tool (LCA) and, in particular, the Life Cycle Energy Assessment (LCEA), which is a framework for evaluating the energy performance of a component or building throughout their life cycle.

2.7.1 Concept of Life Cycle Assessment

Life Cycle Assessment has been declared as a strategy which assists in determining the total environmental impacts of a product (here the building) across its entire phases of life cycle comprising of exploitation of resources, processing raw materials, production, transportation, utilization, reuse, preservation, recycling, and disposal. The LCA is often used as a tool to support analytic decision making. Application of this tool along with other aspects of construction can lead to an effective project. It also helps to replace the current suggested options with other alternatives that make the existing project balance better with respect to its environmental impacts.

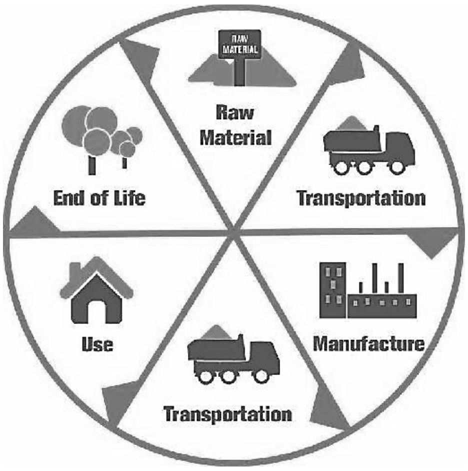

Figure 2.3. Life Cycle Assessment stages (adapted from Abioye Oyenuga, 2017)

The late 1960s and early 1970s were the beginning of the era of LCA attention. Energy analysis was the first focus of those research, but later expanded to include more information on the required resources, the number of pollutants, and waste produced, to gain further information. The 1990s were the time of global growth in this field and the issue of the requirement for a universal standard arose. The incorporation of the International Organization for Standardization (ISO) into this system appeared in this decade. The LCA is a framework for assessing the environmental impacts of a product, process, or service from the cradle to the grave and complies with international standards, ISO 14040. Based on ISO 14040, the LCA is defined as the formulation and evaluation of the inputs, outputs and potential environmental impacts of a product system over the life cycle.

2.7.2 Set of Steps Involved in LCA

According to ISO 14040:2006, for those who are eager to assess the life cycle of their products, information is required for four different phases that are monitored by this system; which are as follows:

1. Goal and scope definition
2. Inventory analysis stage

3. The impact assessment stage
4. Interpretation stages

A framework based on a flowchart suggested by ISO for conducting the Life Cycle Assessment is illustrated in Figure 2.4. The four stages mentioned therein are explained in the following sections.

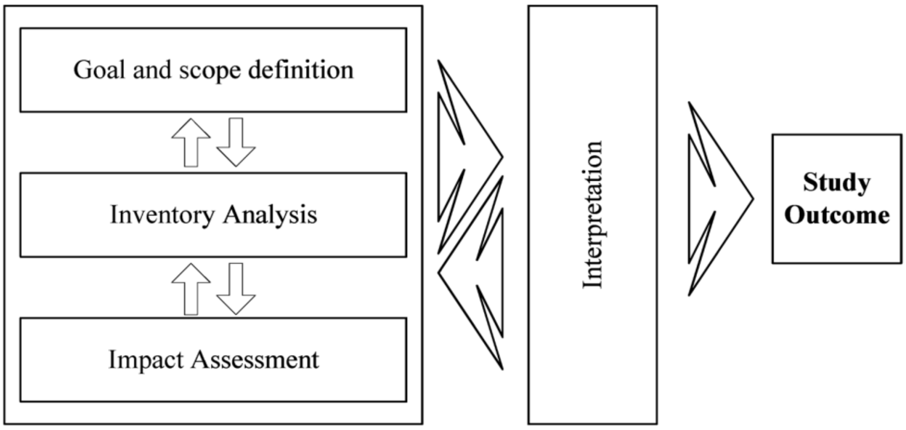

Figure 2.4. Framework of Life Cycle Assessment (ISO 14040)

2.7.2.1 Goal and Scope

First and foremost step in performing a life cycle assessment is to define the goal, i.e. the aim of the asessment and its scope, in order to specify the target for the study. This step is a place to determine the intentions and restrictions that exist in the field under consideration. Boundaries of the system are the main ones, for example the whole life of a product and the Performance unit. Identifying and defining the goal and scope gives direction to the study.

In accordance with ISO 14040 related to the intended program, the reasons for the study and the intended target audiences are stated in the goal definition step of every LCA. This includes the system of the product to be studied, its performances, the related units, the boundaries of the system, designation processes, categories of selected impacts, methods of evaluation of impacts, necessity of data, assumptions, constraints, critical checks and type of report needed for the field.

As it is described by Weidema, Wenzel, Petersen, and Hansen (2004), defining same functional units in LCA can be beneficial for comparing different products and materials with each other. For instance, m^2 is a unit which is mostly used in assessments but depending on the available data this unit might be changed to “Ton” if the environmental load of a material is considered. Hunkeler (2016) stated that the profundity and precision of the study should be taken into account during the goal definition stage.

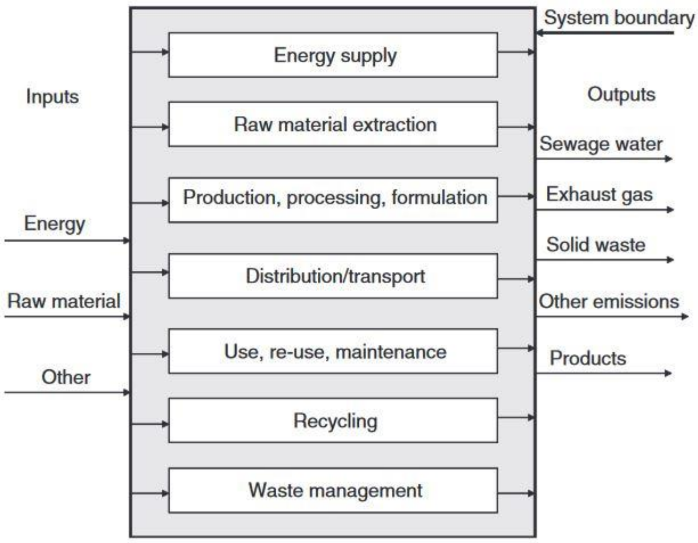

Figure 2.5. System boundary of the inventory modified according to Society of Environmental Toxicology and Chemistry (SETAC, 1991)

Finally, according to ISO 14040, a logical goal definition must be able to respond to two demands: “What is the purpose of considering the study area?” and “Why the assessment of the life cycle has been conducted?”

2.7.2.2 Inventory Analysis

A Life-Cycle Inventory (LCI) is a method that measures the quantity of the raw materials, ambient pollution, water, and solid waste produced during the life cycle of a product or process. Products and operations can be measured, evaluated, and compared through the LCI. Data compilation and qualification of all energy inputs and outputs of a system is included in the inventory analysis section (Khasreen *et al.*, 2009).

Software tools and databases are vital in this phase, as exclusive materials and processes cannot be evaluated whenever an LCA analysis is carried out. So, the LCA tools are linked to the databases of operations, outcomes, and products that are essential to execute an LCA. Emissions into the air and atmosphere, and the utilization of energies can be accounted for through the existing databases in LCI. The derivation of raw materials, transporting, manufacturing and distributing the final product are covered by the databases that are available in the LCI databases (Hollerud, Bowyer, Howe, Pepke, & Fernholz, 2017).

This stage is dedicated to the inventory collection of input/output data according to the system studied. It is a recurring process and the related data are being updated continually (Monahan & Powell, 2011).

2.7.2.3 Impact Assessment

The environmental impacts of the product or method are estimated at this stage. Mainly, the possible contribution of the product or process to the categories of environmental impact is determined. The data that have been obtained from the previous step, i.e. the Life Cycle Inventory Analysis, will be entered into the adequate impact classification specified in the first step. Various or solitary categories of effects can be identified as the consequences of the assessments (ISO 14040, 2006).

It is also described as the phase of a process proposed at recognition and evaluating the significance and weight of the embodied environmental impacts for a product system throughout the life cycle of that product. This is the step that reveals the impacts of resources spent and emissions released into the atmosphere, as classified in the life cycle inventory analysis (Muthu, 2014).

Applying the LCI data, the system assesses the importance of potential environmental impacts and comes up with data and information for the final interpretation step (Monahan & Powell, 2011).

2.7.2.4 Interpretation

Life cycle interpretation is an structured method for recognizing, quantifying, and evaluating information from LCI or LCIA results. The results of the inventory analysis and impact assessment are summed in the interpretation stage. The consequence of the interpretation phase is a collection of conclusions and proposals and suggestions for the study (Hernandez, Oregi, Longo, & Cellura, 2019) (Cao, 2017).

Obtaining the inferences and developing assumptions concerning the doubts that exist in the results is the final step in analyzing the inventory. The calculated results are only characteristic of supporting and recommending decisions on what affects the materials or operations.

2.8 Characteristics of LCA Methods

Numerous LCA methodologies have been implemented to evaluate life cycle impacts. The selection of methods for acquiring product data usually depends on the goal and scope of the task, the expected level of detail, the adequate level of ambiguity, and accessible resources such as time, human resources, expertise, and finances (Stavropoulos *et al.*, 2016).

Due to the variety of applied methods, among all of them, the three most prominent, common, and known methods will be mentioned and discussed separately below.

2.8.1 Process-Based Databases

A process-based analysis is a way of documenting all processes associated with a product's life cycle and considering all inputs and outputs of each method. It is known as the aggregate of all the environmental influences arising from the products and methods demanded in the creation of a building (Moncaster & Song, 2012).
Compilation of data for particular unit processes and connecting them to more extensive methods for representing the environmental impacts of a product or system on its life cycle are progressively being applied to recognize the environmental impacts at the building level (Chae C., Kim S., 2016).
The process-based LCA sorts the product/building into a prominent system, for which the initial data is gathered, and a background system, for which the public data is employed (UNEP SETAC, 2011).

In this method, the International LCA Standard advises the application of acceptable mass, energy, or environmental impact measures. Inputs that are beneath a specific level of mass, energy, or environmental effects can be disregarded and thus eliminated from the evaluation (ISO 14040 and 14044).

It is possible to perform diverse types of process-based analyses according to the system boundary defined in the first level, which is as follows.

- Cradle-to-Gate: evaluation of the product life cycles from the extraction to the plant gate (shipping is also included). This analysis covers all manufacturing processes of the materials.
- Cradle-to-Grave: evaluates the whole life cycle of a product or process, including the extraction, application, and end of life stages.
- Cradle-to-Cradle: consist of a particular cradle-to-cradle assessment where recycling or reuse is the disposal method of the product.
- Gate-to-Gate: the entire manufacture process is the main focal point in a partial LCA examination and looks only at the value of the process.

2.8.2 Input-Output (I-O) LCA

Input-Output Method (IO) is a top-down economic strategy that applies financial segment data, i.e. the national input-output data, to respond to complicated industry dependencies in the modern economy. Nevertheless, I-O methods are also employed at the building level and component level, especially in countries where process-based LCA data are insufficient (Tarancon & Del Río, 2012).
Use-build and symmetric models are the two offered models of table in Input-Output systems. The first one concentrates on the output of industrial sectors.

2.8.3 Hybrids of the Two Methods

The hybrid method is a system that exploits the strengths of both methods (process and IO method) and combines as many process-specific data as possible while covering the rest of the system with common IO data.
The hybrid approach either starts with a complete system, adds process data that make process production obvious, or it starts the process from the LCA, and adds inputs that are not determining the quantity at the process level. Also, the hybrid approach combines many of the infirmities of the process and I-O methods. The cost of the hybrid method can be as much as the process and I-O methods because the target of the hybrid method is to achieve the best quality and highest level of comparability in the estimates. The quality of the hybrid method also depends on the accessibility and quality of the primary and secondary data in the I-O processing method and table.
Several hybrid approaches have been proposed which merge two methods. It can be achieved either starting with an IO table and adding process data to specific production processes or starting with a process-based LCA and adding inputs when no process LCA data is available (Seo *et al.*, 2018).

2.8.4 Comparison of Methods

Framework process-based LCA databases for building materials, construction assistance, energy supply, transportation, and waste management services promote a comparable design, such as economic input-output tables. They both help decrease attempts to quantify embodied energy and greenhouse gas emissions of constructions.

The time required to create databases based on LCA background processes is the same as the time required to create environmentally friendly input output databases. The principal challenges concerning process-based LCA data are the system boundary and cut off criteria, the availability of company or sector-specific reliable and transparent data.

Most of the challenges are related to construction products manufactured overseas, where there are limitations for accessing data. Services such as planning (architectural duties) are usually not considered in the process-based LCA. However, they often have a minor role in comparison with the embodied energy or CO_2 footprint of a building.

If both the LCA database and environmentally extended I-O table are available, reliable, and adequate, the two approaches (process-based and I-O based) do not differ considerably in assessing the embodied energy or GHG emissions of a particular building.

The calculation of the embodied energy relying on an input-output-based hybrid method can be appropriate. The process data on energy inputs can be accumulated and entered into the input-output model to improve its trustworthiness (Dixit, 2013). Table 2.4 illustrates a comparison between the characteristics of each database and methods by presenting the advantages and disadvantages of each.

Table 2.4 Compilation of characteristics of Databases in methods of EE estimation (Azari & Abbasabadi, 2018)

	Process-based LCA	EIO-based LCA	Hybrid LCA
Description	• Tracks, compiles and aggregates the types and quantities of energy used in various stages of building life cycle. • Operation stage is excluded when the objective is only EE estimation.	• Translates the US economy models reported by the Department of Commerce into EE and other environmental impacts. • It uses a system boundary as broad as an entire economy.	• Combines process-based LCA and EIO-based LCA.
Advantages	• Generates building-specific EE results. • Allows for comparison of buildings. • Sources of higher EE can be identified and improvement is possible.	• Generates sector-specific EE results. • Extends system boundary which leads to more comprehensive results. • Allows for comparison of sectors. • Reliance on public national data. • Quicker analysis	• Combines advantages of previous methods and addresses their shortcomings.
Disadvantages	• Data-driven • Time-intensive • Reliance on proprietary data • Often, data from different sources must be combined which adds to uncertainty. • Data uncertainty • Underestimation of results due to narrow system boundary definition	• Does not account for variations within sector. • Does not allow for comparison of buildings within a sector. • Process improvement is not possible. • Data uncertainty	• Potential inconsistency in data sources and models. • Potential methodological inconsistencies • Data uncertainty
Tools/databases (and geographical coverage)	• Athena IE (North America) • AusLCI (Australia) • CMLCA (Europe) • Ecoinvent (Europe) • ELCD (Europe) • GaBi (Germany, US, Europe) • GREET (US) • Inventory of Carbon and Energy (UK) • Korean LCI (Korea) • Okobaudat (Germany) • SimaPro (Europe, Australia) • Tally (US, Europe) • US LCI (US)	• US economy databases • eiolca.net	• Combines tools and data sources available to use in previous two methods.

2.9 Embodied Energy Values of Bricks

Based on the data that have been collected through Bill of Materials in Greece, that helps to determine the weight of the materials used in Kg, the calculation of EE can be provided. The EE can be obtained by multiplying the mass of material achieved from Bom by its relevant EE coefficient in MJ/Kg unit. The observed differences in the values are due to the use of primary energy used in the calculations of primary energy consumption from electricity conversion according to the used database (Dascalaki, Argiropoulou, Balaras, Droutsa, Kontoyiannidis, 2021).

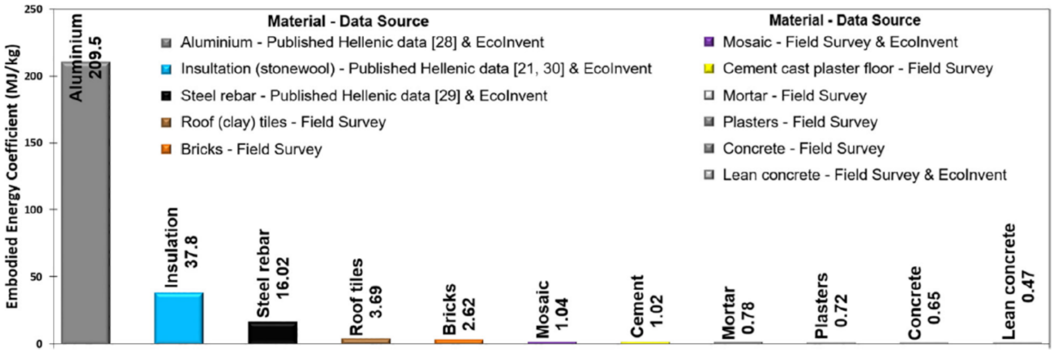

Figure 2.6. EE of different construction materials based on the field surveys and national public sources (Dascalaki *et al.*, 2021)

The values for EE of common materials used mainly in India that includes the spent energy for the extraction of raw material, transportation, and the production of material, are based on actual data of surveys. Differences in the EE of materials among studies arise from assessment methods and energy supply assumptions in terms of end use or primary energy (Praseeda, Reddy, Mani, 2015).

Table 2.5 EE of burnt clay bricks from some of case studies (Praseeda, Reddy, Mani, 2015)

Sl. no.	Processes	Energy (MJ/kg)				
	Type of kiln	Clamp	BTK	Down-draught	Hoffmann	VSBK
1	Indirect energy component					
1a	Extraction of raw materials	0	0	0	0	0
2	Direct energy components					
2a	Raw material transportation	0	0.044	0.022	0.023	0.045
2b	Process energy	2.9	2.18	3.46	2.92	1.16
3	Embodied energy of burnt clay brick (MJ/kg)	2.9	2.22	3.48	2.94	1.2

Table 2.6 EE of building materials in the Indian study versus literature data (Praseeda *et al.*, 2015)

Sl. no.	Building materials	EE in MJ/kg		
		Present study		Values from literature [14,18,20]
		For 1 kW h = 3.6 MJ*	For 1 kW h = 11.22 MJ**	
1	Cement	2.38 and 3.72	2.91 and 4.32	3.60–9.29
2	Steel	32.24	34.23	20.62–42.00
3	Glass	7.88	8.94	6.80–31.50
4	Aluminium rolled coil	141.55	150.69	130.0–236.80
5	Manufactured sand	0.037	0.062	0.10–1.14
6	Clay roofing tile	4.93	5.08	6.50
7	Burnt clay bricks	1.2–4.05	1.2–4.14	1.70–3.00
8	Solid concrete blocks	0.17–0.25	0.23–0.35	0.67–0.90
9	Laterite stone blocks	0.007	0.007	Not available
10	Ceramic tiles	10.63	18.00	2.20–14.87
11	Polished granite stone slab	0.105	0.111	0.01–13.90
12	Polished marble stone slab	1.53	1.53	2.00

* In terms of end use energy.
** In terms of primary energy.

CHAPTER 3

MATERIAL AND METHOD

This section is devoted to describing two important factors in the design of the research: The material and methodology of the study. This chapter presents a complete description of the methods of collecting and gathering required information, the type of materials assessed, and the methods used to achieve the embodied energy of the intended materials in separate sections.

3.1 Material

As it will be discussed more in the following sections, the material part encompasses; the data and information about the most commonly utilized masonary materials in the construction of the exterior walls of buildings in Iran, the data about the required quantities of materials based on proportions and construction criteria in Iran, and the description of the brick production chain in Tehran.

3.1.1 Brick Factories

In order to study the production technology for different types of bricks and measure the energy consumed during the production process in Iran, three brick factories were visited in Tehran. Two of these factories had similar production processes but due to the lack of special devices or meters for measuring the amount of gas and energy consumed, their information was not perfectly accurate. The third production plant had more precise and detailed information than the previous two factories, and due to the popularity of this factory and the abundance and variety of their products, it was possible to collect and obtain reliable information. This factory is 3 Km away from clay mines. A complete description of the production cycle of this factory is presented in detail below.

3.1.2 Types of Bricks

Three types of bricks that have the highest demand in the market were selected to be examined in more detail with respect to their embodied energies. These were: refractory brick generally used as facing bricks, red clay brick in Iran, , and hollow load bearing clay brick, having 10 holes (Figure 3.1).

i. The size of refractory brick is equal to 20×5.5×2.7 cm. The weight of each of these bricks before and after firing is equal to 1.250 and 1.050 Kg, respectively. There is a small amount of iron oxide in this type of brick. The presence of this substance in brick acts like lime and helps to melt silica at a lower temperature and causes the bricks to turn red after burning. This brick has recently become very popular in Iran for the facing of exterior walls because of their resistance to erosion, cold and hot weather and their light weight.

ii. The dimensions of solid red clay bricks are 20×10×5.5 cm. Each red clay brick weighs about 2 and 1.750 Kg before and after firing, respectively. These bricks are produced in beige to red color range. The color obtained in these types of bricks depends on their distance from heat. The bricks that have a smaller distance from the heat are lighter and the bricks that are arranged at a greater distance from the heat have a darker color. One of the most common uses of burnt clay bricks in Iran is the construction of masonry walls.

iii. The dimensions of each hollow clay brick is 21×10×5.5 cm. 1.250 Kg and 1.400 Kg is equal to the weight of each hollow clay brick after and before firing, individually. In the investigated factory, hollow clay bricks are produced in beige color. These bricks are used in the construction of roofs and walls in Iran.

Figure 3.1. Photos taken of refractory bricks (left), red clay bricks (middle), and hollow clay bricks (right), produced in the factory

In addition to the bricks whose data had to be collected from the survey in Iran, three other masonary materials, namely clay bricks, cement blocks, AAC blocks, and also a drywall were slected for comparison and their data were acquired from the ICE database. The description of the size, composition and application of each of these materials is described below and their photographs are shown in Figure 3.2 and Figure 3.3.

i. The dimensions of clay bricks mostly utilized in the construction of external walls in Iran are equal to 21×10×5.5 cm. The approximate weight of the studied clay brick is 2.3 kg. General composition of clay bricks is silica, alumina, with varying amounts of iron oxides and other materials that vary depending on the type of soil. The most common use of bricks in Iran is to build walls, facades, terraces, and also paving.

ii. The dimensions of common concrete blocks used in the construction of external walls in Iran are equal to 40×20×20 cm. Each of the concrete blocks weighs about 14 kg. Concrete blocks are mainly composed of cement and aggregate, which usually includes sand and gravel. They are widely used in building walls throughout Iran.

iii. The size of the AAC blocks is 60×20×20 cm. The weight of AAC block is 549 kg per cubic meter and the volume of each block is equal to 0.024 m^3 according to the dimensions (0.6 m×0.2 m×0.2 m). The general composition of these blocks includes silica, cement, lime, aluminum powder, and water. These blocks are suitable and widely used for the construction of internal and external walls in buildings.

iv. Regarding the description of the drywall which consists of mineral wool, cement panel, and plaster board, it can be stated that mineral wool is cut into the desired dimensions, and according to the area of the test wall which is 27 m^2, it can be concluded that the total required area of this material is equal to 27 square meters which is supplied with a thickness of 10 cm. The mineral wool used has a density of 80 kg/m^3. Fiber cement panel is used as external wall covering. The density of this panel is equal to 1,650 kg/m^3. Portland cement, trass, cellulose, polyethylene fibers, polyvinyl alcohol fibers, and water for mixing cement are the compounds needed to make a cement panel. Also plasterboard which is one of the other components of this type of wall, is composed of calcium sulfate and water. The density of plasterboard is equal to 950 kg/m^3. The main use of this type of wall in Iran is in the construction of external walls that insulate the interior space.

Figure 3.2. Photos of generic clay brick (left), concrete block (middle), AAC block (right)

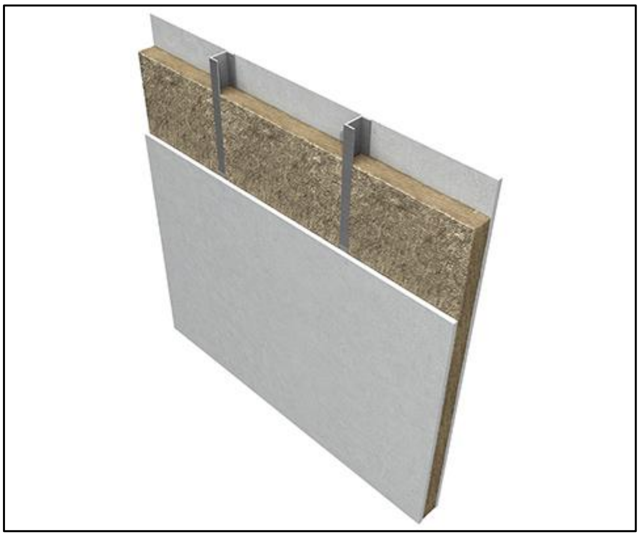

Figure 3.3. Drywall configuration

3.1.3 Test Wall's Characteristics

To investigate the embodied energy of the materials used in the construction of external walls, a hypothetical wall has been determined as the basis of the study, which is assumed to be built with various alternative material configurations. The dimensions of the wall are equal to 10 meters in length and the height of one floor, i.e., 2.70 meters. In the following sections, according to the construction criteria in Iran, the amount of energy consumption of each type of material for wall construction and consequently the mortar required for each wall has been determined and calculated.

Five scenarios of load bearing test wall were considered to compare the EE of different types of materials. Four of these walls were made with masonry and one was a drywall sysem. The comprehensive information about the structures needed to build this wall and the materials used has been calculated based on the Iranian standard number 2800, fourth edition. Detailed description of each of the scenarios related to the test walls using different materials is described below:

i. The wall in the first scenario is made of hollow clay bricks produced in a factory in Iran. Vertical H-shaped steel studs are used in walls of 4 meters and above. In fact, in the test wall, according to this standard, one H-shaped stud is used for every 5 meters, which is formed by connecting 2 U-shaped studs. Also, 2 U-shaped vertical steel studs are used on the right and left sides of the wall. The weight of these studs varies depending on the type of wall construction material. In the construction of brick walls, a stud with a size of 10 and a flange width of 4 cm is used. The weight of each square meter of iron sheet forming these beams, which have a thickness of 2 mm, is equal to 15.6 kg. In the structure of this type of walls, horizontal reinforcing is achieved by trusses, which are installed every 1.5 meters. The length of each truss is 3 meters and weighs 900 grams. Considering that the height of the hypothetical wall is 2.70 meters, as a result, only 1 truss is needed. The material of this truss is galvanized steel sheet. In addition to the mentioned structure, the main material of this wall is Iran's hollow clay brick with dimensions of 21×10×5.5 cm that weighs 1.250 Kg. The 1:3 cement-sand mortar is used in this wall with 1900 Kg/m^3 density and 1 cm thickness.

ii. The wall in the second scenario is made of generic clay brick as listed in ICE database. Apart from the masonry materials and mortar required to build this type of wall, the structure of this wall is similar to the previous wall which was made of Iran's hollow clay bricks. As a result, the EE of the structures used in this type of wall is the same as the previous wall. The masonry material used in this type of wall is clay brick, the dimensions of which are 21 × 10 × 5.5 cm, and its weight is 2,300 kg. The mortar used in this wall is also 1:3 cement-sand, with 1900 Kg/m3 density and with 1 cm thickness.

iii. The wall in the third scenario is made of concrete blocks. The structure used in this type of wall is similar to the previous two walls, with the difference that due to the larger dimensions of the concrete blocks, larger dimensions of the studs are also required. In the structure of the block wall, where the thickness of the material is greater, a stud with a size of 20 cm web and a flange width of 4 cm is used. The thickness of the iron sheet forming these studs is 2 mm, like the beams used in the brick wall, and each square meter of this iron sheet weighs 15.6 kg. The masonry material of this wall is concrete blocks, the dimensions of which are 40 × 20 × 20 cm. Since the weight of these blocks is not mentioned in the ICE database, the weight of the concrete blocks used in Iran, which is equivalent to 14 kg, is considered. Mortar is the last component that plays a role in the construction of this wall. The thickness of the mortar used in the arrangement of these blocks is equal to 1.5 cm. This mortar is cement-sand mortar in a ratio of 1 to 3.

iv. The fourth scenario is for the wall made of AAC blocks. In the structure of the AAC wall, in addition to the AAC blocks, U-bracket is used as an element to connect the blocks to the main structure of the building. The material of these brackets is steel. The method of using this structure is such that a 20 cm bracket is placed after every 3 blocks. Considering the dimensions of these blocks, which are 60 × 20 × 20 cm, as a result, these brackets are installed every 1.8 meters in length and every 60 cm in height. These fasteners are placed on the 4 sides of the wall, which is the wall frame. To connect and stick the blocks together, cement sand mortar is used in the ratio of 1:5.

v. The wall in the fifth scenario is a drywall system. Despite the difference between drywall and other walls, it is one of the popular systems in Iran, and for this reason, it has been chosen to calculate the amount of embodied energy in this wall and compare it with other walls. The structure of the drywall is slightly different from the previous walls. In the structure of this type of wall, a vertical profile is used every 60 cm along the length of the wall to connect the wall to the skeleton of the building, which is called a stud runner. The material of these profiles is galvanized steel, which are generally sold in 3-meter pieces, which have more thickness and strength compared to other lengths. In the structure of this type of wall, in addition to the vertical profiles, stud runners are also used on the 4 sides of the wall, which act like a frame to support this wall. Since the length of the test wall is 10 meters, 2 stud runners are needed for the top and bottom of the wall, each 10 meters long. Also, 2 stud runners with 2.70 meters long are needed for the 2 sides of the wall, which are 2.70 meters high. The length of each stud runner is equal to 3 meters. Each 3-meter profile of these stud runners weighs about 951 grams. Mineral wool batts are used as the infill material in these walls. The thickness of mineral wool batt is equal to 10 centimeters and has 80 kg/m^3 density. In the structure of these walls, two other materials should be used, including a cement board with a thickness of 1.8 cm for the outer part of the wall and two plaster boards each with a thickness of 1.2 cm for the interior of the wall to complete the wall. Each cement board is sold in dimensions of 1.2×2.4 meters and its weight is equal to 78.3 Kg. Each plaster board is also sold in 1.2×2.4 meter dimensions and each board weighs about 30 Kg.

3.2 Method

The processes in accumulating data, evaluation of the desired components, and achievement of the results of this evaluation are all presented in the method section.

3.2.1 Data Collection

The information and data of this research were collected through a visit to a brick factory in Tehran, the capital city of Iran. At first three brick factories were visited and finally Agor factory, which was more reliable and well known was chosen as the main source of information collection related to brick production. Also, the people working in this factory had more comprehensive knowledge and this makes the information more reliable. The information obtained from this factory was gathered during three visits to the mentioned factory. All 3 factories are located in the southernmost part of Tehran and outside the city. They are at a short distance from clay mines which are the source of the raw material required to make bricks so that the amount of transportation between the mine and the factory is minimized.

The information was collected through interviews with factory management and workers. General information, including the number of workers employed, the type of bricks produced, the means of transportation used and their fuel, the existing mills and the amount of electricity they consume, the type of furnaces and the amount of gas they consume have been obtained through interviews with the factory management. Also, the workers in the presence of the factory management presented information regarding the amount of soil used in each type of brick and the weight of different bricks, the dimensions of the bricks, the time required to bake each type of brick, the duration of using each of the mills for different amounts of soil, and their own working hours.

All the interviews were audio-recorded and further observations were noted down. Photographs have been taken of all stages of brick production inside the factory, from the means of transporting soil to grinding it, mixing, molding, filling the kilns, lighting the kilns to prepare the bricks for baking, and the operations of the workers. Also, in some parts of the factory, a video was taken to record the working time of some devices, and then by re-viewing the photos, videos, and recorded sounds, all the necessary tips and information were written down.

In addition to collecting local information related to the production of bricks in a factory in Iran, in order to evaluate the embodied energy of common external walls in Iran, which includes three masonary materials, namely clay bricks, cement blocks, AAC blocks, and also drywall system, the information from the ICE database is used. The assessment boundary of this database in the investigated materials is the same as the evaluated boundary in the bricks produced in Iran that is from cradle to gate.

The number of alternative materials used in each of these types of walls to build the test wall was obtained with the help of a structural engineer in Tehran. All the structures required for the construction of this wall have been calculated for different materials based on Iran's standard No. 2800, 4th edition. According to the required number of materials, the total weight of each of the materials used has been calculated and by applying the embodied energy coefficient provided by ICE Database for each material, the energy of different walls has been calculated.

3.2.2 Calculation of EE for Bricks

The EE calculations in this research are done on bricks based on the weight of the soil, which is equivalent to the soil used in the production of each brick. Each kiln has been selected as an example of other kilns according to its brick capacity, and electricity, gas, and energy consumption have been calculated according to the weight of the soil for the bricks arranged in the kiln to reach the embodied energy of each brick measured in megajoules per kilograms.

The total amount of energy consumed was obtained by summing up the fuel energy for transportation, the electricity used by the mills and the mixer and molding machines, the consumed energy from burning gas, and energy expended for manual labour. In general, the mentioned factors are among the energy consuming items considered in the production line. The calculations in this study are based on the net amount of soil, electricity, and gas that are needed in the production chain of bricks. The waste is not considered since there was no information about how much the gross amount might be. Also, it depends on many factors like workmanship, quality of soil, efficiency of power consuming systems, and efficient amount of gas consumed. Also in the investigated factory, the workers present in the plant reside and live in the same place where they work, therefore, their daily transportation from the factory to their homes is eliminated.

The details of the calculations performed for the energy calculation method of each step involved in the brick production process are as follows:

i. Transportation energy

The fuel consumption data of the vehicles used in the production process of the selected factory has been taken from the manufacturers catalog of these vehicles. This amount of consumption varies depending on the type of machine used and their load carrying capacity. The original Persian catalog and its English translation are shown in Appendix Table A and Table 3.1, respectively.

For more accurate calculations of the embodied energy of materials and the closeness of these figures to reality, the fuel consumption of all means of transportation involved in the brick production process has been considered. Based on the data collected from the production site and observations, the fuel consumed in the two main vehicles involved in this production is diesel. To calculate the transportation energy for each type of brick, first the required weight of soil to fill each kiln is calculated. The fuel consumption of the loader is calculated based on the amount of load, the duration of use of the loader based on the capacity of the loader, and the approximate time of using it to transport the desired amount of soil. As shown in equation 3.1 below, the soil capacity of each brick kiln is obtained by multiplying the number of bricks by their weight after baking, as the loader transport is for grinded soil without the addition of water.

$$\text{Soil capacity of each kiln (Kg)} = \text{number of bricks} \times \text{Weight of baked bricks (Kg)}$$

(3.1)

Considering that the loading capacity of the loader is equal to 2.35 tons, as a result, by dividing the calculated amount of required soil by 2.35, the number of times the loader must go to carry the needed amount of soil from the mound of grinded soil to enter the factory, is determined by Equation 3.2.

$$\text{The number of loader's trips} = \frac{\text{Amount of required soil (tons)}}{\text{2.35 tons (capacity of the loader)}} \qquad \textbf{(3.2)}$$

Since each round trip takes approximately 7 minutes, by multiplying the number of round trips necessary to deliver the soil to each furnace, the duration of using the loader for the soil of each brick is obtained as shown in Equation 3.3.

$$\text{Duration of using the loader} = \text{number of loader's trips} \times \text{7 min (each trip)} \qquad \textbf{(3.3)}$$

Therefore, in order to calculate the amount of diesel consumed, it is necessary to act according to the information provided in Table 3.1. Considering that the amount of fuel consumed per hour of work of a loader with a 123-hp engine is equal to 14 liters, as a result, the amount of fuel consumed per working time of the loader for transporting different soils can be calculated as shown in Equation 3.4.

$$\text{Fuel consumption (L)} = \text{Duration of using the loader (hr)} \times 14\ \text{(L/hr)} \qquad \textbf{(3.4)}$$

Table 3.1 Fuel consumption translated into English (by author); catalog retrieved from manufacturers website http://rahdar44.ir.

Consumption per hour worked	Fuel tank capacity (liters)	Engine power	Machine's name	Image
10 14 18 22 26 30 32	100 150 170 220 250 270 300	75-100 100-125 125-150 150-175 175-200 200-225 225-250	Loader	
Depending on the type of truck, traction and portability between 30 to 45 liters per 100 kilometers.	200	220	Truck	

The energy production capacity of diesel fuel is calculated to be 38 megajoules per liter (Soltani *et al*., 2013). As a result, based on Equation 3.5, to calculate the amount of energy consumed by the loader based on megajoules, the amount of fuel consumed in liters must be multiplied by a factor of 38 MJ/L to calculate the amount of energy obtained from burning the amount of diesel in megajoules.

$$\text{Energy consumed by the loader(MJ)} = \text{Fuel consumption (L)} \times 38\ (\text{MJ/L}) \qquad \textbf{(3.5)}$$

To reach the specified unit of EE, which is MJ/Kg, the amount of fuel used for 1 kg of soil of each type of brick should be calculated. As a result, the amount of energy consumed from diesel fuel should be divided by the total weight of the transported soil in order to obtain the amount of embodied energy resulting from transporting 1 kg of the soil as shown in Equation 3.6.

$$\text{EE of transportation (MJ/Kg)} = \frac{\text{Energy consumed by the loader(MJ)}}{\text{Total weight of the transported soil (Kg)}} \qquad \textbf{(3.6)}$$

ii. Electricity Consumption of Mills And Machines

There are three types of mills and a mixer, a lifting machine, and a press molding machine inside the factory that are used for grinding, mixing, and molding soils for bricks. Since each of these machines has a different power and electric motor and each of the mills is specific to a different type of bricks, as a result, the energy consumption of the mills and machines used in the production of each of the bricks was examined.

To calculate the amount of electricity consumed by the mills and machines, the number of mills needed for the soil should be considered first, according to the type of brick and soil required. Calculations of electricity consumption of these systems depend on the duration of their operation. According to the information collected in relation to the mills and machines, which states the time required to grind, mix, and mold a certain amount of soil, it can be considered as the power of the mill in tons per hour unit as shown in Equation 3.7.

$$\text{Mills and Machines power (ton/hr)} = \frac{\text{Certain amount of soil (ton)}}{\text{Period of time (hr)}} \qquad \textbf{(3.7)}$$

As a result, by considering the total amount of soil required for different bricks to fill each of the kilns, the time required to use each of the mills can be calculated.

$$\text{Time required to use a mill or machin(hr)} = \frac{\text{The total amount of required soil (ton)}}{\text{Mills power (ton/hr)}} \qquad \textbf{(3.8)}$$

The energy of each of the mills and machines is supplied by an electric motor. The power consumption of electric motors is in horsepower units. In order to convert the power of the electric motors into an energy unit, this unit must first be converted from horsepower to kilowatts according to Equation 3.9, and then to megajoules, each of which has a separate conversion factor (1 hp = 0.7456 kW).

$$\text{Energy in hp} \times 0.7456 = \text{Energy in kilowatts} \qquad \textbf{(3.9)}$$

After converting the power consumption of the mills and machines from horsepower unit to kilowatts, the amount of electricity consumed in kilowatts for the period of time the machines and mills is used can be obtained based on Equation 3.10.

$$\text{Electricity consumption (kWh)} = \text{power of electric motor(kW)} \times \text{Time required to use a mill (hr)} \qquad \textbf{(3.10)}$$

Now, in order to be able to reach the unit of embodied energy, i.e., megajoules, the amount of consumed electricity in kWh must be converted into megajoules by applying equation 3.11.

$$\text{Electricity in kWh} \times 3.6 = \text{Electricity in Megajoules} \qquad \textbf{(3.11)}$$

After obtaining the amount of energy consumed for the use of each of mills and machines in megajoule unit, by dividing the calculated amount of energy by the total weight of the soil calculated for the capacity of each kiln, in kilograms, it is possible to calculate the embodied energy of each kilogram of soil in the mills and other power-consuming machines such as mixer, elevator, and molding machine stage as it is shown in Equation 3.12. It should be considered that in calculating the weight of the soil to calculate the amount of electricity consumption in different systems in the 3 stages of the mills, the weight of the examined soil is considered based on the weight of the bricks after baking, which is actually the net weight of the soil without water, but from the mixer stage onwards, the weight of the soil due to the addition of water is considered based on the weight of the bricks before firing.

$$\text{EE of mills or machines (MJ/Kg)} = \frac{\text{Sum of the energy consumed by the mills or machines(MJ)}}{\text{Total weight of the grinded, mixed or molded soil (Kg)}}$$

(3.12)

By summing up the energy consumption calculated from the use of each of the electrical devices that play a role in the production process of a brick, the contribution of that stage to the total embodied energy can be obtained. It should be noted that in these calculations, the amount of energy needed to start and stop the machines is not taken into account, and this energy is only for grinding the soil, mixing it, and molding the bricks.

iii. Gas Consumption in Kilns for Firing

There are special kilns for baking each type of bricks, which differ from each other in terms of capacity and dimensions. Since the firing of bricks in these kilns is done by natural gas, different information and calculations are required for the amount of gas used for firing each type of brick.

Factors involved in the amount of energy caused by burning gas for baking bricks include the weight of soil and the amount of gas consumed per a certain weight of soil. To calculate the weight of the examined soil at this stage, the number of bricks in each furnace must be multiplied by the weight of the bricks before firing, because at this stage, after passing through the mills, water has been added to the soil and the burned gas is used to bake more weight of soil.

After this stage, according to the information collected regarding the amount of gas consumed for baking bricks of each furnace, the amount of energy consumed can be reached. First, the amount of gas consumed per cubic meter must be converted into megajoules. According to the 8th step of Iran's Criteria for Energy Consumption and

Energy Labeling Instruction, to calculate gas consumption in terms of (kWh), it is necessary to multiply the amount of gas consumption by two factors: 0.278 as the megajoule to kWh conversion factor and 37.68 as the calorific value of gas (MJ/m^3), as shown in equation 3.13 or 3.14.

$$\text{Energy from gas consumption (kWh)} \\ = \text{Gas consumption (m3)} \times 0.278\ (\text{kWh/MJ}) \times\ 37.68\ (\text{MJ/m3})$$

(3.13)

Or

$$\text{Energy from gas consumption (kWh)} = \text{ gas consumption (m3)} \times 10.475 \quad \textbf{(3.14)}$$

Then, to obtain the calorific value of each cubic meter of Iran's gas and reach the megajoule unit, the amount of gas consumed based on kWh must be multiplied by a factor of 3.6 based on equation 3.15.

$$\text{Calorific value of each m3 of gas (MJ)} = \text{Energy from gas consumption (kWh)} \times 3.6$$

(3.15)

Finally, according to the Equation 3.16, by dividing the amount of energy obtained from gas burning in megajoules by the total weight of the brick soil of each kiln, the share of the embodied energy resulting from this stage can be reached. It should be considered that the amount of gas loss is not taken into account in the calculations and all the amounts of consumed gas are completely used for baking bricks.

$$\text{EE of gas consumption (MJ/Kg)} = \frac{\text{Amount of energy obtained from gas burning(MJ)}}{\text{Total weight of the brick soil of each kiln (Kg)}}$$

(3.16)

iv. Energy Expended by the Workers

According to the observations obtained from the evidence in the investigated factory, the age range of the workers working in this factory is between 20 and 30 years. Since the work in the manufacturing factories is considered to be almost heavy work, according to Table 2.1, since the heart rate is between 110 and 129, the average energy consumption of each worker is equal to 4.11 kilocalories per minute of work.

In this study, in order to calculate the energy expended by the workers, the number of workers engaged in the production of each type of brick was counted by asking the management. After that, the working hours of the workers have been checked. According to the information presented in table 2.1 and that the average amount of calories expended by each worker in hard labor is equal to 4.11 kilocalories per minute, it is possible to obtain the number of calories expended by them during their working time. In this way, the duration of their work in minutes should be multiplied by the coefficient of the average amount of calories consumed per minute as shown in equation 3.17.

$$\text{Energy expended by a worker (Kcal)} = \text{Duration of a manual work (min)} \times \text{Energy for hard labour (Kcal/min)} \quad \textbf{(3.17)}$$

Since all the units have been standardized, it is necessary to convert the unit of kilocalories to megajoules also, which according to FAO/WHO/UNU, the conversion factor of kilocalories to megajoules is equal to 0.004184. In fact, each kilocalorie is equal to 0.004184 megajoules.

$$\text{Energy expended in MJ} = \text{Energy expended in Kcal} \times 0.004184 \text{ (MJ/Kcal)} \quad \textbf{(3.18)}$$

Finally, to calculate the share of embodied energy of this stage, the amount of energy expended by the workers in megajoules should be divided by the weight of soil required to fill each kiln in Kg.

$$\text{EE of manual work by workers (MJ/Kg)} = \frac{\text{Energy expended by a worker (MJ)} \times \text{No.of workers}}{\text{Total weight of soil required to fill each kiln (Kg)}} \quad \textbf{(3.19)}$$

3.2.3 Calculation of EE for Materials in Test Wall

To calculate the embodied energy of alternative materials in the construction of external walls in Iran, the data was first obtained by interviewing a structural engineer in Iran. All necessary quantities of materials and other accessories needed for construction according to Standard No. 2800, 4th edition of Iran has been calculated. This standard is a set of structural rules for the seismic design of structures against earthquakes, as well as the rules for masonry buildings.

It should be considered that the calculation of the embodied energy of each component of the wall has been done according to equation 3.20.

$$\text{EE of each component} = \text{Amount of required component (Kg)} \times \text{Material's EE coefficient in (MJ/Kg)} \quad \textbf{(3.20)}$$

i. Iran's Hollow Clay Brick

Since the trusses are common between all three walls made of Iran's hollow clay brick, comparable to the generic clay brick listed in ICE, and concrete block and has the same dimensions and weight, its embodied energy can be calculated and then applied to the three walls. The length of the horizontal trusses required to be placed in the middle of this wall is equal to 10 meters. Since each truss is produced in a length of 3 meters, as a result, 3 units of 3-meters and one unit of 1-meter are needed for the desired wall. Each 3-meter truss weighs about 900 grams, so for 3 3-meter units and one 1-meter unit, the total weight will be 3 Kg based on {(3 × 900g) + (1/3 × 900g)}.

The embodied energy of galvanized steel sheet can be obtained by multiplying the amount of required galvanized sheet by its energy coefficient in ICE database. The total embodied energy of the trusses in this wall can be calculated in this way, according to Equation 3.20.

Other elements used in this type of wall are studs. The type of studs implemented in this type of walls, as mentioned earlier, are 2 U-shaped vertical studs and one H-shaped stud. Each square meter of iron sheet forming these studs with a thickness of 2 mm, weighs about 15.6 kg. For the structure of this wall, 4 of these studs, each 2.7 meters long, are needed to be embedded on both sides of the wall as well as in the middle of the wall. Based on ICE database, the embodied energy coefficient of the steel used in these studs is equal to 20.1 MJ/Kg, so, the total embodied energy of the steel studs applied in this wall can be calculated by multiplying the amount of required iron sheet by its energy coefficient in ICE database as it is shown in Equation 3.20.

After the installation of the structural materials, it is time to arrange the bricks and add mortar. To construct the test wall with Iran's hollow clay brick, the number of required bricks should be calculated.

To calculate the number of bricks that are required, the following method as explained in equation 3.21 and 3.22 should be applied. In this way, the length and width of the assumed wall should be divided by the length of the bricks plus the thickness of the mortar and the width of the bricks plus the thickness of the mortar, respectively.

$$\text{Number of required bricks in length} = \frac{\text{Length of the wall (cm)}}{\text{Length of the brick (cm)} + \text{Thickness of the mortar(cm)}} \qquad \textbf{(3.21)}$$

$$\text{Number of required bricks in width} = \frac{\text{Width of the wall (cm)}}{\text{Width of the brick (cm)} + \text{Thickness of the mortar (cm)}} \qquad \textbf{(3.22)}$$

The total number of bricks needed is calculated by multiplying the number of bricks needed in length by the number of bricks required in width as shown in equation 3.23.

$$\text{Total number of required bricks} = \text{Bricks required in length} \times \text{Bricks required in width} \qquad \textbf{(3.23)}$$

The weight of each of Iran's hollow clay brick examined in the studied manufacturing plant is equal to 1.250 Kg.

To calculate the total weight of the bricks used, the required number of bricks obtained from equation 3.23 should be multiplied by the weight of each brick as shown in equation 3.24.

$$\text{Total weight of the bricks (Kg)} = \text{Number of bricks used} \times \text{weight of each brick} \qquad \textbf{(3.24)}$$

The embodied energy coefficient of Iran's hollow clay brick will be calculated in results and to obtain the total embodied energy of the hollow clay bricks used, the total weight of the bricks should be multiplied by its embodied energy factor according to Equation 3.20.

The last component applied in this structure is the mortar. In order to obtain the required volume of this mortar for use in the structure of this wall, the number of bricks required with mortar to cover the wall should be subtracted from the number of bricks required to cover the wall without using mortar based on equation 3.25 and 3.26. The amount of mortar used is calculated from the difference between these two. So:

$$\text{Number of required bricks in length} = \frac{\text{Length of the wall (cm)}}{\text{Length of the brick (cm)}} \qquad \textbf{(3.25)}$$

$$\text{Number of required bricks in width} = \frac{\text{Width of the wall (cm)}}{\text{Width of the brick (cm)}} \qquad \textbf{(3.26)}$$

The required volume of this mortar is calculated according to Equation 3.27 which is:

$$\text{Required volume of mortar} = (\text{number of required bricks without using mortar} - \text{number of required bricks with mortar}) \times \text{volume of a brick} \qquad \textbf{(3.27)}$$

Based on Equation 3.28 and according to the ICE database, considering the density of the mortar, which is 1900 Kg/m^3, the weight of the mortar used is calculated.

$$\text{Weight of the mortar} = \text{Required volume of mortar} \times \text{Density of the mortar} \qquad \textbf{(3.28)}$$

Based on ICE database, the embodied energy coefficient of the 1:3 cement-sand mortar is equal to 1.33 MJ/Kg, so, the total embodied energy of the mortar used in this wall can be calculated based on Equation 3.20.

So, the overall embodied energy of this wall is equal to the sum of the embodied energy of each component used in its construction, which is equal to:

$$\text{Total EE of clay brick wall} = \text{EE of bricks} + \text{EE of trusses} + \text{EE of suds} + \text{EE of mortar} \quad \textbf{(3.29)}$$

ii. Generic clay brick based on ICE database

Apart from the masonry materials and mortar required to build this type of wall, the structure of this wall is similar to the previous wall which was made of Iran's hollow clay bricks. As a result, the EE of the structures used in this type of wall is the same as the previous wall.

To construct the test wall with ICE generic clay brick, the number of required bricks should be calculated using Equation 3.21 and 3.22. The total number of required bricks needed is calculated by applying equation 3.23. The weight of each of generic clay brick examined based on ICE database is equal to 2.300 Kg. To calculate the total weight of the bricks Equation 3.24 is used. According to the ICE database, The embodied energy coefficient of generic clay brick is 3 MJ/Kg and to calculate the total embodied energy of the generic clay bricks Equation 3.20 should be applied.

Mortar is the last component applied in this structure of this wall. Since the amount of mortar used depends on the dimensions of the brick, and the dimensions of this type of brick are the same as Iran's hollow clay brick, and the thickness of the mortar used in this type of brick is equal to 1 cm of mortar and the type of mortar used is 1:3 cement-sand, as a result, the embodied energy of the mortar in this wall is equal to the embodied energy of the mortar used in the wall made of Iran's hollow clay brick. So the total embodied energy of this wall can be calculated according to Equation 3.29.

iii. Concrete block based on ICE database

The number of trusses used in the structure of this wall is the same as the previous two walls made of Iran's hollow clay brick and generic clay brick. As a result, its embodied energy value is the same as the previous two walls, and this value is also applied in the calculation of the total energy of this wall. As mentioned in the description of the structure of this type of wall, another material used in this type of wall is the studs. Each iron sheet to form the stud weighs about 15.6 Kg/m^2. 4 of these studs are applied in the structure of this wall. Based on ICE database, the embodied energy coefficient of the steel used in these studs is equal to 20.1 MJ/Kg, as a result, the embodied energy of the steel studs used in our test wall can be calculated based on Equation 3.20.

The dimensions of the used blocks are equal to 40 × 20 × 20 cm. The number of required blocks to construct the test wall is calculated based on Equation 3.21 and 3.22 and the total number of needed blocks is calculated based on Equation 3.23. Each concrete block weighs about 14 kg. To calculate the total weight of the used blocks equation 3.24 is applied.

The embodied energy coefficient of concrete block with 8 MPa Compressive Strength is 0.59 MJ/Kg. To calculate the total embodied energy of the concrete block, Equation 3.20 should be applied.

The thickness of the mortar used in the arrangement of these blocks is equal to 1.5 cm. This mortar is 1:3 cement-sand mortar. Equations 3.25, 3.26, and 3.27 should be used to obtain the required volume of this mortar for use in the structure of this wall. Based on Equation 3.28 and according to the ICE database, considering the density of the mortar, which is 1900 Kg/m^3, the weight of the mortar used is calculated.

The embodied energy coefficient of the 1:3 cement-sand mortar is equal to 1.33 MJ/Kg based on ICE database. Equation 3.20 can be used to calculated the total embodied energy of the mortar used in this wall. According to Equation 3.29, the total embodied energy of this wall can be calculated.

iv. AAC block based on ICE database

To build this type of wall, the first required component, bracket, is installed first. Since each bracket is installed for 3 blocks, considering the length of this block is 60 cm, these brackets should be placed every 1.8 meters of length. Considering that the length of the test wall is 10 meters, as a result, 5 brackets are installed for the bottom and 5 brackets for the top of the wall. Also, one bracket is placed at the height of the wall for every 3 blocks, i.e., every 60 cm of height. So, considering the height of the wall, which is 2.70 meters, 4 brackets are installed on the left side and 4 brackets on the right side of the wall. Thus, the total number of brackets required for the frame of this wall is equal to 18.

Since the length of each bracket is 20 cm, 3.6 meters of brackets are needed for 18 brackets. The material of these brackets is steel, and its dimensions and weight are equal to the weight of the profiles used in the studs for concrete block wall mentioned in previous scenario. Considering the width of this profile, which is 0.28 m and the required length, which is 3.6 meters, the required area of this steel is equal to 1 square meter. Considering that the weight of each square meter of this steel is equal to 15.6 kg, as a result, the weight of steel for making brackets is also equal to 15.6 kg.

Based on the ICE database and considering that the embodied energy coefficient of steel is equal to 20.1 MJ/Kg the total embodied energy of steel in brackets can be calculated by using Equation 3.20.

Each block's dimension is equal to 60 × 20 × 20 cm, so to calculate the required number of blocks, calculations can be done according to Equation 3.21, 3.22, and 3.23.

The AAC blocks density is 549 Kg/m^3 and the volume of each block is equal to 0.024 m^3 (0.6 × 0.2 × 0.2). Equation 3.30 can be used to calculate the total weight of the used blocks.

$$\text{Total weight of the used blocks} = \text{number of used blocks} \times \text{volume of each block} \times \text{Density of the block} \quad \textbf{(3.30)}$$

According to the ICE database, the embodied energy coefficient for AAC block is equal to 3.5 MJ/Kg. To calculate the total embodied energy of the AAC block, Equation 3.20 should be applied.

The thickness of the mortar used in the structure of this wall is equal to 1.5 cm. This mortar is 1:5 cement-sand mortar. Equations 3.25, 3.26, and 3.27 should be used to obtain the required volume of this mortar. Based on Equation 3.28 and according to the ICE database, considering the density of the mortar, which is 1900 Kg/m^3, the weight of the mortar used is calculated. As presented in the ICE database, the embodied energy coefficient for this type of mortar, which is a 1:5 cement-sand type, is 0.97 MJ/Kg. Equation 3.20 can be used to calculated the total embodied energy of the mortar. According to Equation 3.29, the total embodied energy of this wall can be calculated.

v. Drywall system based on ICE database

To calculate the number of middle vertical profiles that are installed every 60 cm, the length of the 10-meter wall should be divided by 60 cm. As a result, about 16 stud runners, each 2.70 meters long, are needed. In addition, 2 stud ruuners of 10-meters and 2 stud runners of 2.7-meters are needed for the frame of the wall.

As a result, the total length required for the stud runners to build this wall structure is equal to 68.6 meters {(2 × 10 meters) + (16 × 2.7 meters) + (2 × 2.7 meters)}.

The weight of each 3-meter stud runner is equal to 951 grams, so 23 of these profiles will weigh 21.87 kg. The material of stud runners is galvanized steel and Embodied energy of galvanized steel sheet according to ICE is equal to 22.6 MJ/Kg. The embodied energy of the galvanized steel sheet used in our test wall can be calculated based on Equation 3.20.

Bearing in mind that the volume of mineral wool that we needed to build this wall is equal to 2.7 m^3 (10 × 2.7 × 0.1), and since the density of this material is 80 Kg/m^3, as a result, this volume will weigh 216 kg (2.7 m^3 × 80 Kg/m^3). The embodied energy coefficient of mineral wool according to ICE database is equal to 16.6 MJ/Kg. Equation 3.20 can be used to calculate the embodied energy of the used mineral wool. The number of required plasterboard and cemenet boards can be obtained by using Equation 3.31.

$$\text{Number of required plasterboard or cemenet boards} = \frac{\text{Area of the test wall (m2)}}{\text{Area of each plaster board or cement board (m2)}}$$

(3.31)

The weight of the used cement boards or plasterboards can be calculated according to Equation 3.32.

$$\text{Weight of the used boards} = \text{Required number of boards } \times \text{Weigh of each board}$$

(3.32)

The embodied energy coefficient of cement board and plasterboard according to ICE database is 10.40 MJ/K, 6.75 MJ/Kg, respectively. Equation 3.20 can be used to calculate the embodied energy of the used boards.

3.2.4 Implementation of the Steps Involved in LCA

As mentioned in the literature review section, the assessment of the whole or part of the life cycle of materials requires the examination of 4 stages, which are cited in ISO 14040:2006. These are defining the goals and scope; analysing the invetory; assessing the life cycle impacts; and interpreting the results. In the following sections, each of these 4 steps have been explained separately.

3.2.4.1 Goal and Scope Definition Stage

The goals and scope of this research are discussed separately below.

- Evaluating the primary embodied energy in the production of the most widely used type of bricks in Iran and the widely used materials in the construction of external walls of buildings is the main goal and scope of this research.
- Obtaining the embodied energy of the clay bricks, concrete blocks, AAC blocks, and the drywall system used in the construction of external walls in Iran, according to the amount of material utilized and applying the coefficients of each material based on the ICE database.
- In order to compare the results obtained from the investigations and evaluations, the MJ/Kg unit has been chosen as the common unit of measurement.
- Among the different stages during the lifetime of materials, the cradle to gate which is the production stage of materials has been chosen as the main boundary of this research. The examined steps and evaluation units related to each step are categorized in Table 3.2. The investigated factories were built at a distance of 3 km from the clay sources, so the distance to transport the soil from the mines to the factory was very small and ignored. In the process of gathering information, the only stage that the manager and workers of the factory did not have information about was the soil extraction stage because in Iran the extraction process is done by government teams and the brick manufacturers buy the soil from them. For this reason, the energy of that stage of the production process was not include.

Table 3.2 The examined steps and evaluation units related to the LCA of each step of brick production

The examined process	Units
Transportation	MJ/kg
Material production process	MJ/kg
Labor work power	Kcal and MJ/Kg

3.2.4.2 Inventory Analysis Stage

To fulfil the life cycle assessment of examined materials two sets of data sources are relied on. The first source is the the Inventory of Carbon and Energy (ICE) V2.0 database, which was launched in Jan 2011 and is the most acceptable free database for embodied energy and embodied carbon; while the second source is the local factory from where information and data were collected through meetings with the production engineer/ factory manager/ workers, during the site and factory visits. The cases examined in ICE database include mining, construction and production, and the cases examined in the visit of the brick factory include production and construction, transportation, and labor (manpower). The calculations made to reach the results were obtained by multiplying the amount of materials used in the construction of the test external wall by the coefficients provided by the ICE database. These calculations include both these computations and other necessary formulas mentioned in literature review section.

3.2.4.3 The Impact Assessment Stage

For the impact assessment stage, after calculating the amount of energy consumed in each of the stages of producing the examined bricks, in order to reach the final embodied energy, all the energies spent in the production of each type of brick were summed together. After reaching a final number for the embodied energy of each of the bricks, they can be compared from the energy consumption point of view of in the production process. It is also possible to compare the share of energy consumed in each of the production stages with other stages in order to understand which of the production processes play the greatest role in increasing the embodied energy of a brick.

Also, in comparing the test wall with different materials, in addition to comparing the overall EE of the walls with each other, it is possible to understand the most important factor in increasing the embodied energy of a wall.

The results obtained from the environmental impact assessment which is related to the embodied energy of the studied material are described with more detailed and complete explanations in Chapter 4.

3.2.4.4 Interpretation Stage

At this stage the way of interpreting the results is described, i.e. what data was taken into considerations, which stages of EE were taken into consideration, and which sort of environmental impacts were considered,

Section 5 discusses and interprets the outcomes achieved by carrying out the LCA method. The results were compared and the reasons for the differences and factors affecting each of the outcomes were interpreted.

CHAPTER 4

RESULTS

The results of all the equations and calculations performed on the information collected from the visited site as well as the calculations performed on the types of wall materials and as a result of obtaining their embodied energy are presented in detail in this section.

4.1 Calculation of Transportation Energy

Since the transportation of materials by different means of transportation plays an important role in the production of materials and due to the consumption of different fuels, the amount of energy consumed affects the amount of total energy, for this reason, in the following sections, all the calculations related to transportation materials and, of course, the amount of fuel consumed will be calculated for this operation. According to the information collected in the first stage, which is the stage of mining and transferring clay from the sources to the factory, this transportation is done by 24-ton trucks. Another utilized vehicle which is illustrated in Figure 4.1, is a loader capable of carrying two tons of material, which is used inside the factory to move soil and materials from storage to mills.

Figure 4.1. Loader machine with the ability to carry 2.5 tons inside the site to move soil

The highest density of dry clay by considering the optimized moisture, is 1.573 gm/cm^3 (Gupta, R. C *et al.*, 2012). In order for the units to be unified and to be able to be included in the calculations, the amount in kg/m^3 is equal to 1573 kg/m^3.

The most used means of transportation, the loader HWL65-1 was used inside the factory site. The most important technical specifications of this loader are shown in Table 4.1. It has a soil carrying capacity of 1.8 cubic meters and has a power of about 123 horsepower. Usually, 1.5 cubic meters of the tank volume is filled in each transfer. According to the catalog presented in the Table 3.1, the loader with 123 horsepower is placed in the second category, which consumes about 14 liters of diesel per hour of work. Considering that each cubic meter of clay is equivalent to 1573 kg (Gupta, R. C *et al.,* 2012), so the loader with the ability to carry 1.5 cubic meters of soil is equivalent to 2.35 tons of soil. Each round trip from the mill located in the workshop area to the internal mills takes about 7 minutes. This time is necessary for calculating the amount of time the loader works and, as a result, fuel consumption.

Table 4.1 Technical specifications of HWL65-1 loader retrieved from http://hepcoir.com

General	Unit	HWL 65-1
Engine Make	-	SHANGHAI DIESEL
Engine Model	-	SC7H125.1G2
Power at 2300 RPM	hp	123
Engine Type	-	Water-Cooled, 6-cycle
Toruqe Max	Nm	500
Number of Cylinders	-	6
Emission Certification	-	EPA Tier II
Breakout force	KN	101
Bucket capacity	(m^3)	1.8

4.1.1 Refractory Bricks

The size of refractory brick is equal to 20×5.5×2.7 cm and its weight is equal to 1.250 and 1.050 Kg before and after firing respectively. Based on **Equation 3.1**, the soil capacity of refractory brick kiln is:

Soil capacity of refractory brick kiln (Kg)=11000× 1.050(Kg) = 11550 Kg

The number of loader trips to transport 11.550 tons of soil is calculated according to **Equation 3.2**

$\text{The number of loader's trips} = \frac{11550}{2.35 \text{ tons}} \approx 5 \text{ times}$

Based on **Equation 3.3**, the duration of operation of the loader to carry 11.55 tons of soil:

$\text{Duration of using the loader} = 5 \times 7 \text{ min (each trip)} = 35 \text{ min}$

Based on **Equation 3.4**, the amount of fuel consumption during the operation of the loader:

$$\text{Fuel consumption (L)} = 0.58\ (\text{hr}) \times 14\ (\text{L/hr}) = 8.12\ \text{L}$$

Since the energy production capacity of diesel fuel is calculated to be 38 megajoules per liter (Soltani *et al.,* 2013), So **Equation 3.5** is used to convert loader's fuel consumption to energy unit (MJ). So:

$$\text{Energy consumed by the loader(MJ)} = 8.12\ (\text{L}) \times 38\ (\text{MJ/L}) = 308.56\ \text{MJ}$$

Equation 3.6 is used to obtain the EE resulting from transportation of soil for refractory brick. So:

$$\text{EE of transportation (MJ/Kg)} = \frac{308.56}{11550\ (\text{Kg})} = 0.02\ (\text{MJ/Kg})$$

As a result, 0.02 megajoules of energy is used to trasnport per kilogram of soil. By multiplying the obtained number by the weight of each baked brick, the amount of transportation energy consumed for 1 unit is obtained. as a result:

0.02 (MJ/Kg) × 1.050 Kg = 0.021

In conclusion, 0.021 megajoules of energy is consumed to transfer each refractory brick that weighs about 1.05 kg.

4.1.2 Red Clay Bricks

20 x 10 x 5.5 cm are the dimensions of studied red clay bricks. Each red clay brick weighs about 2 and 1.750 Kg before and after firing respectively. Each red clay brick kiln holds 16,000 bricks. Based on **Equation 3.1**, the soil capacity of red clay brick kiln is:

Soil capacity of red clay brick kiln (Kg)=16000× 1.750(Kg) = 28000 Kg or 28 ton

The number of loader trips to transport 28 tons of soil is calculated according to **Equation 3.2**

$\text{The number of loader's trips} = \frac{28}{2.35\ \text{tons}} \approx 12\ \text{times}$

Based on **Equation 3.3**, the duration of operation of the loader to carry 28 tons of soil:

$\text{Duration of using the loader} = 12 \times 7\ \text{min (each trip)} = 84\ \text{min or 1.4 hr}$

Based on **Equation 3.4**, the amount of fuel consumption during the operation of the loader:

$\text{Fuel consumption (L)} = 1.4\ \text{(hr)} \times 14\ \text{(L/hr)} = 19.6\ \text{L}$

Equation 3.5 is used to convert loader's fuel consumption to energy unit (MJ). So:

$\text{Energy consumed by the loader(MJ)} = 19.6\ \text{(L)} \times 38\ \text{(MJ/L)} = 744.8\ \text{MJ}$

Equation 3.6 is used to obtain the EE resulting from transportation of soil for red clay brick. So:

$$\text{EE of transportation (MJ/Kg)} = \frac{744.8}{28000\ \text{(Kg)}} = 0.02\ \text{(MJ/Kg)}$$

As a result, 0.02 megajoules of energy is used to trasnport per kilogram of soil. So the amount of transportation energy consumed for 1 unit of red clay brick is:

0.02 (MJ/Kg) × 1.750 Kg = 0.035

So, 0.035 megajoules of energy is consumed to transfer each red clay brick that weighs about 1.750 kg.

4.1.3 Hollow Clay Bricks

The dimension of each hollow clay brick is 21×10×5.5 cm. 1.250 Kg and 1.400 Kg is equal to the weight of each hollow clay brick after and before firing, individually. Like the red clay brick kiln, each hollow clay brick kiln has a capacity of 16,000 bricks. Based on **Equation 3.1**, the soil capacity of hollow clay brick kiln is:

Soil capacity of hollow clay brick kiln (Kg)=16000× 1.250(Kg) = 20000 Kg or 20 ton

The number of loader trips to transport 20 tons of soil is calculated according to **Equation 3.2**

$$\text{The number of loader's trips} = \frac{20}{2.35\ \text{tons}} \approx 9\ \text{times}$$

Based on **Equation 3.3**, the duration of operation of the loader to carry 20 tons of soil:

$$\text{Duration of using the loader} = 9 \times 7\ \text{min (each trip)} = 63\ \text{min or}\ 1.05\ \text{hr}$$

Based on **Equation 3.4**, the amount of fuel consumption during the operation of the loader:

$$\text{Fuel consumption (L)} = 1.05\ (\text{hr}) \times 14\ (\text{L/hr}) = 14.7\ \text{L}$$

Equation 3.5 is used to convert loader's fuel consumption to energy unit (MJ). So:

$$\text{Energy consumed by the loader(MJ)} = 14.7\ (\text{L}) \times 38\ (\text{MJ/L}) = 558.6\ \text{MJ}$$

Equation 3.6 is used to obtain the EE resulting from transportation of soil for hollow clay brick. So:

$$\text{EE of transportation (MJ/Kg)} = \frac{558.6}{20000\ (\text{Kg})} = 0.02\ (\text{MJ/Kg})$$

As a result, 0.02 megajoules of energy is used to trasnport per kilogram of soil. So the amount of transportation energy consumed for 1 unit of hollow clay brick is:

$0.02\ (\text{MJ/Kg}) \times 1.250\ \text{Kg} = 0.025$

So, 0.025 megajoules of energy is consumed to transfer each hollow clay brick that weighs about 1.250 kg.

4.2 Specifications of Mills

There are 3 different types of mills for grinding and crushing the small stones and soil used in this factory, each of which is used depending on the type of brick produced. Depending on the capacity of the mill and the softness and hardness of the required soil, electric motors with different power are used in mills. The first mill which is presented in Figure 4.2 is a hammer mill that works to crush the soil with a 75-horsepower electric motor. This machine grinds 50 tons of soil in 3 hours. The predominant dimensions of the first stage of gravel mills are 40×40×40 cubic millimeters. The result of this level of grinding is presented in Figure 4.3. This mill is used in the production of refractory brick.

Figure 4.2. First Mill System to grind and crush the boulders into smaller pieces for the refractory brick

Figure 4.3. The results of the first level of grinding

The finely ground soils are transferred to the second mill which is called the Blade Gear Mill, to be crushed further into powder. The mill is located indoors and is powered by an electric motor with a strength of 75-horsepower. This mill machine can grind 10 tons of soil in 2 hours. Figure 4.4 presents the whole of this mill and the transfer rail of soil from this mill.

Figure 4.4. Second mill system to grind and crush the rubble into smaller pieces for the refractory brick

The third type of mills is shown in Figure 4.5. This mill is powered by a 40 hp electric motor. It grinds 50 tons of soil in about 8 hours. As shown in Figure 4.6, the soil is poured into the mill through a gate. The resulting mill soil is collected under the system as presented in Figure 4.7.

Figure 4.5. Third type of Grinding systems with 40 hp electric motor

Figure 4.6. The path of soil entry to the mill system

Figure 4.7. Milled soil obtained from third mill system

4.3 Brickmaking stage

After the grinding stages, the resulting soil is stored, and water is added equal to 3% of the soil weight to go under the press machine. After adding water to the soil, as illustrated in Figure 4.8, it enters the mixer where it is homogenized. This machine has a 15 hp electric motor. This device homogenizes 5 tons of soil in 1 hour. In the last stage, the homogenized soil enters the tank of the pressing machine by the lifting device shown in Figure 4.9. The lifting machine has a 2 hp electric motor.

Figure 4.8. Mixer and soil homogenizer system

Figure 4.9. Lifting system for transferring grinded and moist soil to the molding machine

The next step after all the mills that are common between the three types of bricks is the molding stage by the press molding machine. The press machine shown in Figure 4.10, with a pressure of 250 tons per square meter, produces 10,000 bricks per day in 8 hours. The press machine has an electric motor of 20 hp. The final product of the press machine shown in Figure 4.11 are transferred to the kilns by workers on handwheels and stacked there to be baked.

Figure 4.10. Molding press machine

Figure 4.11. Facing refractory bricks produced from compression molding machine

After baking and cooling, the bricks are transferred by workers to the packaging machine to be prepared for sale to customers (Figure 4.12). The function of the packaging machine, shown in Figure 4.13, is that baked bricks are transferred to this machine after cooling down from the kilns. These bricks are arranged in multiple packages and are guided by the rail in the machine from inside the blue box to the outside of the machine. Inside the blue box, the entered bricks are covered with plastic covers and ready for distribution and sale. This machine has a low power consumption because it is powered by an electric motor with a power of 3 hp and its use time is negligible.

Figure 4.12. Transferring baked bricks to the packaging machine by workers

Figure 4.13. Packaging machine

4.4 Electricity Consumption of Mills

There are three types of mills inside the factory that are used for grinding soils. Each of the mills has a different power and electric motor and as a result, the energy consumption of the mills used in the production of each of the bricks will be examined. The softness and rigidity of the soil required to produce any type of bricks causes the difference in the mills used and the power of these machines.

4.4.1 Refractory Bricks

- **Level 1**

To produce this type of brick, the soil must go through 3 stages of grinding. The first mill required in the production process of this brick is a hammer mill that works with a 75-horsepower electric motor that has been illustrated in Figure 4.2. 50 tons of soil can be grinded in 3 hours with this mill.

In order to fill a refractory brick kiln 11,550 Kg of soil must be grinded (11,000 ×1.050 kg = 11,550 kg / 11.550 tons of soil). Since this mill grinds 50 tons of soil every 3 hours, the mills power is calculated based on Equation 3.7. So:

$$\text{Mills and Machines power (ton/hr)} = \frac{50\ \text{(tons)}}{3\ \text{(hr)}} = 16.7\ \text{(ton/hr)}$$

As a result 16.7 tons of soil is ground every hour, so based on Equation 3.8, time required to use a mill is:

$$\text{Time required to use a mill or machin(hr)} = \frac{11.550\ \text{(ton)}}{16.7\ \left(\frac{\text{ton}}{\text{hr}}\right)} = 0.69\ \text{hr or } 41\ \text{min}$$

In order to convert the power of the electro motor of the mill into an energy unit, this unit must first be converted from horsepower to kilowatts-hour based on Equation 3.9. So:

$$75\ \text{hp} \times 0.7456 = 55.92 \approx 56\ \text{kWh}$$

The amount of electricity consumption during the time that a mill works to grind the required amount of soil is calculated based on Equation 3.10. So:

$$\text{Electricity consumption (kWh)} = \ 56\ (\text{kW}) \times 0.69\ (\text{hr}) = \ 38.64\ \text{kWh}$$

In order to convert the electricity consumption to the unit of EE which is megajoules equation 3.11 is used so:

$$\mathbf{38.64\ kWh \times 3.6 \ = \ 139.104\ Megajoules}$$

- **Level 2**

After first step of grinding, the fine soils are accumulated to enter the second mill cycle that was shown in Figure 4.4. 11,550 Kg of soil must be grinded. This mill has a 75-horsepower electric motor and grinds 10 tons of soil in 2 hours, the mill's power is calculated based on Equation 3.7. So:This mill also.

$$\text{Mills and Machines power (ton/hr)} = \frac{10\ (\text{tons})}{2\ (\text{hr})} = \ 5\ (\text{ton/hr})$$

As a result 5 tons of soil is ground in 1 hour, so based on Equation 3.8, time required to use a mill is:

$$\text{Time required to use a mill or machin(hr)} = \ \frac{11.550\ (\text{ton})}{5\ \left(\frac{\text{ton}}{\text{hr}}\right)} = 2.31\ \text{hr or 138 min}$$

In order to convert the power of the electro motor of the mill into an energy unit, this unit must first be converted from horsepower to kilowatts-hour based on Equation 3.9. So:

$$75\ \text{hp} \ \times 0.7456 = 55.92 \ \approx \ 56\ \text{kWh}$$

The amount of electricity consumption during the time that a mill works to grind the required amount of soil is calculated based on Equation 3.10. So:

$$\text{Electricity consumption (kWh)} = \ 56\ (\text{kW}) \times 2.31\ (\text{hr}) = \ 129.36\ \text{kWh}$$

In order to convert the electricity consumption to the unit of EE which is megajoules equation 3.11 is used so:

$\mathbf{129.36\ kWh \times 3.6\ =\ 465.696\ Megajoules}$

- **Level 3**

After grinding the second stage, the resulting soil is stored, and water is added to the soil to go under the press machine. After adding moisture to soil, as illustrated in Figure 4.8, it enters the mixer to homogenize the soil. This machine has a 15 hp electric motor. This device homogenizes 5 tons of soil in 1 hour. Since the weight of each brick after adding moisture is equal to 1.250 kg, as a result, at this stage, the weight of the soil to be mixed for 11,000 bricks is equal to 13,750 kg.

$$\text{Mills and Machines power (ton/hr)} = \frac{5\ \text{(tons)}}{1\ \text{(hr)}} = 5\ \text{(ton/hr)}$$

As a result 5 tons of soil is mixed in 1 hour, so based on Equation 3.8, time required to use a mixer is:

$$\text{Time required to use a mill or machin(hr)} = \frac{13.750\ \text{(ton)}}{5\ \left(\frac{\text{ton}}{\text{hr}}\right)} = 2.75\ \text{hr or } 165\ \text{min}$$

In order to convert the power of the electro motor of the mixer into an energy unit, this unit must first be converted from horsepower to kilowatts-hour based on Equation 3.9. So:

$$15\ \text{hp} \times 0.7456 = 11.18\ \text{kWh}$$

The amount of electricity consumption during the time that a mixer works to mix the required amount of soil is calculated based on Equation 3.10. So:

$$\text{Electricity consumption (kWh)} = 11.18\ \text{(kW)} \times 2.75\ \text{(hr)} = 30.74\ \text{kWh}$$

In order to convert the electricity consumption to the unit of EE which is megajoules equation 3.11 is used so:

$\mathbf{30.74\ kWh \times 3.6\ =\ 110.66\ Megajoules}$

- **Level 4**

In the last stage, the homogenized soil enters the tank of the pressing machine by the lifting device shown in Figure 4.9. The lifting machine has a 2hp electric motor. Since the lifting device is connected to the molding press machine, then the number of working hours and their output are also equal. The press machine can mold 10,000 bricks every 8 hours and it's power is calculated according to Equation 3.7. As a result, according to the weight of each wet brick mold which is 1,250 kg, 12.500 tons of soil is moved by the lifting device every 8 hours but considering that for filling a kiln, 11,000 bricks is needed, so 13,750 tons of soil must be transported by lifitng device, which according to Equation 3.8, takes 8 hours and 48 minutes to move this amount of soil.

$$\text{Mills and Machines power (ton/hr)} = \frac{12.5\ \text{(tons)}}{8\ \text{(hr)}} = 1.56\ \text{(ton/hr)}$$

As a result 1.56 tons of soil is mixed in 1 hour, so based on Equation 3.8, time required to use a lifting device is:

$$\text{Time required to use a mill or machin(hr)} = \frac{13.750\ \text{(ton)}}{1.56\ \left(\frac{\text{ton}}{\text{hr}}\right)} = 8.81\ \text{hr or } 528\ \text{min}$$

In order to convert the power of the electro motor of the lifting device into an energy unit, this unit must first be converted from horsepower to kilowatts-hour based on Equation 3.9. So:

$$2\ \text{hp} \times 0.7456 = 1.50\ \text{kWh}$$

The amount of electricity consumption during the time that a lifting device works to lift required amount of soil is calculated based on Equation 3.10. So:

$$\text{Electricity consumption (kWh)} = 1.50\ \text{(kW)} \times 8.81\ \text{(hr)} = 13.2\ \text{kWh}$$

In order to convert the electricity consumption to the unit of EE which is megajoules equation 3.11 is used so:

$$\mathbf{13.2\ kWh \times 3.6 = 47.52\ Megajoules}$$

As mentioned above, the lifting machine and the molding press machine are connected to each other as illustrated in Figure 4.10. As a result, the press machine that makes 10,000 molds every 8 hours, which takes 528 minutes or 8 hours and 48 minutes to mold 11,000 bricks, each weighing 1.250 kg.

In order to convert the power of the electro motor of the molding machine into an energy unit, this unit must first be converted from horsepower to kilowatts-hour based on Equation 3.9. So:

$$20\ \text{hp} \times 0.7456 = 14.91\ \text{kWh}$$

The amount of electricity consumption during the time that a molding machine works to mold required amount of soil is calculated based on Equation 3.10. So:

$$\text{Electricity consumption (kWh)} = 14.91\ (\text{kW}) \times 8.81\ (\text{hr}) = 131.3\ \text{kWh}$$

In order to convert the electricity consumption to the unit of EE which is megajoules equation 3.11 is used so:

$$\mathbf{131.3\ kWh \times 3.6 = 472.68\ Megajoules}$$

4.4.2 Red Clay Bricks

In the production process of red clay brick, the soil must go through 1 stage of grinding which was shown in Figure 4.5. This mill system can grind 50 tons of soil in 8 hours, so:

$$\text{Mills and Machines power (ton/hr)} = \frac{50\ (\text{tons})}{8\ (\text{hr})} = 6.25\ (\text{ton/hr})$$

As a result 6.25 tons of soil is mixed in 1 hour. Since 16000 bricks that each weighs 1.750 kg must be grinded, so based on Equation 3.8, time required to use the mill to grind 28 tons of soil is:

$$\text{Time required to use a mill or machin(hr)} = \frac{28\ (\text{ton})}{6.25\ \left(\frac{\text{ton}}{\text{hr}}\right)} = 4.48\ \text{hr or } 269\ \text{min}$$

The mill works with a 40 hp electric motor. In order to convert the power of the electro motor of the mixer into an energy unit, this unit must first be converted from horsepower to kilowatts-hour based on Equation 3.9. So:

$$40 \text{ hp } \times 0.7456 = 29.82 \text{ kWh}$$

The amount of electricity consumption during the time that a mixer works to mix the required amount of soil is calculated based on Equation 3.10. So:

$$\text{Electricity consumption (kWh)} = 29.82 \text{ (kW)} \times 4.48 \text{ (hr)} = 133.59 \text{ kWh}$$

In order to convert the electricity consumption to the unit of EE which is megajoules equation 3.11 is used so:

$$\mathbf{133.59 \text{ kWh} \times 3.6 = 480.92 \text{ Megajoules}}$$

The process of combining and molding this model of bricks is done in a traditional way without the intervention of any device and by workers, and this energy will be calculated in the section of energy consumed by workers. After molding, these bricks are arranged by the workers in the kilns and are prepared for being fired by transferring gas into the kilns. Every 8 working hours, 700 brick molds are produced by the workers every day.

4.4.3 Hollow Clay Bricks

In order to fill a hollow clay brick kiln 20 tons of soil must be grinded (16,000 ×1.250 kg = 20,000 kg / 20 tons of soil).

- **Level 1**

The soil for this brick is grinded with the same mill that was mentioned to be used in the production of red clay bricks (Figure 4.5). As mentioned, 50 tons of soil can be ground by this mill in 8 hours, which is equal to 6.25 tons per 1 hour according to Equation 3.7, so:

$$\text{Mills and Machines power (ton/hr)} = \frac{50\ \text{(tons)}}{8\ \text{(hr)}} = 6.25\ \text{(ton/hr)}$$

6.25 tons of soil is mixed in 1 hour. Since 20 tons of soil must be grinded, so based on Equation 3.8, time required to use the mill to grind 20 tons of soil is:

$$\text{Time required to use a mill or machin(hr)} = \frac{20\ \text{(ton)}}{6.25\ \left(\frac{\text{ton}}{\text{hr}}\right)} = 3.2\ \text{hr or } 192\ \text{min}$$

The mill works with a 40 hp electric motor. In order to convert the power of the electro motor of the mixer into an energy unit, this unit must first be converted from horsepower to kilowatts-hour based on Equation 3.9. So:

$$40\ \text{hp} \times 0.7456 = 29.82\ \text{kWh}$$

The amount of electricity consumption during the time that a mixer works to mix the required amount of soil is calculated based on Equation 3.10. So:

$$\text{Electricity consumption (kWh)} = 29.82\ \text{(kW)} \times 3.2\ \text{(hr)} = 95.42\ \text{kWh}$$

In order to convert the electricity consumption to the unit of EE which is megajoules Equation 3.11 is used so:

$$\mathbf{95.42\ kWh \times 3.6 = 343.51\ Megajoules}$$

- **Level 2**

In the next step, moisture is added to this soil like a refractory brick, and then it enters the mixer. One 15 hp electric motor supplies energy to this device. 5 tons of soil can be homogenized in 1 hour. Since the weight of each brick after adding moisture is equal to 1.400 kg, as a result, at this stage, the weight of the soil to be grinded for 16,000 bricks is 22,400 kg (16,000 ×1.400 kg = 22,400 kg or 22.4 tons). Based on Equation 3.7, the power of the mixer is:

$$\text{Mills and Machines power (ton/hr)} = \frac{5\ \text{(tons)}}{1\ \text{(hr)}} = 5\ \text{(ton/hr)}$$

So 5 tons of soil is mixed in 1 hour, so based on Equation 3.8, time required to use a mixer is:

$$\text{Time required to use a mill or machin(hr)} = \frac{22.4\ (\text{ton})}{5\ \left(\frac{\text{ton}}{\text{hr}}\right)} = 4.48\ \text{hr or } 269\ \text{min}$$

In order to convert the power of the electro motor of the mixer into an energy unit, this unit must first be converted from horsepower to kilowatts-hour based on Equation 3.9. So:

$$15\ \text{hp}\ \times 0.7456 = 11.18\ \text{kWh}$$

The amount of electricity consumption during the time that a mixer works to mix the required amount of soil is calculated based on Equation 3.10. So:

$$\text{Electricity consumption (kWh)} = \ 11.18\ (\text{kW}) \times 4.48\ (\text{hr}) = \ 50.08\ \text{kWh}$$

In order to convert the electricity consumption to the unit of EE which is megajoules Equation 3.11 is used so:

$$\mathbf{50.08\ kWh \times 3.6\ =\ 180.28\ Megajoules}$$

- **Level 3**

Finally, the soil that has been homogenized enters the tank of the press machine through the lifting device. The lifting machine and the press machine can lift and mold 10,000 bricks every 8 hours. each wet brick mold weights 1,400 kg, so 14 tons of soil is transferred by the elevator every 8 hours.

$$\text{Mills and Machines power (ton/hr)} = \frac{14\ (\text{tons})}{8\ (\text{hr})} = \ 1.75\ (\text{ton/hr})$$

As a result 1.75 tons of soil is mixed in 1 hour, so based on Equation 3.8, time required to use a lifting device to lift 22.4 tons of soil (16000×1.400) is:

$$\text{Time required to use a mill or machin(hr)} = \frac{22.4\ (\text{ton})}{1.75\ \left(\frac{\text{ton}}{\text{hr}}\right)} = 12.8\ \text{hr or } 768\ \text{min}$$

In order to convert the power of the electro motor of the lifting device into an energy unit, this unit must first be converted from horsepower to kilowatts-hour based on Equation 3.9. So:

$2 \text{ hp } \times 0.7456 = 1.50 \text{ kWh}$

The amount of electricity consumption during the time that a lifting device works to lift required amount of soil is calculated based on Equation 3.10. So:

$\text{Electricity consumption (kWh)} = 1.50 \text{ (kW)} \times 12.8 \text{ (hr)} = 19.2 \text{ kWh}$

In order to convert the electricity consumption to the unit of EE which is megajoules equation 3.11 is used so:

$\mathbf{19.2 \ kWh \times 3.6 = 69.12 \ Megajoules}$

The press machine same as the lifting device has to work for 12.8 hours to mold 10000 bricks. According to Equation 3.9, the power of the electro motor of the molding machine is:

$20 \text{ hp } \times 0.7456 = 14.91 \text{ kWh}$

The amount of electricity consumption during the time that a molding machine works to mold required amount of soil is calculated based on Equation 3.10. So:

$\text{Electricity consumption (kWh)} = 14.91 \text{ (kW)} \times 12.8 \text{ (hr)} = 190.84 \text{ kWh}$

In order to convert the electricity consumption to the unit of EE which is megajoules equation 3.11 is used so:

$\mathbf{190.84 \ kWh \times 3.6 = 687.02 \ Megajoules}$

4.5 Specifications of Kilns

The manufacturing plant under investigation has 9 kilns, of which 6 kilns are for refractory bricks and 3 kilns are for red clay bricks and hollow clay bricks. Each of these kilns has its own dimensions, capacity and temperature characteristics, which are different depending on the type of brick and its firing. In the following, more characteristics of each of these types of kilns are described in detail. A significant point regarding the kilns is that the bricks are fired with natural gas in all kilns and the gas is injected into the kilns through appropriate pipelines as it is illustrated in

Figure 4.14. The Kilns are with fixed fire and the indoor air and smoke rises from the sides of the bricks arranged in the kiln and causes the bricks to bake. The work of these kilns is not continuous and after the clays are baked and turned into bricks, the workers open the entrance of the oven and wait for the bricks inside the oven to cool down. The end part of the kiln is covered, so that the gas of the kiln does not escape from the space and is sucked from the bottom of the kiln, so the hot gas returns its heat to the clay arranged in the kiln and by performing this the heat of the kiln gas is not wasted and the bricks are made the same and homogenized.

Figure.4.14. Gas injection through gas pipelines

i. Refractory Bricks' Kilns

The temperature of the kilns used to fire refractory bricks is equal to 1150 degrees Celsius. The dimensions of these kilns are 4, 2.8, and 1.80 meters, respectively, in length, width, and height. The capacity of each refractory brick kiln is equal to 11,000 brick molds. Each of these kilns are occupied 4 days a week for baking and 3 days for cooling, emptying or arranging. Each kiln produces 44,000 bricks per month, and with 6 furnaces for refractory bricks, 264,000 bricks produced per month. Since the production capacity of each furnace in one week is equal to 11,000 bricks, as a result, each furnace produces 44,000 bricks in 1 month or 4 weeks. With 6 such kilns, the refractory production capacity of this factory is equal to 264,000 molds per month. Each refractory brick kiln consumes 3,000 cubic meters of gas in 4 days. Each kiln is lit four times a month. Each kiln produces 44,000 bricks per month, and with 6 kilns for refractory bricks, 264,000 bricks are produced per month. One of this kind of kilns is shown in Figure 4.15.

Figure 4.15. Stacking refractory bricks by labors in the kiln

ii. Red Clay and Hollow Clay Bricks’ Kilns

The red clay and hollow clay bricks are baked in the same kilns, but not concurrently. The dimensions of these kilns in terms of length, width and height are 6.0, 1.8, and 2.0 meters respectively. The temperature of the kilns used to fire red clay bricks as well as the hollow clay bricks was 900 degrees Celsius. To bake any type of red solid or hollow clay bricks, the kilns must be lit for 3 days, and the remaining 4 days of the week are spent for cooling the bricks, emptying, and arranging them. The capacity of each of these kilns is equal to 16,000 brick molds and since each kiln is lit four times a month, 64,000 bricks are produced from each kiln monthly. Considering that 3 kilns are used for baking the red clay bricks, the monthly production of this type of brick is equal to 192,000 molds. 1,000 cubic meters of gas is consumed in 3 days of baking bricks. The photos taken of the arrangement of hollow clay bricks and red clay bricks in these kilns are shown in Figures 4.16 and 4.17, respectively.

Figure 4.16. Stacked hollow clay bricks in kiln

Figure 4.17. Arrangement of red clay bricks in the kiln

The type of gas transfer inside this type of kiln is through burner in the center of the kilns, in which heat is transferred in a circular manner inside the furnace. In this type of kilns, the arrangement is such that the bricks are baked depending on their distance from the heat flame, and the heat passes through the bricks rotationally.

Figure 4.18. Gas burner in the center of the kiln.

4.6 Gas Consumption in Kilns for Firing

Each of these kilns consume different amounts of gas to fire the bricks placed inside them, depending on the type and number of bricks. In the following, the interpretation and calculation of the gas consumption in the production of each type of bricks under consideration will be discussed.

4.6.1 Refractory Bricks

As mentioned before, 11,000 refractory brick molds is bakes insided each kiln . 3000 cubic meters of gas is used to fire 11,000 bricks.

In order to calculate gas consumption in terms of (kWh) Equation 3.13 or 3.14 must be used. So:

$$\text{Energy from gas consumption (kWh)} = 3000\ (\text{m3}) \times 0.278\ (\text{kWh/MJ}) \times 37.68\ (\text{MJ/m3}) = 31{,}425\ \text{kWh}$$

Then, to obtain the calorific value of each cubic meter of Iran's gas and reach the megajoule unit Equation 3.15 is used. So:

$$\text{Calorific value of each m3 of gas (MJ)} = 31{,}425\ (\text{kWh}) \times 3.6 = 113{,}130\ \text{MJ}$$

Finally, Equation 3.16 is used to calculate the EE of this stage. So:

$$\text{EE of gas consumption (MJ/Kg)} = \frac{113{,}130\ (\text{MJ})}{13{,}750\ (\text{Kg})} = 8.22\ (\text{MJ/Kg})$$

4.6.2 Red Clay Bricks

To bake 16,000 bricks in 3 days, about 1,000 cubic meters of gas is consumed. Since each red clay brick in the kiln weighs 2 kg. As a result,16,000 bricks weigh 32 tons so, 1,000 m^3 of gas are used to bake 32 tons of soil.

According to Equation 3.13 or 3.14, gas consumption in terms of (kWh) is:

$$\text{Energy from gas consumption (kWh)} = 1000\ (\text{m3}) \times 0.278\ (\text{kWh/MJ}) \times 37.68\ (\text{MJ/m3}) = 10{,}475\ \text{kWh}$$

T obtain the calorific value of each cubic meter of Iran's gas and reach the megajoule unit Equation 3.15 is used. So:

$$\text{Calorific value of each m3 of gas (MJ)} = 10{,}475\ (\text{kWh}) \times 3.6 = 37{,}710\text{MJ}$$

Finally, Equation 3.16 is used to calculate the EE of this stage. So:

$$\text{EE of gas consumption (MJ/Kg)} = \frac{37710\ (\text{MJ})}{32000\ (\text{Kg})} = 1.17\ (\text{MJ/Kg})$$

4.6.3 Hollow Clay Bricks

About 1,000 cubic meters of gas are consumed to bake 16,000 brick molds in 3 days. The weight of each brick before baking is equal to 1,400 kg. 16,000 bricks have a weight equivalent to 22,400 tons of soil, so 1,000 cubic meters of gas is used to bake 22,400 tons of soil.

According to Equation 3.13 or 3.14, gas consumption in terms of (kWh) is:

$$\text{Energy from gas consumption (kWh)} = 1000\ (\text{m3}) \times 0.278\ (\text{kWh/MJ}) \times 37.68\ (\text{MJ/m3}) = 10{,}475\ \text{kWh}$$

T obtain the calorific value of each cubic meter of Iran's gas and reach the megajoule unit Equation 3.15 is used. So:

$$\text{Calorific value of each m3 of gas (MJ)} = 10{,}475\ (\text{kWh}) \times 3.6 = 37{,}710\text{MJ}$$

Finally, Equation 3.16 is used to calculate the EE of this stage. So:

$$\text{EE of gas consumption (MJ/Kg)} = \frac{37710\ (\text{MJ})}{22400\ (\text{Kg})} = 1.68\ (\text{MJ/Kg})$$

4.7 Energy Expended by the Workers

The energy spent by workers in the factory is a factor that is considered and calculated in some research in the field of embodied energy, especially focusing on the production process of materials. In order to make the results more accurate and to bring the numbers closer to the actual amount of energy used to produce bricks, the energy used by workers has also been calculated. Also, by examining this component, the contribution of this part of the spent energy to the total energy can be measured. Depending on the type of brick and production steps and required labor, these figures are different for each type of brick.

4.7.1 Refractory Bricks

During the visit to the factory and according to the information provided by the factory management and the supervisor, 6 workers are working in the production of refractory bricks, that 2 of these 6 workers are responsible for filling and emptying the furnaces. 1 person is responsible for handling the bricks produced from the molding press, 1 person is responsible for filling the hopper and elevator connected to the press machine, and 2 people are responsible for moving and transferring the soil to the mills.

Since the number of calories consumed by each worker is equal to 4.11 kilocalories per minute, based on equation 3.17, energy expended by a worker (Kcal) is:

$$\text{Energy expended by a worker (Kcal)} = 480\ (\text{min}) \times 4.11\ (\text{Kcal/min}) = 1973\ \text{Kcal}$$

Equation 3.18 in used in order to convert the unit of kilocalories to megajoules. So:

$$\text{Energy expended by a worker (MJ)} = 1973\ (\text{Kcal}) \times 0.004184\ \left(\frac{\text{MJ}}{\text{Kcal}}\right) = 8.25\ \text{MJ}$$

Equation 3.19 is used to calculate the share of embodied energy of this stage. So:

$$\text{EE of manual work by workers (MJ/Kg)} = \frac{8.25\ (\text{MJ}) \times 6}{11550\ (\text{Kg})} = 0.004$$

4.7.2 Red Clay Bricks

Based on the data provided by the manager of the factory and the workers',8 workers are working in the production of refractory bricks. 5 of these 8 workers are engaged in manual molding. Each worker can produce 700 molds of red clay bricks in 8 working hours per day, and with 5 workers, 3500 molds can be produced daily, which will provide 16,000 bricks needed to fill the furnace in 5 working days. 2 workers are responsible for filling and emptying the furnaces and transporting the ready bricks, and one person is responsible for filling the mill tank to obtain the desired soil.

Since the number of calories consumed by each worker is equal to 4.11 kilocalories per minute, based on equation 3.17, energy expended by a worker (Kcal) is:

$$\text{Energy expended by a worker (Kcal)} = 480\ (\text{min}) \times 4.11\ (\text{Kcal/min}) = 1973\ \text{Kcal}$$

Equation 3.18 in used in order to convert the unit of kilocalories to megajoules. So:

$$\text{Energy expended by a worker (MJ)} = 1973\ (\text{Kcal}) \times 0.004184\ (\frac{\text{MJ}}{\text{Kcal}}) = 8.25\ \text{MJ}$$

Equation 3.19 is used to calculate the share of embodied energy of this stage. So:

$$\text{EE of manual work by workers (MJ/Kg)} = \frac{8.25\ (\text{MJ}) \times 8}{28000\ (\text{Kg})} = 0.002$$

4.7.3 Hollow Clay Bricks

Based on personal observations and collected information, the number of workers engaged in the production of this type of brick is equal to 6 people. 2 of them have the responsibility to fill and empty the kilns. 1 person handles the bricks produced from the molding press machine, 1 person fills the hopper attached to the press machine, and 2 people are responsible for transferring the soil to the mills.

Since the number of calories consumed by each worker is equal to 4.11 kilocalories per minute, based on equation 3.17, energy expended by a worker (Kcal) is:

$$\text{Energy expended by a worker (Kcal)} = 480\ (\text{min}) \times 4.11\ (\text{Kcal/min}) = 1973\ \text{Kcal}$$

Equation 3.18 in used in order to convert the unit of kilocalories to megajoules. So:

$$\text{Energy expended by a worker (MJ)} = 1973\ (\text{Kcal}) \times 0.004184\ (\frac{\text{MJ}}{\text{Kcal}}) = 8.25\ \text{MJ}$$

Equation 3.19 is used to calculate the share of embodied energy of this stage. So:

$$\text{EE of manual work by workers (MJ/Kg)} = \frac{8.25\ (\text{MJ}) \times 6}{20000\ (\text{Kg})} = 0.002$$

4.8 Total Embodied Energy of Bricks

To assess embodied energy of studied building materials within the "cradle to gate" boundary in their life cycle, all the direct and indirect involved procedures and operations in the production of bricks are considered. It comprises the energy that has been expended for extraction, production, transportation, and the labors participated in production chain.

As a result, according to the elaborations and calculations fulfilled in the previous sections, the total embodied energy for each type of brick is calculated according to the following equation:

$$EE_{\text{brick type i}} = EE_{\text{production i}} + EE_{\text{transportation i}} + EE_{\text{manual work i}}$$

Each of the factors involved in this equation is as follows: EE in all of them expresses embodied energy. "i" indicates the type of brick. "$EE_{\text{production i}}$" includes the energy spent during the production of type i bricks, which includes the electricity consumed in the mills and the thermal energy obtained from the gas fuel for baking the bricks. "$EE_{\text{transportation i}}$" encompasses the energy consumed due to the fuel consumption to transport the soil required in the production of type i bricks, which varies depending on the weight of the transported soil and the distance traveled. "$EE_{\text{labor work i}}$" comprises all the energy spent by the workers involved in the production of type i bricks.

In the following, the embodied energy of each type of brick is calculated. All the factors involved in this calculation, which were calculated separately in the previous sections, have been added together.

4.8.1 Refractory Bricks

EE of Transportation: 308.56 MJ ÷11550 (Kg) = 0.02 MJ/Kg

Mills' Energy: 139.104 MJ + 465.696 MJ + 110.66 MJ + 47.52 MJ + 472.68 MJ = 1235.66 MJ

EE of the mills: 1235.66 MJ ÷ 11550 Kg = 0.1 MJ/Kg

Calorific value of consumed gas: 113,130 MJ

EE of consumed gas: 113,130 MJ ÷ 13,750 Kg = 8.22 MJ/Kg

EE of manual labor: (8.25 MJ × $6_{\text{(number of workers)}}$) ÷ 11550 Kg = 0.004 MJ/Kg

The sum of all the involved factors will be as follows:

EE $_{\textbf{refractory brick}}$: 0.02 MJ/Kg + 0.1 MJ/Kg + 8.22 MJ/Kg + 0.004 MJ/Kg = 8.344 MJ/Kg

4.8.2 Red Clay Bricks

EE of Transportation: 744.8 MJ÷ 28000 (Kg)= 0.02 MJ/Kg

Mills' Energy: 480.92 MJ

EE of the mills: 480.92 MJ ÷ 28,000 kg = 0.017 MJ/Kg

Calorific value of consumed gas: 37,710 MJ

EE of consumed gas: 37,710 MJ ÷ 32000 Kg = 1.17 MJ/Kg

EE of labor work: (8.25 MJ × $8_{\text{(number of workers)}}$) ÷ 28000 Kg = 0.002 MJ/Kg

The sum of the total amount of all the involved elements will be as follows:

EE $_{\text{Red clay brick}}$: 0.02 MJ/Kg + 0.017 MJ/Kg + 1.17 MJ/Kg + 0.002 MJ/Kg = 1.209 MJ/Kg

4.8.3 Hollow Clay Bricks

Transportation: 0.02 MJ/Kg

Mills' Energy: 343.51 MJ + 180.28 MJ + 69.12 MJ + 687.02 MJ = 1279.93 MJ

EE of the mills: 1279.93 MJ ÷ 20000 Kg = 0.064 MJ/Kg

Calorific value of consumed gas: 37,710 MJ

EE of consumed gas: 37,710 MJ ÷ 22400 Kg = 1.68 MJ/Kg

EE of labor work: (8.25 MJ × 6$_{\text{(number of workers)}}$) ÷ 20,000 Kg = 0.002 MJ/Kg

The sum of the embodied energy of all the steps involved in the production of this type of brick is as follows:

EE $_{\text{Hollow clay brick}}$: 0.02 MJ/Kg + 0.064 MJ/Kg + 1.68 MJ/Kg + 0.002 MJ/Kg = 1.766 MJ/Kg

4.9 Calculation of Embodied Energy of Walls

In this section, all the walls studied in this research are explained in terms of their constituent and structural components, and also the EE of the whole wall is calculated based on the EE of all its components. Finally, all the embodied energies obtained from the components of each wall are added together and the final energy of the test wall is obtained.

4.9.1 Iran's Hollow Clay Brick

As mentioned in section 3.2.3, this wall consists of stud runners, trusses, Iran's hollow clay bricks, and mortar. In the following, the embodied energy calculations related to each of these components have been done.

- **Stud runners:**

  Two U-shaped and one H-shaped vertical studs are used. The area of the profile used in these studs according to its 0.18 meters length and 2.7 meters height that is needed to make one stud is equal to 0.486 m^2 (2.7 m x 0.18 m = 0.486 m^2).

  Since each iron sheet to form a beam weigh about 15.6 Kg/m^2, so, 0.486 m^2 of this steel sheet weighs 7.58 Kg (0.486 m^2 × 15.6 Kg/m^2).

  Due to the need to apply 4 of these beams in our structure, the total weight of these iron beams is equal to 30.32 kg (4 × 7.58 Kg).

  Based on ICE database, the embodied energy coefficient of the steel used in these studs is equal to 20.1 MJ/Kg. According to **Equation 3.20**, the amount of embodied energy of the steel used in our hypothetical wall is:

  Total embodied energy of steel studs = 30.32 Kg × 20.1 MJ/Kg = 609.432 MJ

- **Trusses:**

  Required length and amount of the horizental trusses to be placed in the middle of the wall was 10 meter and the total weight of the used trusses is equal to 3 kilos. According to ICE database, the embodied energy of galvanized steel sheet is equal to 22.6 MJ/kg. As a result, according to **Equation 3.20**, the total embodied energy of the trussesapplied in this wall will be obtained.

  Total embodied energy of trusses= 3 Kg × 22.6 MJ/Kg = 67.8 MJ

- **Iranian hollow clay brick**

To calculate the number of bricks that are required, the **Equation 3.21, 3.22**, and **3.23** should be applied. So:

$$\text{Number of required Hollow clay bricks} = \frac{1000}{21+1} \approx 46$$

$$\text{Number of required bricks} = \frac{270}{5.5+1} \approx 42$$

Total number of required bricks = 46 × 42 = 1932

The weight of each hollow clay brick examined in the studied manufacturing plant is equal to 1.250 Kg, therefore, according to **Equation 3.24**, the total weight of the used hollow clay bricks is:

1932 × 1.250 Kg = 2415 Kg

The total embodied energy of the hollow clay bricks used is calculated according to **Equation 3.20**, so:

Total EE of the hollow clay bricks: 2415 Kg × 1.766 MJ/Kg = 4264.89 Mj

- **1:3 cement-sand mortar:**

To calculate the required volume of mortar, first, based on the **Equation 3.25** and **3.26**, the number of bricks required without using mortar should be calculated, which is equal to:

$$\text{Number of required bricks in length} = \frac{1000}{21} = 48$$

$$\text{Number of required bricks in width} = \frac{270}{5.5} = 49$$

So, based on **Equation 3.23**:

Total number of required bricks without mortar = 48 × 49 = 2352

Now according to **Equation 3.27** and considering that the volume of each brick is equal to 0.0011 m3 (0.21 m × 0.1 m × 0.055 m), the required volume of mortar is:

Required volume of mortar: (2352 – 1932) × 0.0011 m^3 = 0.46 m^3

According to **Equation 3.28**, the weight of the used mortar is:

Weight of the mortar: 0.46 m^3 × 1900 Kg/m^3 = 874 Kg

According to ICE database, the embodied energy of 1:3 cement-sand mortar is equal to 1.33 MJ/Kg. So based on **Equation 3.20**:

Total embodied energy of the used mortar: 874 Kg × 1.33 MJ/Kg = 1,162.42 MJ

So, based on Equation 3.29:

Total EE of wall made of Iran's hollow clay brick is: 4264.89 MJ + 67.8 MJ + 609.432 MJ + 1,162.42 = 6104.54 MJ

4.9.2 Generic Clay Brick Wall

According to section 3.2.3, the trusses and studs used in this type of wall is exactly the same as the wall made of Iranian hollow clay bricks. For this reason, the embodied energy of these two components is the same as the previous wall. As a result, the embodied energy of these two materials in this wall is also equal to:

- **Stud runners**
  Total embodied energy of steel studs = 30.32 Kg × 20.1 MJ/Kg = 609.432 MJ
- **Trusses**
  Total embodied energy of trusses = 3 Kg × 22.6 MJ/Kg = 67.8 MJ

- **Generic clay bricks**

To calculate the number of bricks that are required, the **Equation 3.21, 3.22**, and **3.23** should be applied. So:

$$\text{Number of required Hollow clay bricks } = \frac{1000}{21+1} \approx 46$$

Number of required bricks $= \dfrac{270}{5.5+1} \approx 42$

The total number of required bricks is = 46 × 42 = 1932

The weight of each generic clay brick based on ICE is equal to 2.300 Kg, therefore, according to **Equation 3.24**, the total weight of the used hollow clay bricks is:

1932 × 2.300 Kg = 4,443.6 Kg

The total embodied energy of the generic clay bricks used is calculated according to **Equation 3.20**, so:

Total EE of the generic clay bricks: 4,443.6 Kg × 3 MJ/Kg = 13,330.8 Mj

- **Mortar:**

To calculate the required volume of mortar,based on **Equation 3.25** and **3.26**, the number of bricks required without using mortar should be calculated, which is equal to:

Number of required bricks in length $= \frac{1000}{21}$ = 48

Number of required bricks in width $= \frac{270}{5.5}$ = 49

So, based on **Equation 3.23**:

Total number of required bricks without mortar = 48 × 49 = 2352

Based on **Equation 3.27** and considering that the volume of each brick as 0.0011 m3 (0.21 m × 0.1 m × 0.055 m), the required volume of mortar is:

Required volume of mortar: (2352 – 1890) × 0.0011 m^3 = 0.5 m^3

According to **Equation 3.28**:

Weight of the mortar: 0.5 m^3 × 1900 Kg/m^3 = 950 Kg

Based on ICE database, the embodied energy of 1:3 cement-sand mortar is 1.33 MJ/Kg. So based on **Equation 3.20**:

Total embodied energy of the used mortar: 950 Kg × 1.33 MJ/Kg = 1,263.5 MJ

So, based on **Equation 3.29**:

Total EE of wall made of generic clay brick is: 13,330.8 + 67.8 MJ + 609.432 MJ + 1,263.5 = 15,271.53 MJ

4.9.3 Concrete Block Wall

The number of trusses used in the structure of this wall is the same as the wall made of Iran's hollow clay brick. So its embodied energy value is the same as the previous walls. So:

- **Trusses**
  Total embodied energy of trusses= 3 Kg × 22.6 MJ/Kg = 67.8 MJ
- **Stud runners:**
  The area of the profile used in these studs according to its 0.28 meters length and 2.7 meters height that is needed to make one stud is equal to 0.756 m2 (2.7 m x 0.28 m = 0.756 m2). Based on the weight of the used iron sheet that is 15.6 Kg/m2, 0.756 m2 of this steel sheet weighs 11.79 Kg (0.756 m2 × 15.6 Kg/m2). Since 4 of these studs are applied in the structure of wall, the total weight of these iron studs is equal to 47.16 kg (4 × 11.79 Kg).
  Based on ICE database, the embodied energy coefficient of the steel used in these studs is equal to 20.1 MJ/Kg, so according to **Equation 3.20**:
  Total embodied energy of steel in studs = 47.16 Kg × 20.1 MJ/Kg = 947.91 MJ
- **Concrete block**
  To calculate the number of bricks that are required, the **Equation 3.21, 3.22**, and **3.23** should be applied. So:

$$\text{Number of required blocks} = \frac{1000}{40 + 1.5} \approx 24$$

$$\text{Number of required blocks} = \frac{270}{20 + 1.5} \approx 13$$

The total number of required blocks = 24 × 13 = 312

The weight of each of the concrete blocks used is equal to 14 kg, therefore, according to **Equation 3.24**, the total weight of the used concrete blocks is:

312 × 14 Kg = 4368 Kg

The total embodied energy of the concrete blocks used is calculated according to **Equation 3.20**, so:

Total EE of the concrete block = 4368 Kg × 0.59 MJ/Kg = 2577.12 MJ

- **Mortar:**

To calculate the required volume of mortar,based on **Equation 3.25** and **3.26**, the number of blocks required without using mortar should be calculated, which is equal to:

$\text{Number of required block in length without mortar} = \frac{1000}{40} = 25$

$\text{Number of required blocks in width without mortar} = \frac{270}{20} \approx 14$

Based on **Equation 3.23**:

Total number of required blocks without mortar = 25 × 14 = 350

Based on **Equation 3.27** and considering that the volume of each block is equal to 0.016 m^3 (0.4 m × 0.2 m × 0.2 m), The required volume of mortar is:

Required volume of mortar: (350 – 312) × 0.016 m^3 = 0.61 m^3

According to **Equation 3.28**:

Weight of the mortar: 0.61 m^3 × 1900 Kg/m^3 = 1159 Kg

Based on ICE database, the embodied energy of 1:3 cement-sand mortar is 1.33 MJ/Kg. So based on **Equation 3.20**:

Total embodied energy of the used mortar: 1,159 Kg × 1.33 MJ/Kg = 1,541.47 MJ

So, based on **Equation 3.29**:

Total EE of wall made of concrete block is: 2577.12 + 67.8 + 947.91 + 1,541.47 = 5134.3 MJ

4.9.4 AAC Block Wall

- **Brackets**

The total number of brackets required for the frame of this wall is equal to 18. Since the length of each bracket is 20 cm, 3.6 meters of brackets are needed. The required area of steel for making brackets is 1m^2 (0,28 m × 3.6 m).

Each square meter of this steel weighs 15.6 kg so, the weight of steel for making brackets is also equal to 15.6 kg.

The embodied energy coefficient of steel is equal to 20.1 MJ/Kg based on the ICE database. According to **Equation 3.20,** total embodied energy of steel is:

Total embodied energy of steel in brackets: 15.6 Kg × 20.1 MJ/Kg = 313.56 MJ

- **AAC blocks**

Each AAC block's dimension is equal to 60 × 20 × 20 cm, so to calculate the required number of blocks, calculations can be done the same as **Equation 3.21**, **3.22**, and **3.23**, which were mentioned in the construction of the cement block wall. So:

$$\text{Number of required blocks with mortar} = \frac{1000}{60 + 1.5} \approx 16$$

$$\text{Number of required blocks with mortar} = \frac{270}{20 + 1.5} \approx 12$$

Total number of required blocks = 16 × 12 = 192

The density of AAC block is 549 Kg/m^3 and the volume of each block is equal to 0.024 m^3 (0.6 × 0.2 × 0.2), as a result, according to **Equation 3.30**, Total weight of the used blocks is:

Total weight of the used blocks = 192 × 0.024 m^3 × 549 Kg/m^3 = 2529.7 Kg

According to the ICE database, the EE coefficient for AAC block is equal to 3.5 MJ/Kg, so based on **Equation 3,20**, the total embodied energy of AAC blocks is:

Total embodied energy of AAC blocks: 2,529.7 Kg × 3.5 MJ/Kg = 8853.9 MJ

- **Mortar**

The required volume of mortar is calculated based on **Equation 3.25** and **3.26**, the number of blocks required without using mortar should be calculated, which is equal to:

$\text{Number of required AAC block in length without mortar} = \frac{1000}{60} = 17$

$\text{Number of required AAC blocks in width without mortar} = \frac{270}{20} \approx 13$

Based on **Equation 3.23**:

Total number of required blocks without mortar = 17 × 13 = 221

Based on **Equation 3.27** and considering that the volume of each block is 0.024 m^3, the required volume of mortar is:

Required volume of mortar: (221 – 192) × 0.024 m^3= 0.69 m^3

According to **Equation 3.28**:

Weight of the mortar: 0.69 m^3 × 1900 Kg/m^3 = 1311 Kg

Based on ICE database, the embodied energy of 1:5 cement-sand mortar is 0.97 MJ/Kg. So based on **Equation 3.20**:

Total embodied energy of the used mortar: 1311 Kg × 0.97 MJ/Kg = 1271.67 MJ

So, based on **Equation 3.29**:
Total EE of AAC block wall = EE of AAC blocks + EE of steel in brackets + EE of mortar

Total EE of AAC block wall = 8853.9 + 313.56 + 1,271.67 MJ/Kg = 10439.13 MJ/Kg

4.9.5 Dry Wall System

- **Stud runners**

Based on the chapter 3.2.3, the total length required for the stud runners to build this wall structure is equal to 68.6 meters {(2 × 10 meters) + (16 × 2.7 meters) + (2 × 2.7 meters)}. The length of each stud runner is equal to 3 meters, as a result, 23 stud runners are needed (68.6 ÷ 3). 23 stud runners weigh 21.87 Kg.

The embodied energy of galvanized steel sheet according to ICE is equal to 22.6 MJ/Kg based on the ICE database. According to **Equation 3.20,** total embodied energy of stud runners is:

Total embodied energy of galvanized steel stud runners = 21.87 Kg × 22.6 MJ/Kg = 494.26 MJ

- **Mineral Wool**

The required volume of mineral wool is equal to 2.7 m^3 (10 m ×2.70 m × 0.1m). The mineral wool used has a density of 80 kg/m^3, So, the volume we needed to build this wall was equal to 2.7 m^3, as a result, this volume will weigh 216 kg (2.7 m^3 × 80 Kg/m^3).

The embodied energy coefficient of mineral wool according to ICE database is equal to 16.6 MJ/Kg. According to **Equation 3.20,** total embodied energy of mineral is:

Total embodied energy of mineral wool = 216 Kg × 16.6 MJ/Kg = 3,585.6 MJ

- **Cement board**

The number of required cemenet boards can be obtained by using Equation 3.31.

$$\text{Number of required cemenet boards} = \frac{27\ (\text{m2})}{2.88\ (\text{m2})} \approx 10$$

The weight of the used cement boards can be calculated according to Equation 3.32. So:

$\text{Weight of the used cement boards} = 10 \times 78.3 = 783$ Kg

The embodied energy coefficient of cement board is 10.40 MJ/Kg. Equation 3.20 can be used to calculate the embodied energy of the used boards. So:

Total embodied energy of cement boards = 783 Kg × 10.4 MJ/Kg = 8,143.2 MJ

- **Plasterboard**

The number of required plasterboards and cemenet boards can be obtained by using Equation 3.31.

$$\text{Number of required plasterboards} = \frac{27\ (\text{m2})}{2.88\ (\text{m2})} \approx 10$$

The weight of the used plasterboards can be calculated according to Equation 3.32. So:

Weight of the used plasterboards = 10 × 30 = 300 Kg

The embodied energy coefficient of plasterboard is 6.75 MJ/Kg. Equation 3.20 can be used to calculate the embodied energy of the used boards. So:

Total embodied energy of plasterboards = 300 Kg × 6.75 MJ/Kg = 2,025 MJ

So, based on **Equation 3.29**:

Total EE of drywall system = EE of stud runners+ EE of mineral wool + EE of cement board + EE of plasterboard

Total EE of drywall system = 494.26 MJ + 3585.6 + 8143.2 + 2,025 = 14,248.06 MJ/Kg

In order to be able to measure the amount of EE per square meter of the wall, this analysis is also calculated in the unit of MJ/m^2, and the obtained results are shown in Table 4.2.

Table 4.2 Calculation of EE per square meter of the studied walls

	Total energy (MJ)	Method of calculating energy in MJ/m^2	Results of EE of the wall (MJ/m^2)
Iran's hollow clay brick wall	6104.54	6104.54 ÷ 27 m^2	226.1
Generic clay brick wall	15,271.53	15,271.53 ÷ 27 m^2	565.6
Concrete block wall	5134.3	5134.3 ÷ 27 m^2	190.1
AAC block wall	10439.13	10439.13 ÷ 27 m^2	386.6
Dry wall system	14,248.06	14,248.06 ÷ 27 m^2	527.7

In the comparisons made in this study and according to the obtained results, it can be seen that in the unit of MJ/m^2, the wall with generic clay brick has the highest embodied energy, and after that, the wall of the dry system is in the second place. The main reason for the lower embodied energy of the wall made of concrete blocks and Iranian bricks compared to other materials is the hollowness of these materials. Since the embodied energy is directly related to the weight of materials and the amount of materials used in the production of each material, their hollowness causes their embodied energy to decrease compared to other materials. The EE calculations for the Iranian brick wall were based on the data collected during this research but that for the rest of the walls is obtained from the ICE database.

CHAPTER 5

DISCUSSION

The data related to the production of bricks in Iran were discussed for a better understanding of the amount of energy involved in the production of these materials. This information includes taking detailed data from the production plants and observing and collecting information regarding the way of brick production, which includes all the processes that consume energy in this cycle. This data includes the accumulation of information from the means of transportation that played a role in the production of these bricks. In addition, the mills, which play the most important role in brick production and operate with electricity consumption, have been investigated. Also, brick kilns, which consume gas, and the firing of bricks is done through gas combustion, are among the other factors investigated among energy consumers. In order to be more accurate, the energy results of the workers involved in the production of bricks have also been examined depending on the type of bricks produced and the number of workers required and their daily working hours.

5.1 Energy Analysis Related to Transportation

In order to calculate the amount of fuel consumed by the loader, which is used for most of the transportations and transfers in the factory, first the average time needed to move between the mills was measured and recorded. Then, according to the type of brick produced and the amount of soil required to fill each furnace, the weight of the transported load was calculated, and then according to the catalog provided by the manufacturer of loaders, the amount of fuel consumed was calculated based on the weight of the load and the duration of use. The loader was calculated.

Considering the equality of the soil of all three types of bricks and according to the calculations, the amount of fuel consumed per kilogram of soil is the same for all three types of bricks, and the only difference is not based on the amount of energy per kilogram of soil, but per brick unit.

As the weight of the load is directly related to the amount of fuel consumed by the means of transportation, as a result, the amount of fuel consumed for red clay brick is more than other bricks due to its greater weight. All the calculations that were first based on the amount of fuel consumption, which is diesel, have been converted into embodied energy units, i.e., megajoules per kilogram. This unit conversion is obtained by multiplying the amount of fuel consumed based on liters by the number 38, which is the amount of specific energy obtained from diesel fuel.

In Table 5.1, the embodied energy resulting from the transportation of all 3 types of examined bricks is summarized and also in this table, in addition to the embodied energy per kilogram of soil, the energy obtained from the transportation of soil for per unit of brick is also expressed in all three types.

Table 5.1 Summary of the energy from diesel burning for soil transportation by loader

	Energy of burning diesel in transportation (MJ)	
Brick Type	**Per Kg**	**Per Brick**
Refractory Brick	0.02	0.021
Red Clay Brick	0.02	0.035
Hollow Clay Brick	0.02	0.025

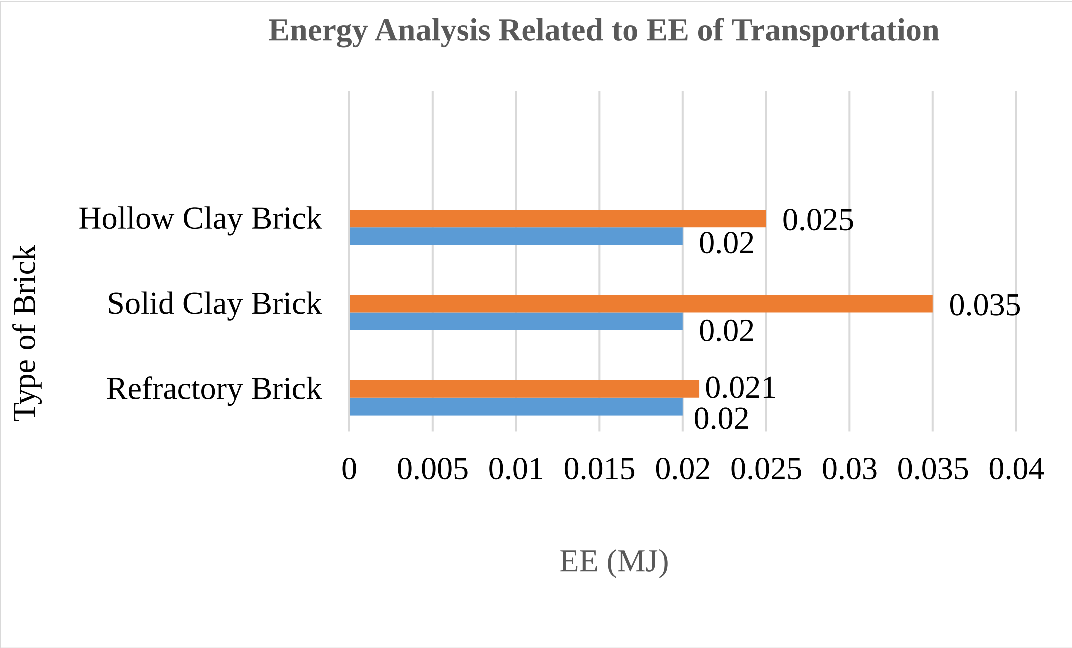

Figure 5.1. Energy analysis related to EE of transportation

5.2 Energy Analysis of Mills and Machines

Mills are considered as the most important element in the brick production cycle because most of the energy consumed during the brick production period is consumed by mills. In this section, all the equipment that operate by electric motors have been examined and the amount of electricity or energy consumed by each device per kilogram of soil needed to make each brick has been calculated.

The detailed information acquired from calculations to obtain the energy consumption of each of the electrical equipment involved in the production of refractory, red clay, and hollow clay bricks are shown in Table 5.2, 5.3, and 5.4, respectively.

Table 5.2 Details of electricity consuming systems and the amount of electricity consumed at each stage in the production of 11000 refractory bricks

Power Consuming System	**Energy Consumption for 11,000 Bricks (MJ)**
Hammer mill	137.75
Second mill	463.68
Homogenizing mill	110.66
Lifting machine	47.52
Molding press machine	472.32
Total	1231.93

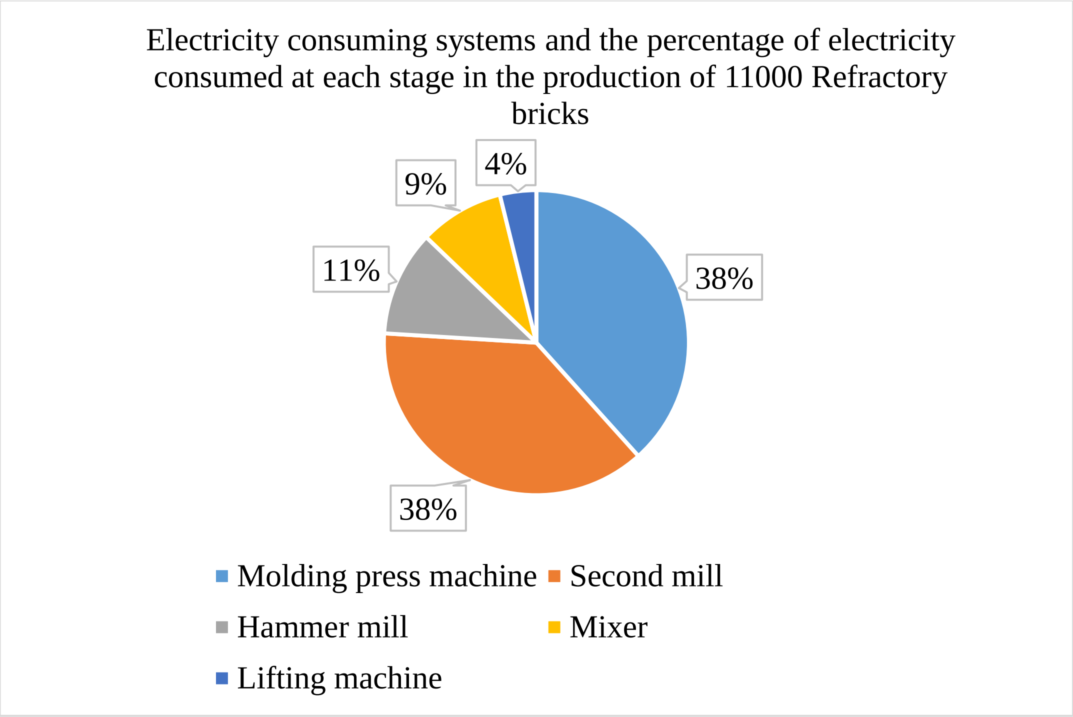

Figure 5.2. The percentage of electricity consumed at each stage in the production of 11000 Refractory bricks

Table 5.3 Details of electricity consuming systems and the amount of electricity consumed at each stage in the production of 16000 red clay bricks

Power Consuming System	**Energy Consumption for 16,000 Bricks (MJ)**
First mill	481.32
Total	481.32

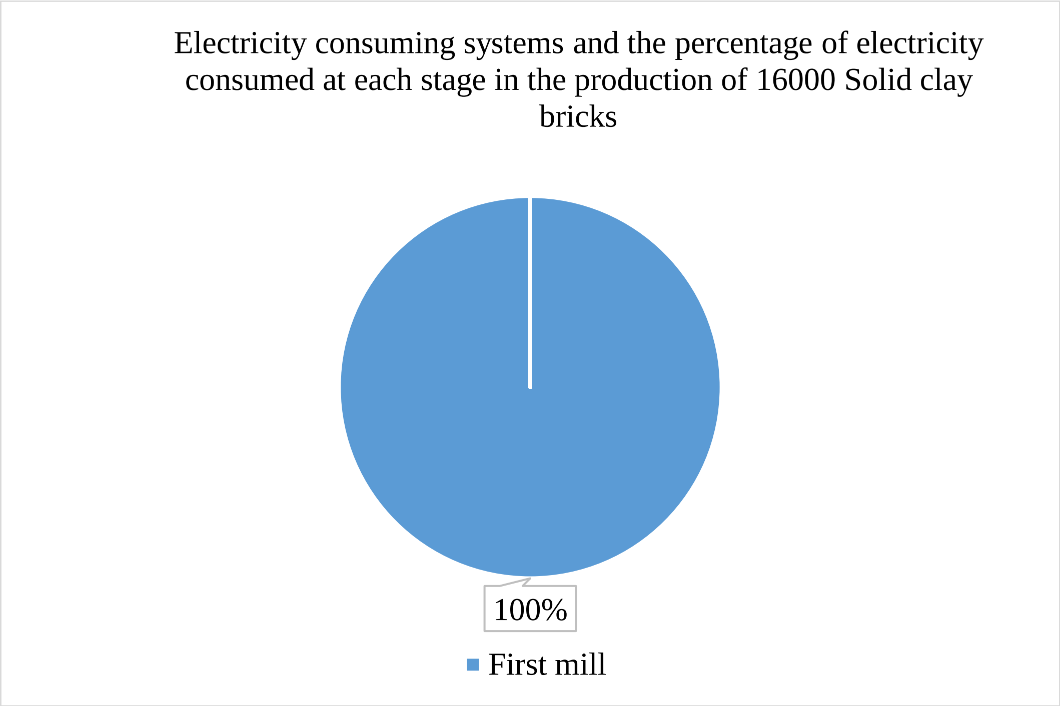

Figure 5.3. The percentage of electricity consumed at each stage in the production of 16000 Solid clay bricks

Table 5.4 Details of electricity consuming systems and the amount of electricity consumed at each stage in the production of 16000 hollow clay bricks

Power Consuming System	**Energy Consumption for 16,000 Bricks (MJ)**
First mill	343.51
Homogenizing mill	190.44
Lifting machine	69.12
Molding press machine	687.02
Total	1290.09

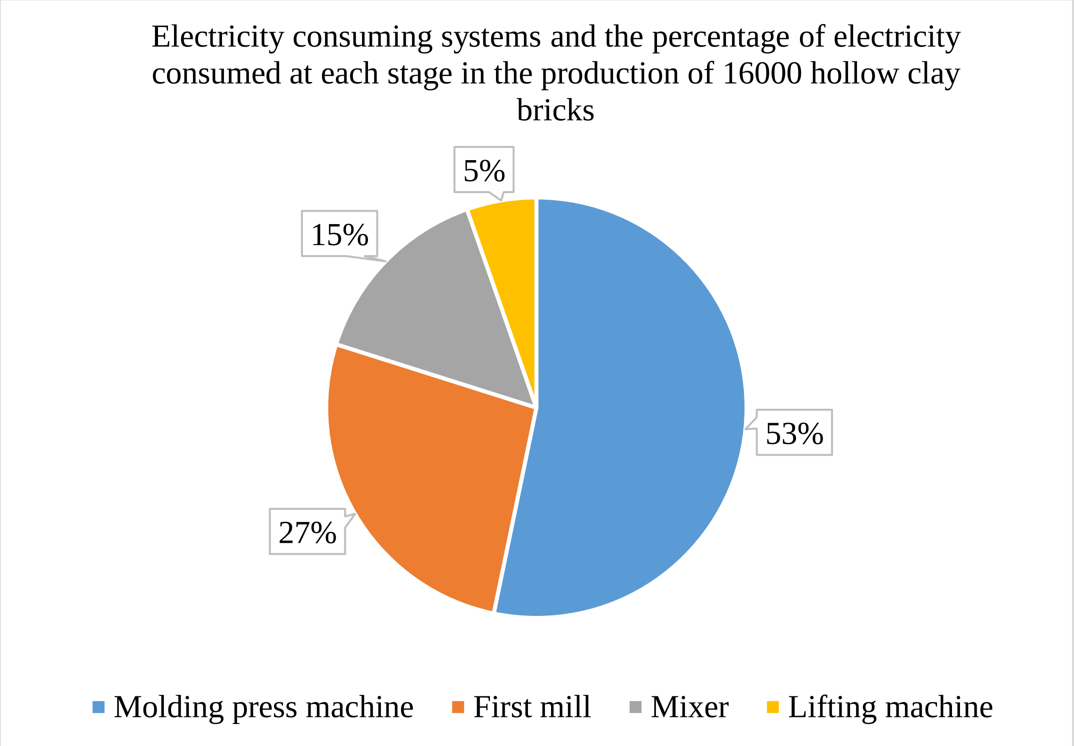

Figure 5.4.The percentage of electricity consumed at each stage in the production of 16000 hollow clay bricks

The total energy consumption from mills and electrical devices involved in brick production for refractory, red clay, and hollow clay bricks is equal to 1231.93, 481.32, and 1290.09 MJ respectively.

Considering that these values are the amount of electricity consumed to produce different number of each type of bricks, in order to be comparable, these values were converted into the unit of embodied energy, which is MJ/Kg, so that the amount of energy spent per 1 kilogram of soil for each type of brick can be compared. These amounts in embodied energy unit is equal to 0.1 MJ/Kg, 0.017 MJ/Kg, and 0.064 MJ/Kg for refractory, red clay, and hollow clay bricks. In Figure 5.5, the values of EE of the electricity that is used for each type of brick are compared.

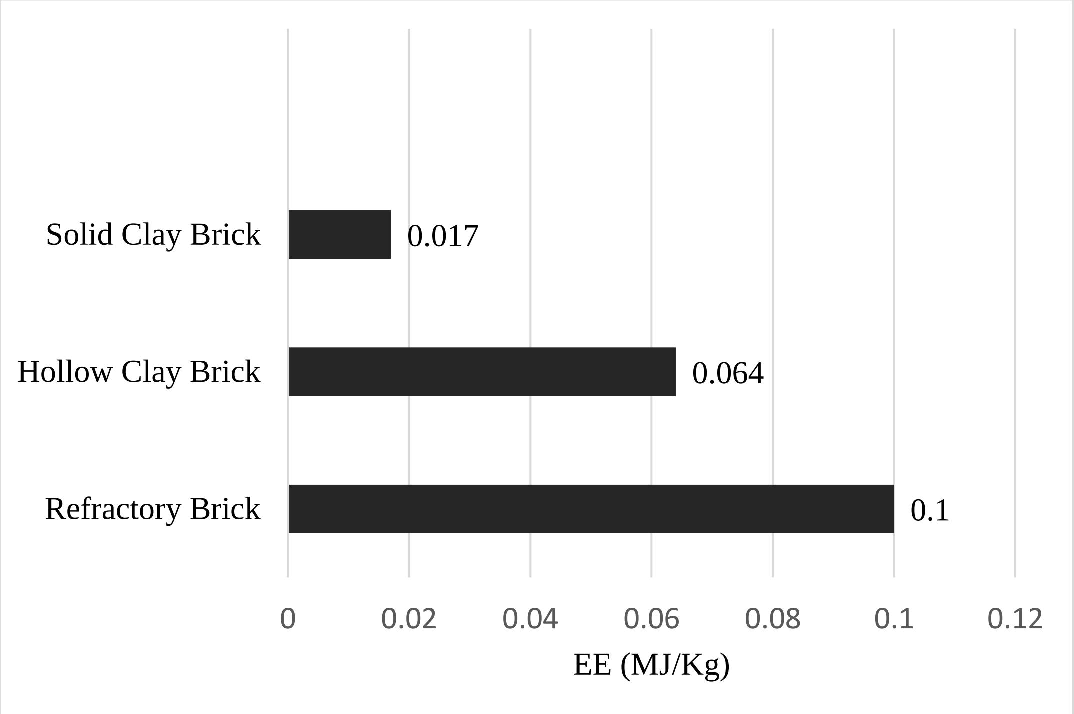

Figure 5.5. Comparison of the total EE of the electricity used for each type of brick

5.3 Energy Analysis of Kilns Gas Consumption

After mills and power consuming systems, furnaces are the second most important factor affecting the amount of embodied energy. In fact, the amount of gas used for baking bricks and as a result the energy released from this gas fuel is an important factor in the amount of embodied energy of the examined bricks.

In the surveys conducted, the information related to the capacity of the furnaces and the required temperature and gas consumption for periodic baking of bricks were collected and after performing the relevant calculations, the amount of gas consumption per kilogram of soil for different bricks was obtained.

According to the calculations and the equations, the caloric value of the consumed gas for refractory, red clay, and hollow clay bricks is equal to 113,130 MJ, 37,710 MJ, 37,710 MJ, respectively. In order to equalize the units with the aim of making them comparable with each other, all this amount of consumed gases has been converted into a unit of embodied energy, in which case this amount is equal to 8.22 MJ/Kg, 1.17 MJ/Kg , and 1.68 MJ/Kg for refractory, red clay, and hollow clay bricks as shown in Table 5.5.

Table 5.5 EE of consumed gas for produced bricks

Type of Brick	**EE of Consumed Gas (MJ/Kg)**
Refractory Bricks	8.22
Red Clay Bricks	1.17
Hollow Clay Bricks	1.68

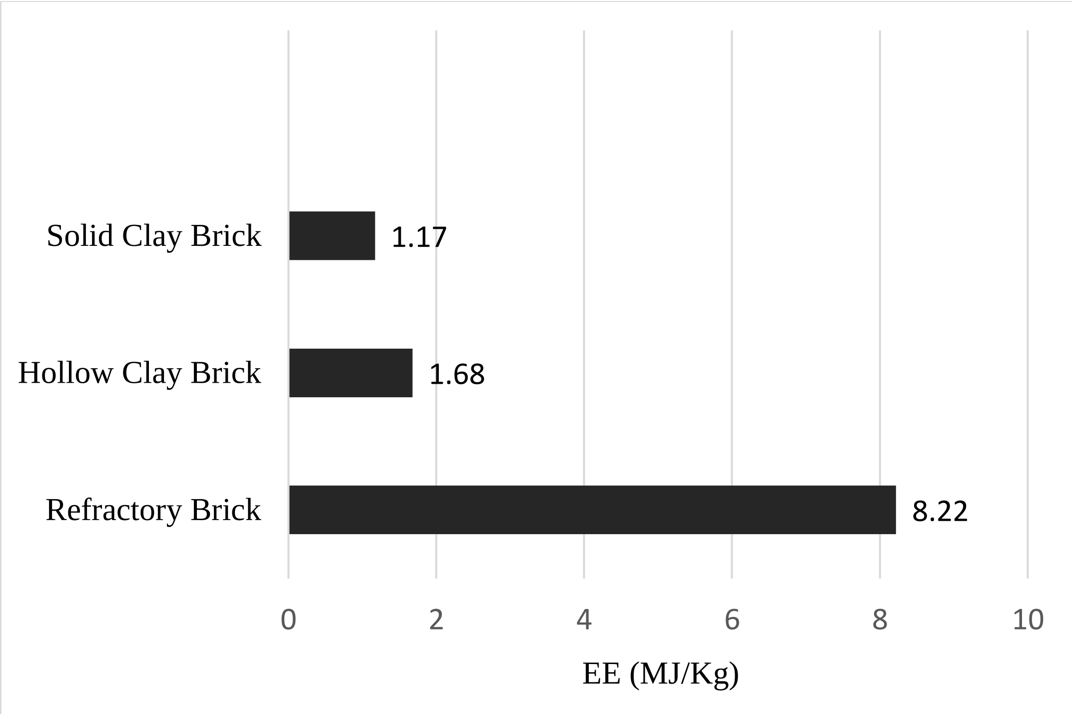

Figure 5.6. Comparison of the total EE of the consumed gas for each type of brick

From the comparison of the amount of gas used between the bricks, it can be seen that the gas used for refractory brick is more than the other 2 types of bricks because the temperature required to fire this brick is higher and the kiln flame must be on for longer duration for refractory bricks and more time is needed to bake it.

5.4 Energy Analysis of Employed Labors

Energy expenditure of labor force is another factor that is involved in the amount of embodied energy of materials during the production cycle. Although the influence of this factor is insignificant, for the results to be as accurate as possible, it is better to calculate and include their contribution to the total energy of the materials.

According to the reviewed studies and the placing of construction material production work in the group of hard jobs, the amount of energy consumed by each worker is based on the difficulty of the work and the number of calories consumed per minute of their work.

According to the calculations, the obtained results are briefly presented in Table 5.6. This table shows the amount of energy consumed by each worker per kilogram of soil that forms different bricks.

Table 5.6 Energy expenditure by each worker to produce bricks to fill each kiln with each type of brick.

Brick Type	**Soil weight (Kg)**	**Energy expenditure (MJ/Kg)**
Refractory bricks	11550	0.0007
Red clay bricks	28000	0.0003
Hollow clay bricks	20000	0.0004

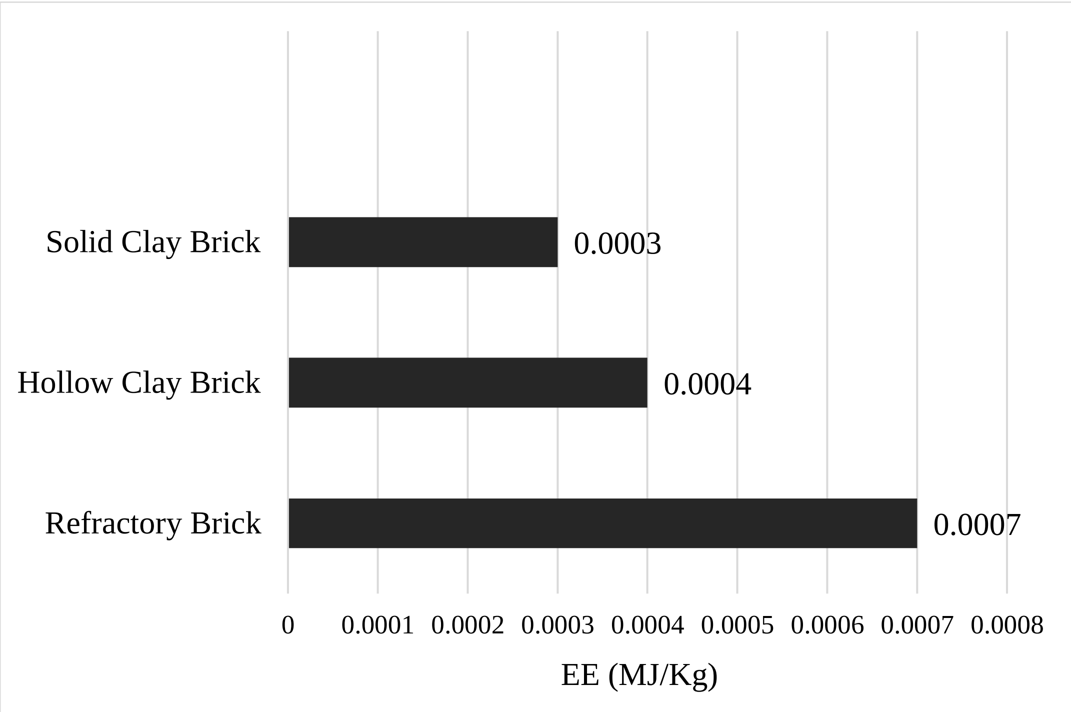

Figure 5.7. Comparison of the total EE of the energy expended by workers for 1 kg of bricks

5.5 Total Embodied Energy of the Bricks

After calculating the EE resulting from each part of the steps involved in the production process of each brick, the EE of the desired brick was reached by summing up the numbers obtained in all the steps. The final results are presented in Table 5.7. Considering that the energy of each stage has a role in the total energy obtained, by calculating the percentage of each stage's contribution to the total energy, the role of each operation in forming the final EE can be seen (Table 5.8).

Table 5.7 The embodied energy of each stage of the brick production cycle

Production Stages	**Types of Bricks**		
	Refractory brick	**Red clay brick**	**Hollow clay brick**
Transportation Energy (MJ/Kg)	0.02	0.02	0.02
Mills and Machines Energy (MJ/Kg)	0.1	0.017	0.064
Consumed Gas Energy (MJ/Kg)	8.22	1.17	1.68
Manual Labor Energy (MJ/Kg)	0.004	0.002	0.002
Total (MJ/Kg)	8.344	1.209	1.766

Table 5.8 Percentage share of EE of each stage in the total EE

Production Stages	**Each stage's contribution to total EE**		
	Refractory brick	**Red clay brick**	**Hollow clay brick**
Transportation Energy (MJ/Kg)	0.23 %	1.7 %	1.20 %
Mills and Machines Energy (MJ/Kg)	1.22 %	1.5 %	3.70 %
Consumed Gas Energy (MJ/Kg)	98.5 %	96.7 %	95 %
Manual Labor Energy (MJ/Kg)	0.05 %	0.1 %	0.1 %
Total (MJ/Kg)	8.344	1.209	1.766

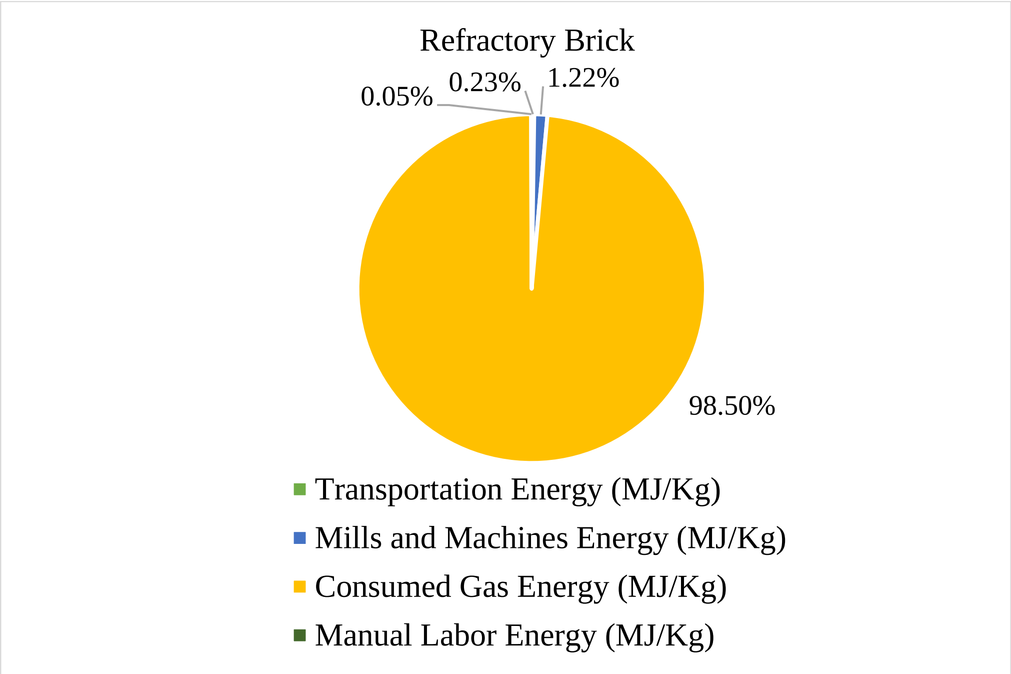

Figure 5.8. Percentage share of EE of each stage in the total EE of refractory brick

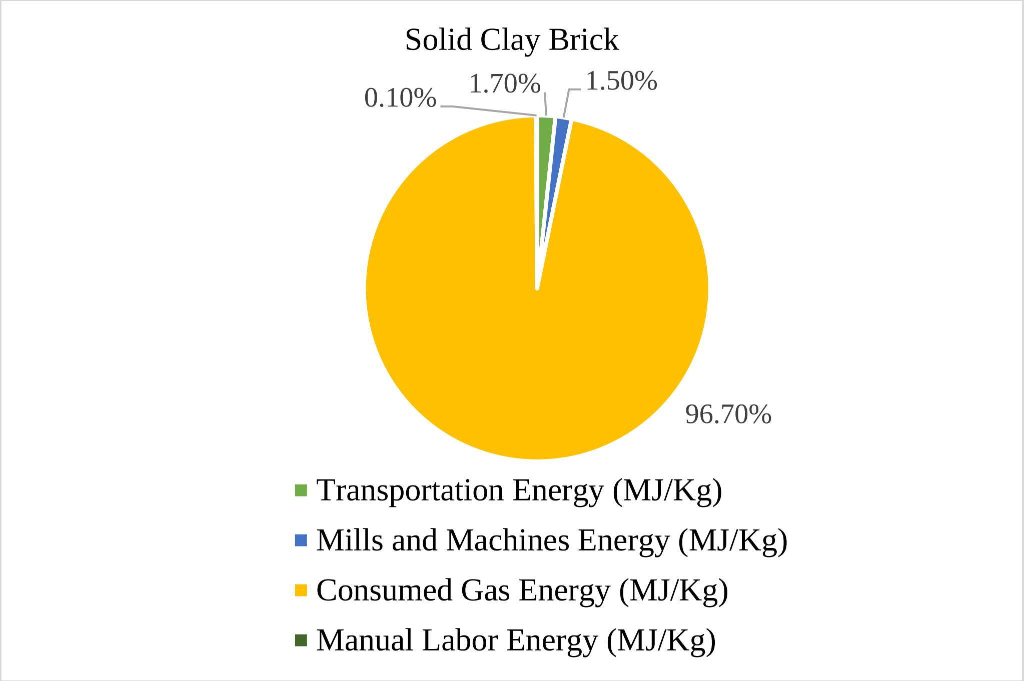

Figure 5.9. Percentage share of EE of each stage in the total EE of solid clay brick

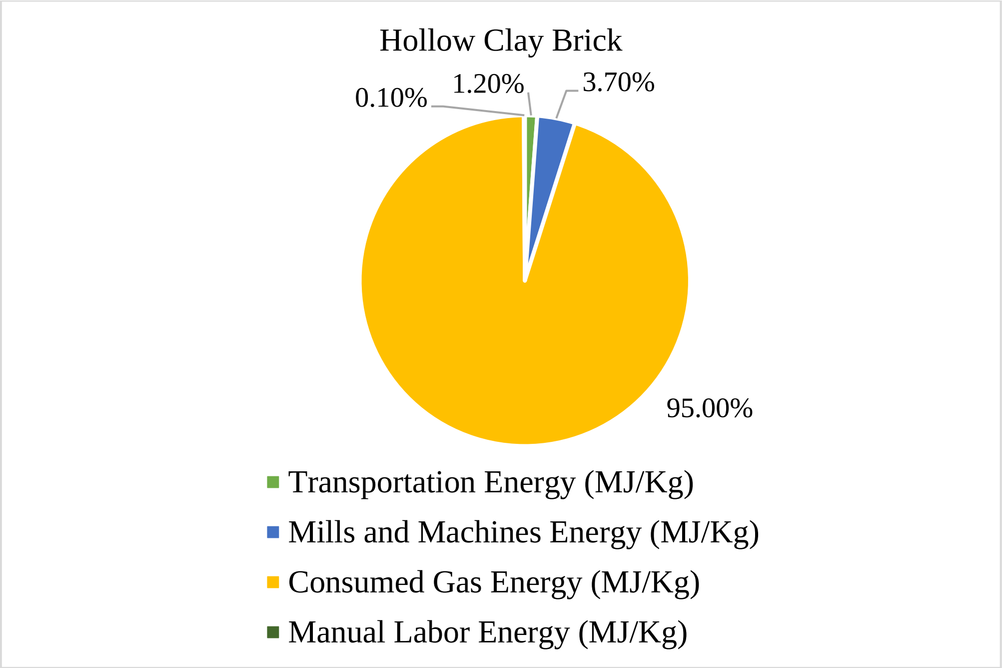

Figure 5.10. Percentage share of EE of each stage in the total EE of hollow clay brick

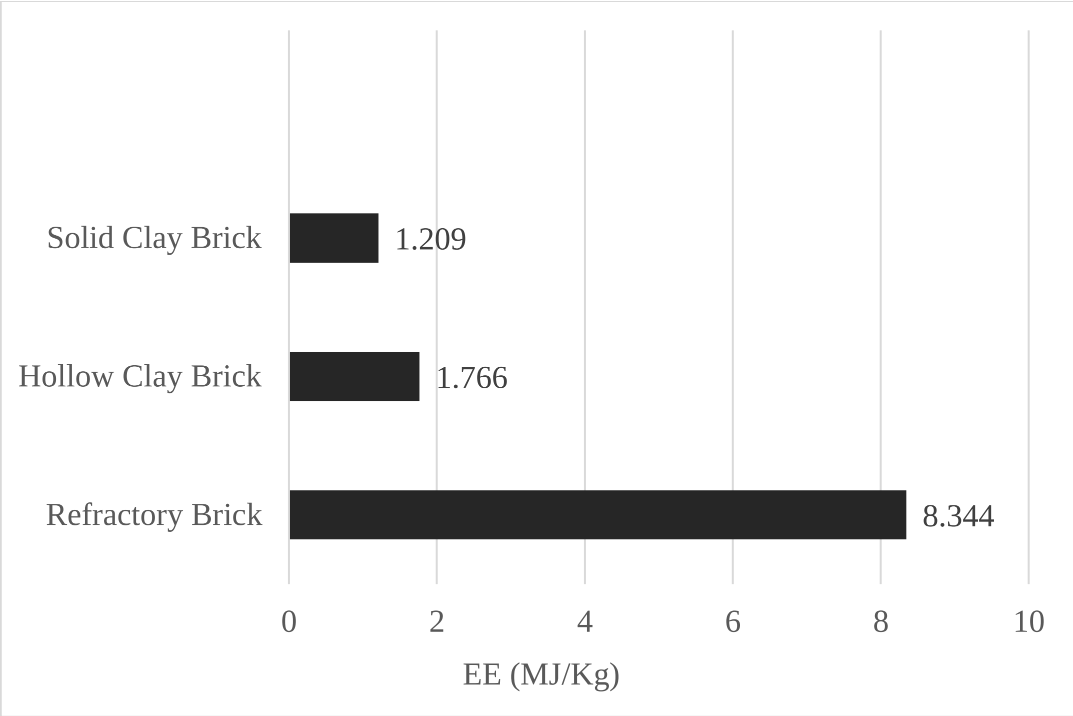

Figure 5.11. Comparison of the total embodied energy of bricks

In order to understand how the EE of Iranian bricks as calculated in this research compares with that presented in international studies the results collected from literature by Hammond (2008) are presented in Figure 5.12. It can be seen that the embodied energy of bricks in different studies was found to be different over time, and it can also be seen that the calculated embodied energy for bricks made in Iran is in the range of calculated numbers in other countries.

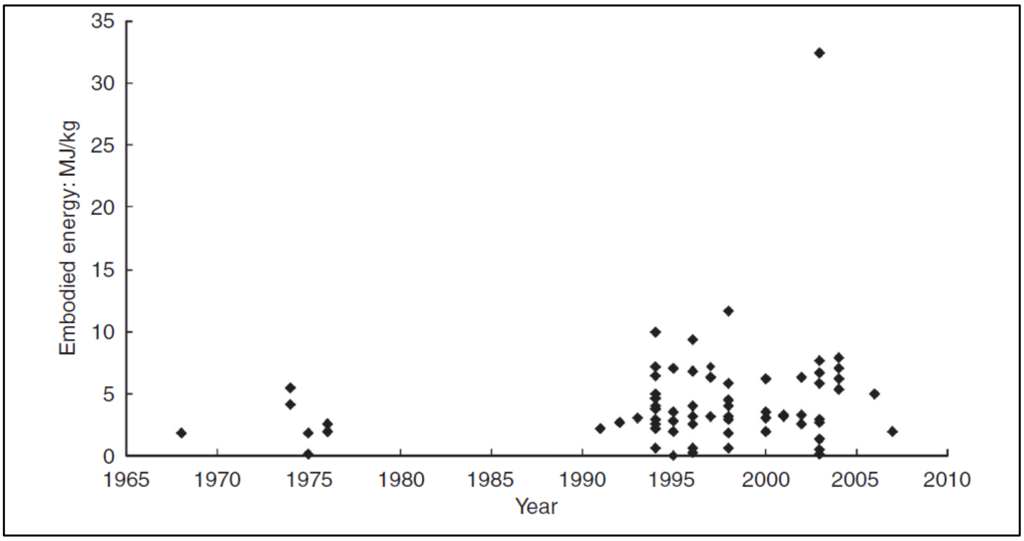

Figure 5.12. Variation in EE of clay bricks over time (Hammond, 2008)

5.6 Energy Analysis of the Test Wall with Alternative Materials

After the measurements and calculations performed on 3 types of bricks produced in Iran and relying on real and local data, the embodied energy of a hypothetical external wall with different alternative materials that are common in the construction industry of Iran was investigated. These calculations are based on the data provided by the ICE database.

The type of materials and other required components have been obtained through inquiries from structural engineers. Also, the structures required for the construction of this wall have been calculated for different materials based on Iranian Standard No. 2800 document. The structure used in this wall is different depending on the type of material that is chosen as wall filler.

Based on the calculations and obtaining the necessary amount of each of these types of materials and then the necessary components such as beams, galvanized sheets, stud runner, and cement-sand based mortar, this capability is provided to be able to multiply the weight or, the required volume of each of the materials in the coefficient provided by ICE database to reach the embodied energy of the whole wall.

The embodied energy of the hypothetical wall with alternative materials is presented in Figure 5.3, which can be compared more easily.

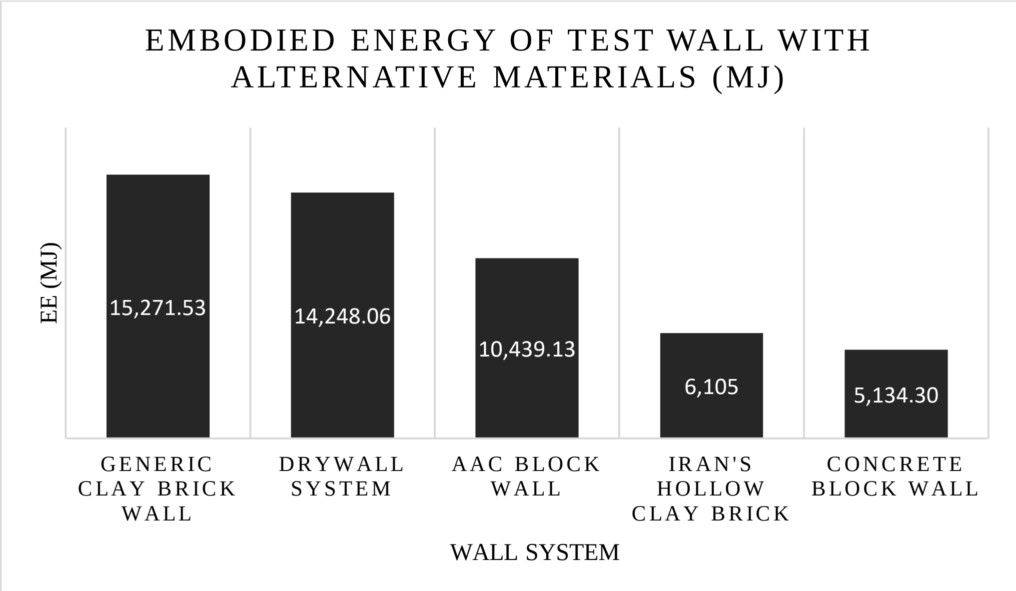

Figure 5.13. Embodied energy of the test wall with alternative materials

Based on the obtained results, it can be seen that the wall made of generic clay brick has the highest embodied energy value, followed by drywall system, AAC block, concrete block, and Iranian hollow clay brick, respectively.

5.7 Limitations

In the process of gathering information, the only stage that the manager and workers of the factory did not have information about was the soil extraction stage because in Iran the extraction process is done by government teams and the brick manufacturers buy the soil from them. For this reason, the energy of that stage of the production process was not included. Since the investigated factories were built at a distance of 3 km from the clay sources, so the distance to transport the soil from the mines to the factory was very small and ignored.

The calculations in this study are based on the net amount of soil, electricity, and gas that are needed in the production chain of bricks. The waste is not considered since there was no information about how much the gross amount might be. Also, it depends on many factors like workmanship, quality of soil, efficiency of power consuming systems, and efficient amount of gas consumed. Also in the investigated factory, the workers present in the plant reside and live in the same place where they work, therefore, their daily transportation from the factory to their homes is eliminated. And it has to be mentioned that the energies used in this study are expressed based on the end use energy consumption, not the primary energy.

CHAPTER 6

CONCLUSION

The information related to the production of 3 samples of the most widely used types of bricks in Iran, which are produced in Tehran, was studied and analyzed. During these investigations, all the processes involved in the production of a brick were examined. In fact, from the time of transporting soil, grinding soil and rocks to molding and baking bricks.

This inspection border, which is called the cradle to gate, is one of the most fundamental stages in the life cycle of materials because a significant amount of energy is spent in this stage so that a material can enter other cycles and be usable.

Considering the lack of a database specific to the construction materials produced in Iran and also the absence of information related to the Iran in most of the databases available in life cycle assessment tools, in order to achieve more realistic results and closer to the reality in Iran, the importance of field investigations and collection of information from the production plants cannot be overestimated.

During the research conducted on the visited site, information was collected regarding the brick production process. The type of transportation vehicle used in the factory, its fuel consumption, and the amount of fuel consumption for transporting different loads have been calculated and checked. Also, the type of mills needed to produce each type of the bricks and the electric motors of each according to the power consumption have been checked. In addition, information related to the kilns used to bake each type of brick and the amount of gas used to bake each kind of bricks has been collected. In order to make the results as accurate as possible, the energy consumed by the labors engaged in the production of each type of brick has also been checked.

In all the calculations, although the results were obtained in different units, but to unify the data and obtain the final embodied energy, they were all converted to the unit of embodied energy, i.e., MJ/Kg.

Based on studies and calculations, the amount of embodied energy resulting from transferring the soil by the loader used in the site is equal to 0.02 MJ/kg. In fact, 0.02 megajoules of energy is used for transferring 1 kg of soil. Since the primary soil used for all 3 types of bricks is the same, as a result, this amount of energy per 1 kg of soil is the same for all 3 types of bricks, and the only difference is the energy per brick, which varies according to the weight of the bricks. The amount of energy obtained from the burning of diesel fuel for each refractory brick is equal to 0.021 megajoules, 0.035 megajoules for each red clay brick and 0.025 megajoules for each hollow clay brick.

It can be concluded that the fuel burning rate of the loader has a direct connection with the weight of its load or the weight of bricks. The greater the weight of the brick or the more soil needed to make the brick, the more energy the loader will consume. Since the weight of each mold of red clay brick is more than the other 2 types of bricks, as a result, the amount of embodied energy resulting from its displacement is also higher.

In the calculations, the maximum amount of electricity consumed by mills to fill hollow clay brick kilns is equal to 1290.09 MJ of energy per production of 16,000 bricks, 1231.93 MJ to produce 11,000 refractory bricks and the minimum amount of energy required for grinding soil is for red clay brick, which is equal to 481.32 MJ to fill the kiln with 16,000 bricks. However, in the unit of embodied energy, this amount is equal to 0.1 MJ/Kg for refractory brick, 0.064 MJ/Kg for hollow clay brick, and 0.017 MJ/Kg for red clay brick, respectively, from the highest to the lowest value.

Since for the production of refractory bricks, it is necessary to pass the soil through several stages of grinding and each of these mills consumes electricity and energy, as a result, the embodied energy resulting from grinding the soil to make firebrick is more than other 2 types of bricks.

After that, comparing the amount of gas consumed, the highest amount of gas consumed, in order from the highest to the lowest amount, is equal to 3000 cubic meters for baking 11,000 firebricks and 1000 cubic meters for baking 16,000 bricks of each type of hollow clay brick and red clay brick. Comparing the amount of gas consumed based on the megajoule unit, the highest amount of gas consumed, from the highest to the lowest, is equal to 113,130 MJ for firing 11,000 firebricks and then 37,710 MJ for firing 16,000 hollow clay bricks and 16,000 red clay bricks, respectively. To compare the amount of gas consumed based on the unit of embodied energy, it can be stated that the amount of embodied energy resulting from the burning of gas fuel is equal to 8.22 MJ/Kg for refractory brick, 1.68 MJ/Kg for hollow clay brick and 1.17 MJ/Kg for red clay brick.

Compared to the other 2 types, the production of refractory brick requires more heat and temperature, and the flame and gas entering the furnace of this type of brick must be lit for 4 days, while the time for firing red clay brick and hollow clay brick is 3 days. As a result, the amount of consumed gas and the embodied energy of refractory brick is more than other bricks.

Finally, in the calculations obtained regarding the energy of the workers, it was observed that the amount of energy consumed by the workers, although small, is needed to achieve accurate results, and the effect of this factor will be greater in larger scales. Based on the calculations, the amount of energy consumed by the 8-hour activity of workers in the factory for refractory bricks, red clay, and hollow clay bricks is equal to 0.0007, 0.0003, and 0.0004 MJ/Kg. Factors affecting energy consumption by workers include working hours, work difficulty, and the number of calories consumed by them per minute of activity.

EE $_{\textbf{refractory brick}}$ = 8.344 MJ/Kg

EE $_{\textbf{Red clay brick}}$ = 1.209 MJ/Kg

EE $_{\textbf{Hollow clay brick}}$ = 1.766 MJ/Kg

After completing the surveys conducted on the field research related to brick production, the stage of investigation of the embodied energy resulting from the construction of a hypothetical external wall with the most widely used materials in Iran is reached. In this research, the basis, and criteria for calculating the embodied energy coefficients and the values are provided by the Ice database, which is currently considered as one of the most reliable databases and is used in most of available research. The 4 main materials under investigation are clay bricks, cement blocks, AAC blocks, and a drywall system each of which has its own embodied energy coefficient based on ICE.

Based on all the calculations done to assess the amount of embodied energy in the construction of the wall with each of these materials and other accessories used in the construction of each wall, the results show that the embodied energy per use of each of the materials i.e., Iran's hollow clay brick, generic clay brick, concrete block, AAC block, and drywall system are equal to 6,105 MJ, 15,271.53 MJ, 5,134.30 MJ, 10,439.13 MJ, and 14,248.06 MJ, respectively. According to the obtained values, it can be seen that the clay brick wall has the highest embodied energy, followed by the drywall system in the second place, AAC block in the third place, Iran's hollow clay brick in the forth and concrete block in the last place.

Considering that the embodied energy coefficient of clay brick is 3 and AAC block is 3.5 MJ/Kg, but the final embodied energy of a brick wall is more than that of AAC block, because according to the dimensions of bricks for filling and arranging a wall, larger number of bricks is required, and this causes the embodied energy of a brick wall to be higher than that of AAC block wall.

Regarding the use of dry wall, it should be noted that despite the lower weight of the components compared to blocks and bricks, the embodied energy of this wall is very high because the components of this wall have a much higher embodied energy than other materials examined in this are research and it should be kept in mind that despite the popularity of this wall in Iran, due to the high speed of work and ease of implementation, and probably higher thermal insulation, it has negative environmental effects due to the EE factor.

This study was for EE assessment from cradle to gate stage but for the life cycle embodied energy analysis, in addition to the EE of the materials that are evaluated for refractory, solid clay, and hollow clay bricks and various types of walls in this study, the operational energy as well as carbon dioxide emission should also be considered. The goal of sustainable and environmentally friendly construction will be achieved by considering these factors. Due to the lack of reliable and relevant EPD for bricks produced in Iran, the results of this study can contribute to the development of the EPD database in Iran for construction industries.

REFERENCES

Alwan, Z., & Jones, P. (2014). The importance of embodied energy in carbon footprint assessment. *Structural Survey, 32*(1), 49–60. https://doi.org/10.1108/SS-01-2013-0012

Athena Sustainable Materials Institute. (2014). User Manual and Transparency Document, (September), 50. Retrieved from www.athenasmi.org

Azari, R., & Abbasabadi, N. (2018). Embodied energy of buildings: A review of data, methods, challenges, and research trends. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2018.03.003

Building and Housing Research Center (BHRC) (2015*). Iranian Code of Practice for Seismic Resistant Design of Buildings*. Standard No. 2800-05, 4th Ed, Iran.

Birgisdottir, H., Moncaster, A., Wiberg, A. H., Chae, C., Yokoyama, K., Balouktsi, M., … Malmqvist, T. (2017). IEA EBC annex 57 'evaluation of embodied energy and CO2eq for building construction.' *Energy and Buildings, 154*, 72–80. https://doi.org/10.1016/j.enbuild.2017.08.030

Cao, C. (2017). *Sustainability and life assessment of high strength natural fibre composites in construction*. *Advanced High Strength Natural Fibre Composites in Construction*. Elsevier Ltd. https://doi.org/10.1016/B978-0-08-100411-1.00021-2

Claridge, D. E., Clayton, M. J., & Yan, W. (2013). Embodied Energy Calculation: Method and Guidelines for a Building and Its Constituent Materials, (December 2013). Retrieved from https://oaktrust.library.tamu.edu/bitstream/handle/1969.1/151701/DIXIT-DISSERTATION-2013.pdf?sequence=1

Crawford, R. H. (2014). Post-occupancy life cycle energy assessment of a residential building in Australia. *Architectural Science Review*, *57*(2), 114–124. https://doi.org/10.1080/00038628.2013.819556

Dascalaki, E. G., Argiropoulou, P., Balaras, C. A., Droutsa, K. G., & Kontoyiannidis, S. (2021). Analysis of the embodied energy of construction materials in the life cycle assessment of Hellenic residential buildings. Energy and Buildings, 232, 110651.

Dixit, Manish K., Fernández-Solís, J. L., Lavy, S., & Culp, C. H. (2012, August 1). Need for an embodied energy measurement protocol for buildings: A review paper. *Renewable and Sustainable Energy Reviews*. Pergamon. https://doi.org/10.1016/j.rser.2012.03.021

Dixit, Manish Kumar, Fernández-Solís, J. L., Lavy, S., & Culp, C. H. (2010). Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings*, *42*(8), 1238–1247. https://doi.org/10.1016/j.enbuild.2010.02.016

Dumani, N. (2009). CRADLE-TO-GATE ENERGY AND GREENHOUSE GAS EMISSIONS OF SOUTH AFRICAN CONCRETE AND REBAR Residential sector Commercial sector Building materials Manufacturing other Other Mining Transport, 1–8.

Ezema, I. C., Fagbenle, O. I., & Olotuah, A. O. (2015). Estimating embodied energy in residential buildings in a nigerian context. *International Journal of Applied Engineering Research*, *10*(24), 44140–44149.

Gupta, R. C., Thomas, B. S., Gupta, P., Rajan, L., & Thagriya, D. (2012). An experimental study of clayey soil stabilized by copper slag. *International Journal of Structural & Civil Engineering Research*, *1*(1), 110-119.

Hammond, G. P., & Jones, C. I. (2008). Embodied energy and carbon in construction materials. *Proceedings of the Institution of Civil Engineers-Energy*, *161*(2), 87-98.

Henry, A. F., Elambo, N. G., Tah, J. H. M., Fabrice, O. E., & Blanche, M. M. (2014). Embodied energy and CO2 analyses of mud-brick and cement-block houses. *AIMS's Energy*, *2*(1), 18-40.

Hernandez, P., Oregi, X., Longo, S., & Cellura, M. (2019). *Life-Cycle Assessment of Buildings*. *Handbook of Energy Efficiency in Buildings*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-812817-6.00010-3

Hollerud, B., Bowyer, J., Howe, J., Pepke, E., & Fernholz, K. (2017). A review of Life Cycle Assessment Tools, (February), 11.

Holtzhausen, H. J. (2007). Embodied energy and its impact on architectural decisions. *WIT Transactions on Ecology and the Environment*, *102*, 377–385. https://doi.org/10.2495/SDP070361

Iranian National Standards Organization. Isiri 14253: residential building-criteria for energy consumption and energy labeling instruction, http://standard.isiri.gov.ir. Accessed 25 May 2022

Khasreen, M., Banfill, P. F. G., & Menzies, G. (2009). Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. *Sustainability*, *1*(3), 674–701. https://doi.org/10.3390/su1030674

Mari, T. S. (2007). Embodied energy of building materials A comparative analysis of terraced houses in Malaysia. *41st Annual Conference of the Architectural Science Association at Deakin University*, (Raia 2004), 165–173.

Miller, A. J. (1998). Energy Implications of the Transportation of Building Materials. *Materials and Technologies for Sustainable Construction*, *2*, 803–810.

Monahan, J., & Powell, J. C. (2011). An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy and Buildings*, *43*(1), 179–188. https://doi.org/10.1016/J.ENBUILD.2010.09.005

Monteiro, A. C. S. (2015). *Assessing initial embodied energy in building structures using LCA methodology* (Doctoral dissertation).

Muthu, S. S. (2014). Estimating the overall environmental impact of textile processing: life cycle assessment (LCA) of textile products. *Assessing the Environmental Impact of Textiles and the Clothing Supply Chain*, 105–131. https://doi.org/10.1533/9781782421122.105

Paulsen, J. S., & Sposto, R. M. (2013). A life cycle energy analysis of social housing in Brazil: Case study for the program "mY HOUSE MY LIFE." *Energy and Buildings*, *57*, 95–102. https://doi.org/10.1016/j.enbuild.2012.11.014

Poulianiti, K. P., Havenith, G., & Flouris, A. D. (2018). Metabolic energy cost of workers in agriculture, construction, manufacturing, tourism, and transportation industries. *Industrial health*.

Praseeda, K. I., Reddy, B. V., & Mani, M. (2015). Embodied energy assessment of building materials in India using process and input–output analysis. Energy and Buildings, 86, 677-686.

Pullen, S., Holloway, D., Randolph, B., Troy, P., Park, H., Bay, K., & Bay, C. (2006). Energy profiles of selected residential developments in Sydney with special reference to embodied energy. *Proceedings of the Australian & New Zealand Architectural Science Association (ANZA ScA) 40th Annual Conference*, 73–80.

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings*, *42*(10), 1592–1600. https://doi.org/10.1016/j.enbuild.2010.05.007

Ramesh, Talakonukula, Prakash, R., & Kumar Shukla, K. (2013). Life Cycle Energy Analysis of a Multifamily Residential House: A Case Study in Indian Context. *Open Journal of Energy Efficiency*, *02*(01), 34–41.

https://doi.org/10.4236/ojee.2013.21006

Rauf, A., & Crawford, R. H. (2015). Building service life and its effect on the life cycle embodied energy of buildings. *Energy*, *79*(C), 140–148. https://doi.org/10.1016/j.energy.2014.10.093

Saber E, Hajitabar N, Daneshmandi H, Choobineh A, Morad M. (2014). Estimation of Energy Expenditure Using the Systematic Workload Estimation (SWE) Among Male Workers of a Steel Industry. *Journal of Health System Research*, *9*(12), 1273-1282.

Seo, S., Foliente, G., & Ren, Z. (2018). Energy and GHG reductions considering embodied impacts of retrofitting existing dwelling stock in Greater Melbourne. *Journal of Cleaner Production*, *170*, 1288–1304. https://doi.org/10.1016/j.jclepro.2017.09.206

Shukla, A., Tiwari, G. N., & Sodha, M. S. (2009). Embodied energy analysis of adobe house. *Renewable Energy*, *34*(3), 755–761. https://doi.org/10.1016/j.renene.2008.04.002

Soltani, A., Rajabi, M. H., Zeinali, E., & Soltani, E. (2013). Energy inputs and greenhouse gases emissions in wheat production in Gorgan, Iran. *Energy*, *50*, 54-61.

Stavropoulos, P., Giannoulis, C., Papacharalampopoulos, A., Foteinopoulos, P., & Chryssolouris, G. (2016). Life Cycle Analysis: Comparison between Different Methods and Optimization Challenges. *Procedia CIRP*, *41*, 626–631. https://doi.org/10.1016/j.procir.2015.12.048

Stephan, A., & Crawford, R. H. (2016). The relationship between house size and life cycle energy demand: Implications for energy efficiency regulations for buildings. *Energy*, *116*, 1158. https://doi.org/10.1016/j.energy.2016.10.038

Tarancon, M. A., & Del Río, P. (2012). Assessing energy-related CO2 emissions with sensitivity analysis and input-output techniques. *Energy*, *37*(1), 161–170. https://doi.org/10.1016/j.energy.2011.07.026

United Nations University, & World Health Organization. (2004). *Human Energy Requirements: Report of a Joint FAO/WHO/UNU Expert Consultation: Rome, 17-24 October 2001* (Vol. 1). Food & Agriculture Org.

Zabalza Bribián, I., Valero Capilla, A., & Aranda Usón, A. (2011). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment*, *46*(5), 1133–1140. https://doi.org/10.1016/j.buildenv.2010.12.002

APPENDICES

A. The original tables in Persian

Table A. The main Persian Fuel consumption catalog retrieved from the site http://rahdar44.ir, introduced by the creators.

میزان مصرف در هر ساعت کار	ظرفیت مخزن سوخت (لیتر)	قدرت موتور اسب بخار	نام دستگاه	تصویر
۱۰ ۱۴ ۱۸ ۲۲ ۲۶ ۳۰ ۳۲	۱۰۰ ۱۵۰ ۱۷۰ ۲۲۰ ۲۵۰ ۲۷۰ ۳۰۰	۱۰۰-۷۵ ۱۲۵-۱۰۰ ۱۵۰-۱۲۵ ۱۷۵-۱۵۰ ۲۰۰-۱۷۵ ۲۲۵-۲۰۰ ۲۵۰-۲۲۵	لودر	
بر حسب نوع کامیون و کشنده و باری بودن بین ۳۰ تا ۴۵ لیتر در ۱۰۰ کیلومتر	200	220	کامیون	

Table B. Estimation of energy consumption based on heart rate while doing work in the studied workers (Saber *et al*., 2014)

انرژی مصرفی ($Kcal.min^{-1}$)					
حداکثر	حداقل	انحراف استاندارد	میانگین		ضربان قلب حین انجام کار (bpm)
۴/۵۶	۱/۱	۰/۷۳۴	۲/۶۵	(n=۶۷)	کارهای سبک (<۹۰)
۴/۹	۱/۹۴	۰/۷۰۶	۲/۹	(n=۲۶)	کارهای متوسط (۱۰۹ – ۹۰)
۵/۶۴	۲/۶۷	۱/۰۷	۴/۱۱	(n=۷)	کارهای سنگین (۱۲۹ – ۱۱۰)
-	-	-	-	(n=۰)	کارهای بسیار سنگین (۱۴۹ – ۱۳۰)
-	-	-	-	(n=۰)	کارهای بسیار بسیار سنگین (۱۷۰ – ۱۵۰)