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A comparative study of life cycle carbon emissions and embodied energy between sun-dried bricks and fired clay bricks

Marwa Dabaieh [a, b, *], Jukka Heinonen [c], Deena El-Mahdy [d], Dalya M. Hassan [d]

[a] Department of Urban Studies, Faculty of Culture and Society, Malmö University, Sweden
[b] Department of Architecture Design and Media Technology, Aalborg University, Denmark
[c] Faculty of Civil and Environmental Engineering, University of Iceland, Iceland
[d] The British University in Egypt, Architectural Engineering Department, Egypt

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A B S T R A C T

This study presents a comparison of the life cycle carbon emission ($LCCO_2$) and embodied energy calculation between two kinds of bricks, sun-dried and fired clay, as means of evaluating the energy and climate impact of each brick type and the economics of production. Focus is paid to the differences across the whole production chain between sun-dried clay bricks, which represent the traditional norm, and fired clay bricks, which are the most widely-used walling materials in conventional buildings. A case study was carried out in Dakhla Oasis in the Western Desert of Egypt. The results of this study show that if sun-dried bricks are used instead of fired bricks, a reduction of up to 5907 kg CO_2e (in CO_2 emissions) and 5305 MJ of embodied energy for every1000 bricks produced could be achieved. The paper concludes by offering alternative scenarios for brick-making and suggestions for improving sun-dried brick production. The methodology used in this study contributes to the development of an investigative-comparative way to assess choices between building materials. It also intends to help inform local homeowners and building practitioners not only in Egypt, but also globally, about resource depletion, energy consumption, and harmful emissions from fired industrial bricks as a common building construction material.

1. Introduction

Worldwide, buildings are significant consumers of energy, water, and raw materials. The building sector consumes between 30 and 40% of society's total energy and is responsible for roughly 1/3 of the total CO_2 emitted into the atmosphere. Adding to this problem, worldwide energy consumption is expected to double by 2030 (IPCC, 2014). The high level of CO_2 emissions from the building sector is due to high levels of energy consumption throughout the raw material extraction, production and transportation processes which are powered by fossil fuel sources (Hootman, 2012; Koroneos and Dompros, 2007). The environmental footprint of the building sector includes: 30% raw materials use, 25% output of solid waste, 25% water use, and 12% of land use, 10–20% of which is consumed during extraction and processing of raw materials, manufacturing of products, construction, and demolition (UNEP, 2009). With rapid population growth, an increase in material embodied energy and carbon emissions is expected due to our energy intensive construction techniques (UN-Habitat, 2011). This problem is expected to escalate more rapidly in emerging countries, where urbanization rates and economic growth are rising annually between 1 and 3% compared with 0.3% in OECD countries (Woodward and Holbrook, 2013). Furthermore, the issue has recently been raised that higher attention should be given to buildings' embodied emissions which occur early in the life cycle, rather than focusing on use phase emissions which take place over a long time-span and might not yield energy savings that are as high as expected (Säynäjoki et al., 2012, 2017). In addition, energy savings are receiving high priority in the world today due to growing environmental and economic concerns (Cruz et al., 2017).

Construction materials greatly affect CO_2 emissions. Energy consumption during the manufacturing and transportation of materials is directly related to GHG emissions (Reddy, 2009; Syngros et al., 2017). The embodied energy (EE) of buildings is

* Corresponding author. Nordenskiöldsgatan 1, 205 06, Malmö, Sweden.
E-mail addresses: marwa.dabaieh@mau.se (M. Dabaieh), heinonen@hi.is (J. Heinonen), deena.elmahdy@bue.edu.eg (D. El-Mahdy), dalya.maguid@bue.edu.eg (D.M. Hassan).

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divided into two main categories—direct and indirect. Direct EE is the energy consumed during transportation and installation of building materials, while indirect EE is related to the energy used in acquiring, processing, and manufacturing of building materials, including transportation activities related to these processes (Syngros et al., 2017). Thus, the correct selection of materials is essential in helping save energy and reduce CO_2 emissions (Gonzalez and Navarro, 2006). Natural materials such as soil, stones, and timber or biomass are considered ideal building materials because they help keep emissions low, have the smallest carbon footprint and can be recycled and reused (Syngros et al., 2017).

In Egypt, the built environment is responsible for around 50% of greenhouse gas emissions (GHG) (NREA, 2013), making it the largest emitter. Furthermore, it makes the need for decarbonisation of buildings one of the most critical and immediate challenges that the construction industry currently faces. The Western Desert of Egypt (which is more than 1/3 of the total Egyptian land mass) has recently experienced rapid urbanization (Dabaieh, 2011). A wide range of building materials are being used in building construction throughout the Western Desert (Schijns et al., 2008). Most materials are either industrialized ones created elsewhere or non-local materials which are excavated, processed, manufactured and then transported to the building site (Dabaieh, 2015). Fired bricks are one of the common brick types used and consume a considerable amount of energy associated with a considerable depletion of natural resources and GHG emissions during manufacturing and transportation processes (Skinder et al., 2014; Kumbhar et al., 2014; Darain et al., 2013; Oti and Kinuthia, 2012). This results in an elevation of the embodied energy and consequently elevated CO_2 emissions. Despite the fact that industrial building materials and methods are often not a sustainable way of building in the Western Desert, some people favour this solution due to recent changes in social and cultural norms (Dabaieh, 2013).

Furthermore, building construction is estimated to grow in Egypt at a rate of 6.6% per year between 2005 and 2030 resulting in a continuous increase in the demand for bricks as a main building material (CAPMAS, 2018). There are several types of industrial bricks in Egypt such as cement, sand, and clay bricks. Each year, billions of tonnes of industrial bricks are produced locally for use in construction projects. It is estimated that around one million workers are employed in Egypt's brick-manufacturing industry. Fired clay bricks, locally referred to as "red bricks," are arguably the most commonly used material in construction today in Egypt, nevertheless, fired clay brick kilns are one of the most dangerous workplaces. According to the 2014 Census, 87.5% of building walls in Egypt are built from fired clay bricks (CAPMAS, 2014). However, over the past few decades, the development of other materials such as concrete blocks, fly ash bricks, stabilized mud blocks, etc., has created viable alternatives to fired clay bricks but still yields no influential impact in replacing the pollution laden fired clay brick industry.

Based on the aforementioned facts, one could argue that there is a crucial need to study buildings' material carbon lifecycle under bad environmental conditions as in Egypt and focus on ways to reduce carbon emissions. The aim of this study is to utilize life-cycle carbon emission calculations ($LCCO_2$) as an assessment framework to compare two building materials, sun-dried and fired clay bricks, applied in a real case study at Balat Town in Dakhla Oasis in the Western Desert of Egypt. This was done in order to ascertain which material has the lowest $LCCO_2$, and what the mitigation potential is for switching towards wider utilization of this material. The different phases of sun-dried bricks' and fired clay bricks' lifecycles were examined, from raw material extraction, manufacturing, transport, and use, to waste processing. At each phase of the bricks' lifecycle, the energy and material consumption, as well as CO_2 emissions released into the environment were recorded. This paper details the important contribution of CO_2 emissions and embodied energy and explains in a comprehensive comparative approach the estimated embodied energy and CO_2 for the two selected types of bricks. The results address concerns about the possibility of reducing the CO_2 emissions if fired clay bricks are replaced by sun-dried clay bricks in contemporary buildings in the Western Desert area and in Egypt at-large. The study also shows the economic benefits of sun-dried bricks, especially in remote areas in Egypt, which might yield similar results in other regions that share the same climate and use bricks as a main construction material.

1.1. Brick production

Early studies and experience using sun-dried clay bricks (adobe) proved that using local and natural earth materials in buildings is energy efficient (Fathy, 1973), low in toxicity (Norton, 1997), safe, and durable (Kennedy, 2004), especially if obtained from the local environment. Adobe bricks are traditional, eco-friendly and energy-efficient construction materials that can achieve great carbon savings (Christoforou et al., 2016; Pacheco-Torgal and Jalali, 2012). Furthermore, extraction of the raw material (earth) has minimal environmental impacts (Christoforou et al., 2016), which is particularly important in regions where clay as a raw material is locally abundant.

Casting sun-dried clay brick is an inherited tradition in the Western Desert. Clay is a widely available resource, typically found everywhere houses are built (Fathy, 1973). Furthermore, locals know where to source proper soil for clay bricks from experience, and timeless trials and errors. They choose building sites where the soil is rich in animal manure and far from agricultural land in order to avoid soil that is high in salt or recently subjected to fertilizers (Dabaieh, 2011).

Sun-dried clay bricks can be cast on-site easily and quickly, thus eliminating the need for raw material transportation. However, if transportation is needed, donkey carriages are used, which incur no monetary costs and leave no carbon footprint. Despite the seemingly primitive nature of donkey carriages, using them reduces CO_2 emissions and embodied energy in transportation. In addition, they are very economical when compared to other means of heavy transportation.

As for labour, if locals cast bricks themselves, which is normally the case, the cost of workers' fees are eliminated. From the study site investigation in Balat, it was concluded that one person can cast up to 700 bricks (25 cm $\times$ 12 cm x 7 cm) in 8 working hours. Normally, less energy-intensive techniques like casting sun-dried clay bricks are more labour-intensive. However, in a country like Egypt, where labour costs are reasonable, less energy-intensive techniques have both the advantage of reducing construction-related energy and CO_2 emissions together with creating employment possibilities.

Fired bricks are now becoming a common building material in the Western Desert, subsequently demanding energy in the bricks' lifecycle right from manufacture to demolition. Along the lifecycle of fired bricks, various natural resources are consumed, including energy, water, and soil. Moreover, various pollutants are released back into the environment. The impact on the environment from producing fired red brick varies; however, within the production process, the burning phase is always accountable for the highest amount of CO_2 emissions and can have harmful impacts on the environment. In addition, using clay extracted from riverbeds contributes to resource depletion, while diesel used in brick furnaces is a main source of air pollution (Le and Oanh, 2010). Moreover, fired brick requires production and transport machinery and infrastructure. These environmental inputs and outputs result in many environmental problems like global warming, over-excavation, acidification, and atmospheric pollution (Fouda, 2001), which all impact human health and natural resources (Lebel and Kane, 1990).

1.2. Literature review

A number of multidisciplinary studies exist in the literature on the environmental burden of industrial bricks in relation to the effects of location, structural form, and energy systems (Yahya and Boussabaine, 2010; Zhang et al., 2006). Furthermore, studies on life-cycle assessment methodologies using eco-indicators and other methods of estimating the eco-costs of construction waste have also been investigated alongside studies on the impact of brick waste from construction sites on the environment (Li, 2006; Sarkis, 2001; Yahya and Boussabaine, 2010). In order to minimize the environmental impact of new buildings, especially in developing countries, a number of studies have also developed criteria for selecting and assessing materials (Sameh, 2014; Singh et al., 2009).

The majority of research dealing with sun-dried clay bricks discusses the environmental and economic benefits associated with using them (Dethier and Eaton, 1983; Facey, 1997; Pacheco-Torgal and Jalali, 2012; Djamil, 2016). A decent number of research studies have also focused on energy consumption, carbon dioxide emissions and waste generation during clay brick production (Facey, 1997; Pacheco-Torgal and Jalali, 2012); yet, their long-term environmental benefits have been ignored. On the other hand, research dealing with thermal performance and embodied energy of mud bricks or fired bricks in developing countries, conducted by Chel et al. (2009), didn't focus on economic factors. A study in Singapore examined the environmental impacts of replacing concrete with bricks using an attributional life-cycle approach. The study shows that bricks increase negative net environmental impacts and suggests new sustainable brick-making approaches to create what they termed as “green demand” (Kua and Kamath, 2014).

It is evident that several efforts are being made in search of new environmentally friendly materials. From these efforts is an increased preference for the adoption of using more clay-based materials for sustainable construction (Marcelino-Sadaba et al., 2017). Research shows that using low-energy intensive earth building materials and traditional construction techniques could be tools for reducing CO_2 emissions (May and Reid, 2010; Rael, 2009). Moreover, Morel et al. (2001), claim that using local materials has social and economic benefits as well as a reduction on costs compared to the use of either imported or industrialized building materials and methods. Pacheco-Torgal and Jalali (2012) also highlighted the resulting minimal generation of waste during the production and use of adobe (unfired clay bricks), in addition to the importance of transportation energy. Other benefits of using earth local natural building materials include their ability to be locally produced, recycled, or re-used (Morel et al., 2001).

To the contrary, most industrialized fired brick material must be incinerated or buried in order to be disposed (Hussain and Ali, 2019; Le and Oanh, 2010). Although there is a large and growing body of empirical evidence that shows how indigenous building materials are more advantageous and environmentally friendly than industrialized building materials (Dethier and Eaton, 1983; Facey, 1997; Pacheco-Torgal and Jalali, 2012), the latter are still more widely favoured. Nevertheless, Venkatarama Reddy and Jagadish (2003) showed how the benefits of low-energy building materials and technologies can result in about a 50% reduction of the embodied energy of a whole building system. Furthermore, there are few relevant studies that tackle the impact of the production of adobe bricks on the environment (Christoforou et al., 2016).

In terms of assessment methodologies for building materials, life-cycle studies are useful approaches used for the analysis and documentation of technical options and alternatives to minimize the environmental impacts of any process or product (Christoforou et al., 2016). Life cycle assessment (LCA) methods have been used in the building sector since 1990 (Fava, 2006; Säynäjoki et al., 2017) for gauging the impact of products or materials on the environment throughout their entire life span (see Kumbhar et al., 2014; Singh et al., 2011; Le and Oanh, 2010). Furthermore, research indicates that LCA methods have been used in several cases all over the world as a way of investigating the impact of brick production on energy and emissions through different material phases starting from raw material acquisition up through final packaging and transportation to site (see Fernandes et al., 2019; Bories et al., 2016; Christoforou et al., 2016; Kumbhar et al., 2014; Kua and Kamath, 2014; Koroneos and Dompros, 2007). LCA studies are also a good tool for helping make decisions on building materials. This is present for Life Cycle Assessment (LCA), Life Cycle Energy Assessment (LCEA) and Life Cycle Carbon Emissions Assessment ($LCCO_2A$) studies (Chau et al., 2015).

In the construction industry, Life Cycle Assessment (LCA) methods are used to evaluate the environmental impacts of materials and quantify their related emissions over a given material's entire life cycle (Marcelino-Sadaba et al., 2017; Christoforou et al., 2016; JRC European Commission, 2011). LCA Studies are mainly divided into three main streams, Life Cycle Assessment (LCA), Life Cycle Energy Assessment (LCEA), and Life Cycle Carbon Emissions Assessment ($LCCO_2A$). $LCCO_2A$, which is the main focus of this study, is mainly concerned with all the CO_2 equivalent emission outputs that take place over the different phases of a building's life cycle, which includes material production, transportation, construction, operation, maintenance, and end of life (Kumanayake and Luo, 2018; Chau et al., 2015). This is particularly important with rising greenhouse gas emissions that ultimately cause huge global warming problems (Chau et al., 2015). Furthermore, $LCCO_2$ is considered the best approach to measure CO_2 emissions, which usually take place over a building's entire life cycle (Kumanayake and Luo, 2018).

Several methods have been developed by researchers in various countries to help evaluate $LCCO_2$ emissions based on the unique characteristics of construction industries in each country (Forsberg and Malmborg, 2004). A study by Zhanga and Wang (2017) for example presented a method for analysing $LCCO_2$ of regional construction sectors in China including building materialization, operation, and disposal phases. In Sri Lanka, Kumanayake and Luo (2018) developed a life cycle CO_2 emissions estimator tool for buildings in the country that could help compare life cycle CO_2 emissions of different buildings and provide a way to evaluate the compliance of buildings to the CO_2 emissions standards of the country. A study by Chou and Yeh (2015), developed a system that combined the evaluation of CO_2 emissions with cost calculation methods during the building construction phase.

In terms of brick production, LCA studies have been taking place since 2007 and continue to date (see Huarachi et al., 2019; Koroneos and Dompros, 2007; López- Aguilar et al., 2016; Talang et al., 2017). LCA studies have been conducted on buildings with clay brick veneer, demonstrating the significant impact of clay bricks on the overall embodied CO_2 of the building (see Thormark, 2006; Ajayi et al., 2015; Takano et al., 2014; Kua and Kamath, 2014; Marcelino-Sadaba, 2017). According to Khan et al. (2019), brick kilns are one of the main causes of pollution and harmful gas emissions in the construction industry, particularly with brick manufacturing being one of the fastest growing industries worldwide. Research indicates that the brick firing process can lead to the emission of harmful polluting gases to the atmosphere, such as carbon dioxide (CO_2), carbon monoxide (CO), chlorine (CL2), ammonia (NH3), sulphur dioxide (SO2), nitrogen oxide (NO), hydrogen cyanide (HCN), and fluorine (F) (Ukwatta et al., 2018; Kadir and Mohajernai, 2015; Toledo et al., 2004). The concentrations of these emissions differ according to the kiln type, firing time, and technology and fuel used (Ukwatta et al., 2018). Kumbhar et al. (2014) and Subrahmanya (2006) also compared brick kiln technologies in terms of their energy usage, efficiency, and GHG emissions, highlighting the possibility of using alternative renewable fuel options in the clay brick industry. Furthermore, a study by Huarachi et al. (2019), presented a review for all LCA related studies that have been conducted in relation to bricks. However, few studies, were found that discussed $LCCO_2$ of fired clay bricks.

On the other hand, research indicates that while manufacturing and production processes are viewed as main sources of economic growth, they can also contribute to social and environmental problems (Baldwin et al., 2005). Thus, there is a growing global interest in the adoption of more sustainable and environmentally friendly practices in the manufacturing process. An important concept from these practices, related to LCA, is called 'Extended Product Responsibility' (EPR) (Madu et al., 2002; Barde and Stephen, 1997). EPR is the principle that all main parties involved at any point along the product chain share responsibility for the environmental impacts of the whole product system (White et al., 1999). EPR is an important consideration in achieving a green supply chain (Gunasekaran and Spalanzani, 2012) and when attempting to adopt more sustainable approaches during the brick production process.

The reduction of GHG emissions has also received some attention in Egypt. In an effort to reduce GHG emissions from the brick industry, the Egyptian government together with the United Nations Convention on Climate Change, started a project to switch from high carbon-intensive fuel in heat generation to a less carbon-intensive one by using natural gas in brick factories instead of coal. A three-year monitoring study of 152 brick factories that had made the switch showed a considerable reduction in GHG emissions – reaching up to 157,604 tonnes (Lehmann, 2007). However, the pilot study was stopped after the initial 153 factories, leaving the rest of the polluting brick kilns in Egypt. Moreover, the production costs of firing bricks are only increasing in Egypt, becoming an economic burden to many. In 2013, due to the rise of diesel prices, the cost of fired clay bricks increased from 180 Egyptian pounds (EGP) to 380 EGP per 1000 bricks to mount rapidly in 2019 to reach 1800 EGP. Ogila (2014) stated that brick quality and cost in Egypt have become more important recently due to the increasing demand for bricks as a main material in the construction industry.

There is limited research on alternative solutions for reducing the environmental impacts of the brick industry in Egypt. Ogila tested cement kiln dust as a clay substitute for producing quality fired red clay bricks in order to achieve a low-weathering and high resistance brick compared to conventional ones available on the Egyptian market (Ogila, 2014). Akmal et al. (2011) investigated the use of a rice-straw based cement brick mixture. Their experimental research proved that recycled bio-brick not only helps to decrease air pollution when compared to the common Egyptian practice of burning rice straw to dispose of the material, but it also reduces construction costs and enhances the thermal properties of the bricks. In terms of LCA and $LCCO_2$ studies, very few robust research papers were found discussing its utilization in the assessment of building materials in Egypt (Ali et al., 2014).

Similarly, few studies assessing the environmental burdens of buildings have focused on the residential sector (Ali et al., 2015) or have used LCA in assessing environmental impacts of the brick industry in Egypt. A limited number of individual researches in Egypt was found to be concerned with the use of sun-dried mud bricks as an environmentally friendly and economical building material for remote desert areas (see Schijns et al., 2008). Furthermore, there is a gap in research that surveys and tests Egyptian building materials and their relation to environmental, economic, and social benefits. Moreover, there is insufficient informative research globally focusing on LCAs of bricks, especially sun-dried bricks as an environmentally friendly material option. It is also apparent that using $LCCO_2$ as an assessment tool in brick production is not a widely explored field. Furthermore, reliable formal databases and information are limited in regard to the environmental impact and economies of production. Hence, the need for this research is evident in order to set assessment criteria between the two selected types of bricks.

2. Methodology

2.1. Case study selection

The study investigations were made in the town of Balat (25° 34 'N, 29 °16 'E), at the eastern entrance of the Dakhla Oasis in the Western Desert of Egypt, 800 km SE of Cairo, see Figs. 1 and 2. It was chosen as a case study because sun-dried clay brick production is still used in building construction. However, nowadays it is not as widely used for residential buildings as it was 20 years ago. These days, clay brick is mainly cast to construct fences, build animal barns, restore old buildings, and erect other temporary structures on agricultural land. Few inhabitants build their homes with clay bricks, typically using fired clay bricks brought from a brick kiln at the town border 30 km away, instead. Gradually, handmade and sun-baked clay brick production is becoming replaced by industrialized processes. For this reason, the town of Balat was a suitable location for the purposes of this research. A database was created to record the comparison between the production and use of sun-dried and fired clay bricks. The raw materials required to produce the two types of bricks are from the same source. In order to compare the two bricks, two buildings were constructed in the centre of town, one from sun-dried and the other from fired bricks. The two buildings were used as investigative cases. All the calculations were based on how the brick production process occurs in real life.

2.2. Methodological framework

The methodology applied is an investigative empirical site survey in the town of Balat located in Dakhla Oasis in the Western Desert of Egypt as described in section 2.1. It is a comparative life cycle carbon emission ($LCCO_2$) and embodied energy (EE) study between sun-dried and fired clay bricks. $LCCO_2$ is used as a tool for evaluating carbon emission as one of the harmful environmental impacts of the manufacturing processes that bricks undergo during their whole life cycle. This work is carried out in four main steps, listed below. The life cycle inventory calculation process is illustrated in Fig. 3.

1 Site investigations for tracing and documenting brick production supported by documentation from literature.
2 $LCCO_2$ and EE calculations for both the sun-dried and fired clay bricks based on an actual site investigation of brick production, the calculations are based on in-situ investigations and measurements together with available data from a literature search.
3 A comparative analysis of CO_2 emissions and EE during material production until disposal.

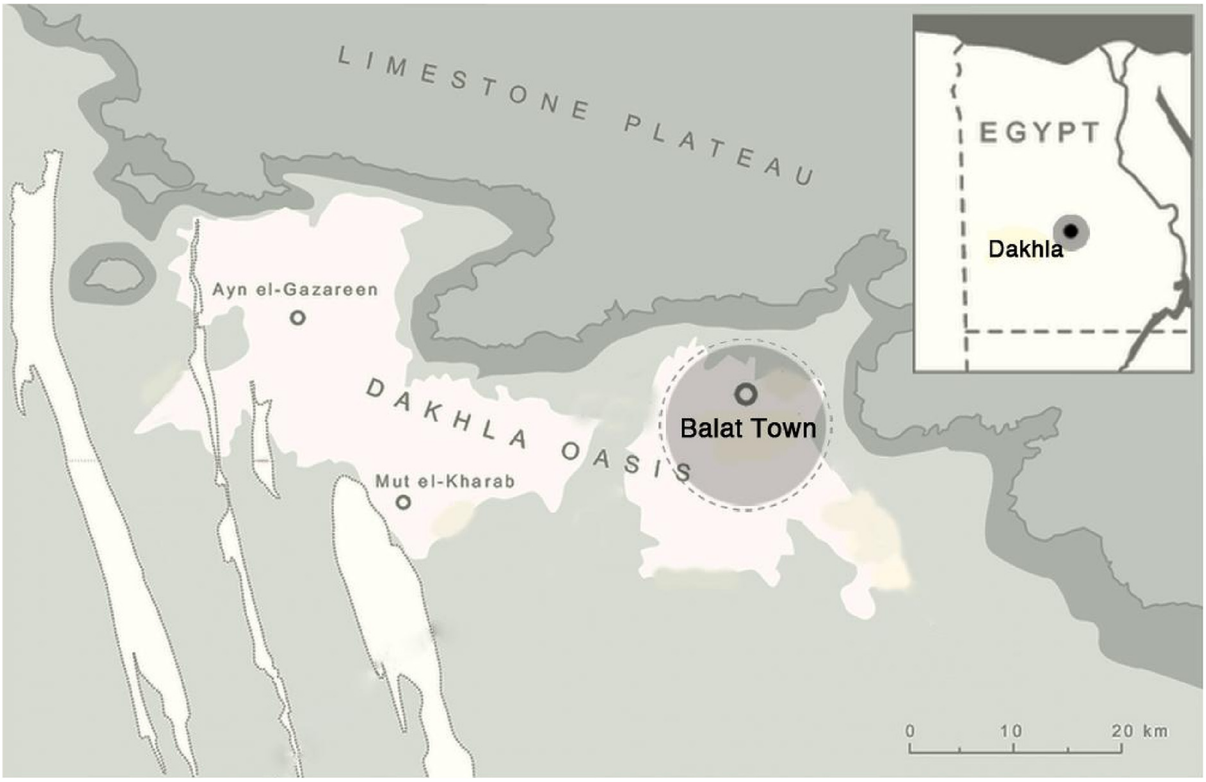

Fig. 1. A map showing the Dakhla Oasis in Egypt and the case study of Balat Town.

Fig. 2. Image from the case study of Balat Town in Dakhla Oasis, Egypt.

4 Investigation for alternative scenarios for brick production and recommendations for reducing emissions during brick production.

The main midpoint impact category involved in this study is climate change, which incorporates CO_2 as one of the main greenhouse gases that causes an increase in temperature in the lower atmospheric layers and directly impacts human health and environmental degradation. Fig. 4 shows the brick life cycle system boundaries and the phases considered in this study.

2.3. System boundaries and CO_2 emission calculations

Based on life cycle theory (ISO, 2006), $LCCO_2$ emissions calculations for both types of bricks were divided into two stages, the manufacturing stage (including extraction, production of building material, and transportation to building site) and the demolition stage (including building demolition, waste material recycling, and processing) as shown in Fig. 5. The operations and maintenance stages are left out of the calculations as they are almost negligible for clay bricks.

According to (Sartori and Hestnes, 2007) maintenance of materials is approximately 1% of total life cycle energy requirements. However, the use phase was shown in the system boundaries because it is the same in each type of brick. Both types of bricks use manual installation in order to layer the bricks with negligible maintenance. The total embodied energy calculations intended to cover the whole supply chain of the materials but didn't take into account non-material inputs as hybrid figures were not available. In the case of fired brick, calculations are made based on the actual and real-life situation when producing fired bricks in the case study location in the Western Desert. All the calculations were based on the actual optimum scenario as it occurs when casting sun-dried bricks in the Western Desert at the time of this study.

One thousand bricks are used as a functional unit during the different comparison phases between the sun-dried and fired clay brick. Conversely, in other studies, like in Christoforou et al. (2016), 1 kg of brick is used in order to compare bricks with different construction and building materials. Yet, it is common in the brick production tradition in Egypt to measure bricks by volume (1000-brick unit) (Virginia, 2009) and still in the conventional brick industry rather than by weight. Accordingly, the study here followed the same norm in order to achieve more accurate calculations and outcomes.

The life cycle phases investigated for the two types of brick processes comprising: pre-production, production, usage, and after use. The pre-production phase includes the acquisition of raw material for the bricks, transportation, and on-site building process. The production of the material phase considers the energy needs for the production process. The after-use phase includes the energy and emissions that accompany the disposal and re-use of brick

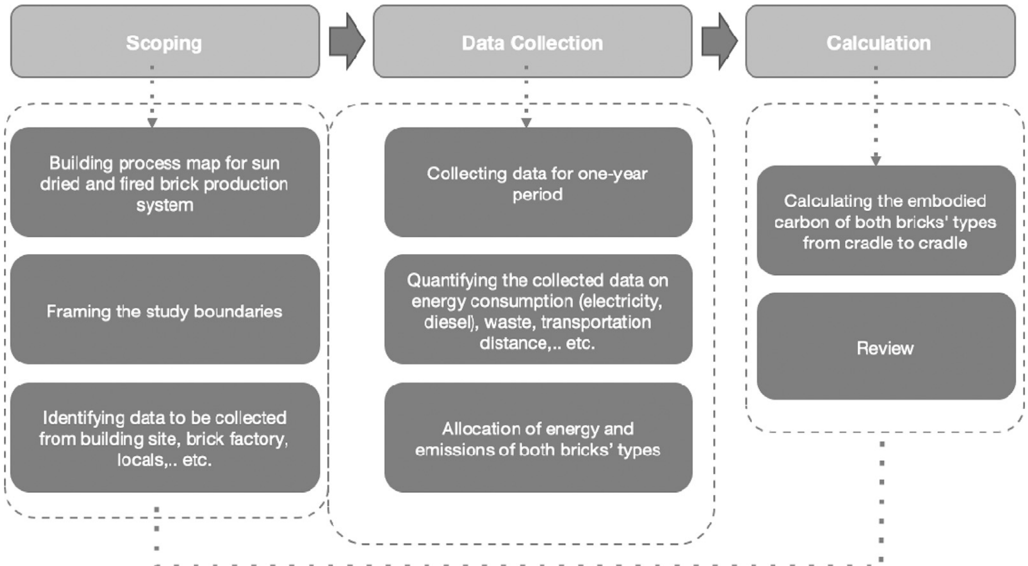

Fig. 3. The life cycle inventory calculation process followed for sun-dried and fired clay bricks.

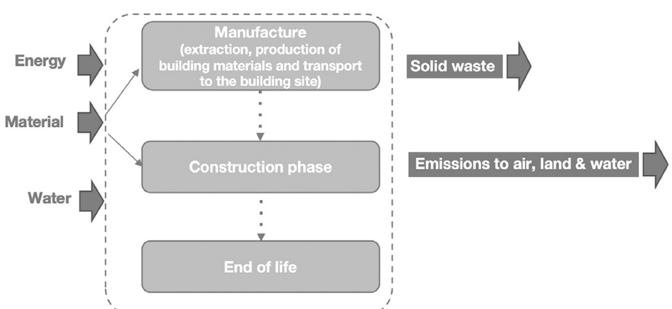

Fig. 4. Brick life cycle system boundaries and the phases considered in this study.

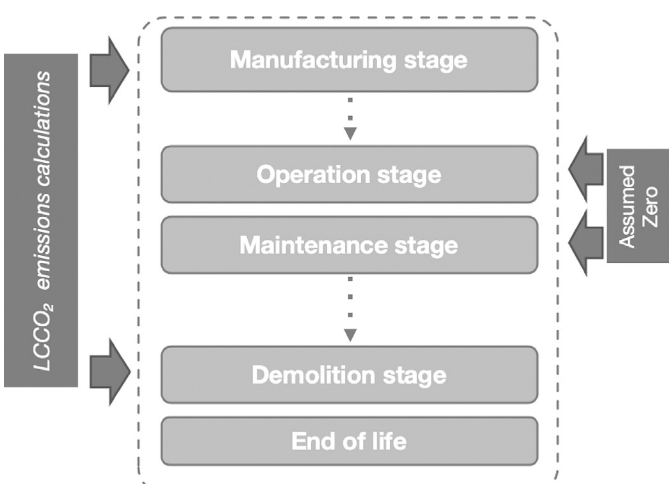

Fig. 5. $LCCO_2$ emissions calculation stages.

material. The assumptions are made to separate the impacts related to construction materials and impacts related to grey energy, that is, the energy contained in building materials. System boundaries for sun-dried and fired bricks and descriptions of life cycle stages are shown in Figs. 6 and 7.

2.4. $LCCO_2$ and EE calculation

For quantifying carbon emissions, a set of equations were used following the same procedures applied by Huang et al. (2016) and Peng (2016). For fuel emissions, Equation (1) was used to calculate the emissions from fuel used in machines for brick manufacturing and in vehicles used in transportation. Equations (2) and (3) are based on the formula suggested by the IPCC (2006) program report for inventorying greenhouse gases. For carbon emission calculations, Equation (4) was used to calculate material extraction, manufacturing, transportation, construction, and disposal.

$$\text{Fuel Use } CO_2 \text{ (kg)} = \text{Fuel Used(litre)x Fuel Type } (\text{kg}CO_2/\text{litre}) \quad (1)$$

$$C = \Sigma_{i,j,k} AD_{i,j,k}.EF_{i,j,k} \quad (2)$$

$$EF_{i,j,k} = c_k.\eta_{i,j,k}.\frac{44}{12} \quad (3)$$

where C is the amount of CO_2 emissions, AD is the level of activity, EF is the emission factor, i is the industry and region, $_j$ is the equipment and technology used, k is the type of fuel used, C_k is the carbon content, and $\eta_{i,j,k}$ is the oxidation rate.

$$\text{CE(S)} = \text{CE(S1)+CE(S2)+CE(S3)+CE(S4)} + \text{CE(S5) Equ.} \quad (4)$$

where CE(S1) is the carbon emissions at the material extraction stage, CE(S2) is the carbon emissions at manufacture stage, CE(S3) is the carbon emissions at the material transportation stage, CE(S4) is the carbon emissions at the construction stage, and CE(S5) is the carbon emissions at the disposal stage.

For the embodied energy it was calculated for raw material extraction, material production, transportation and building construction, and maintenance. Equations (5) and (6) were used.

$$E_{emb,inital,i} = E_{extraction,i} + E_{manufacture,i} \quad (5)$$

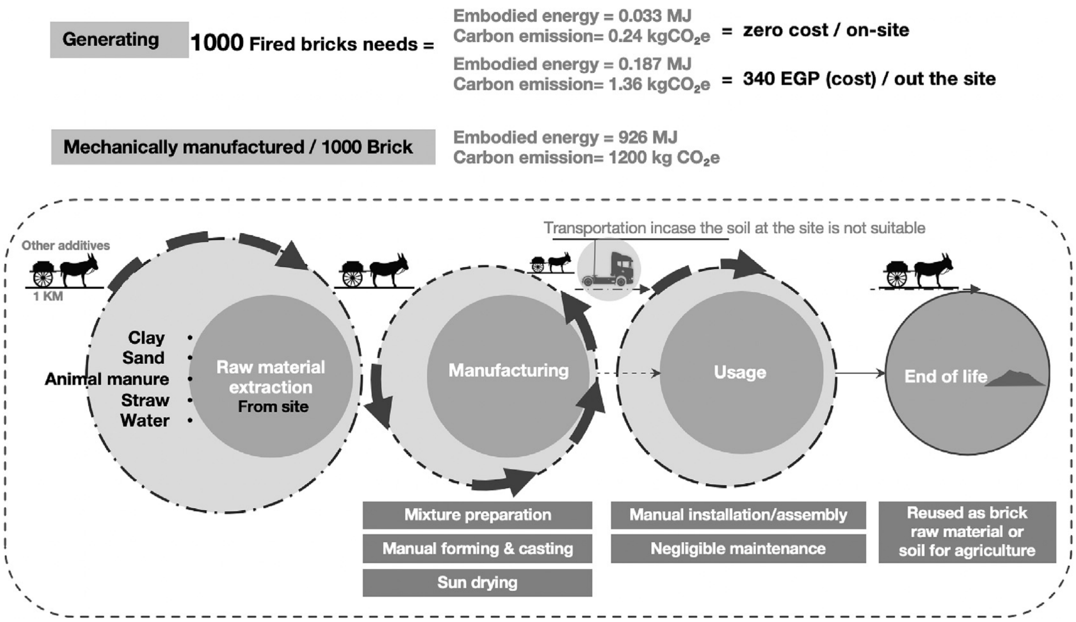

Fig. 6. System boundaries for sun-dried clay bricks.

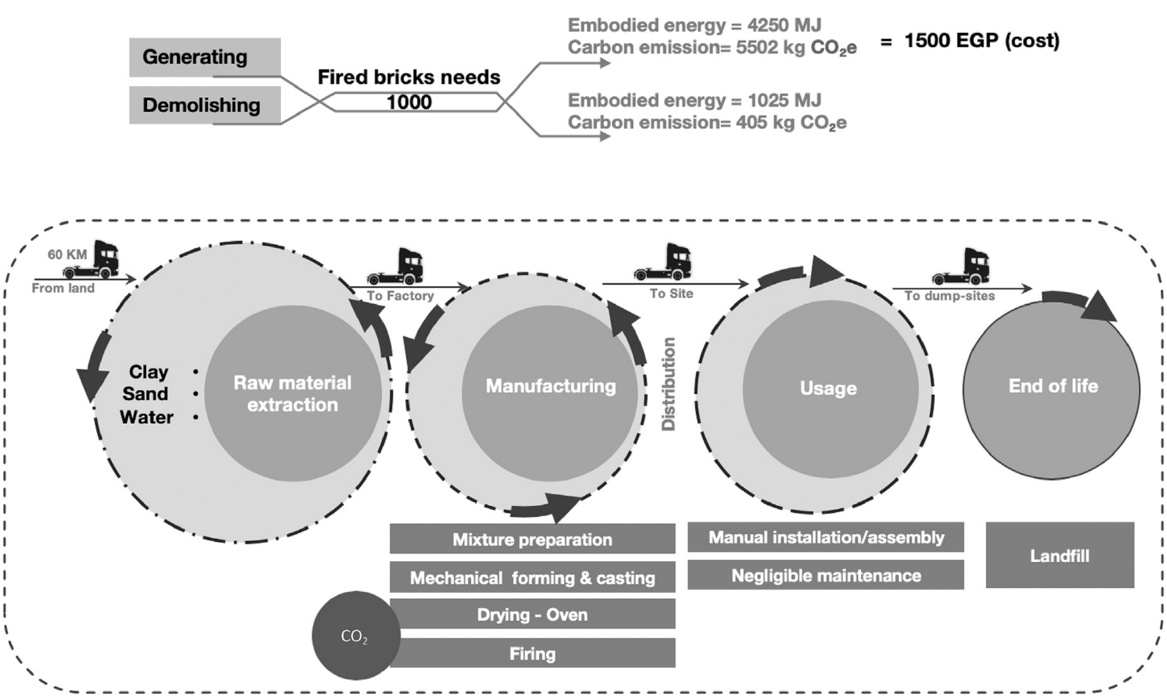

Fig. 7. System boundaries for fired clay bricks.

$$E_{emb,inital} = \sum_{1}^{i} \alpha_i m_i \tag{6}$$

Where *Eemb, initial,i* is the initial embodied energy of the ith type of building material (in MJ); *Eemb, initial* is the initial embodied energy of the whole building (in MJ); ⟨i is the embodied energy intensity factor for the ith type of building material (in MJ/kg); and mi is the mass of the ith type of building material (in kg); and *mi* should include not only the quantities of building material in-place but also the wastages incurred during construction. Embodied energy intensity value for bricks were extracted from (Chau et al., 2015) as 0.9–4.6 MJ/kg.

3. Results and discussion

3.1. Site investigations and brick production process

Based on field investigations, as shown in Fig. 8, in order to produce sun-dried bricks, sand and soil are dug-up from the building site and then ground to and mixed with water, straw, and manure in proportions that differ depending on the type of the soil

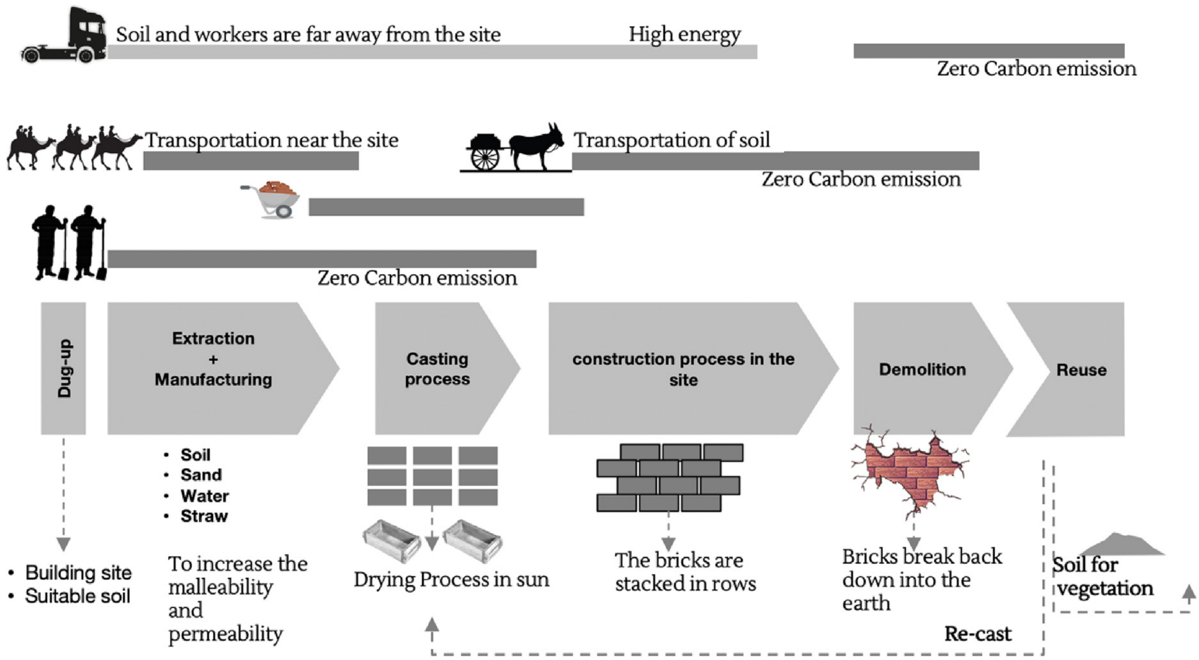

Fig. 8. The process of producing sun-dried clay bricks.

used. The process starts with the addition of water to the soil in order to achieve the proper consistency, plasticity, and workability. Straw and dung are added to increase the malleability and permeability. Finely chopped rice or wheat straw is mixed with the mud to act as a shrinkage compensator and for reinforcement. This helps the entire mud brick block to dry evenly from inside and outside. It also increases compaction, which reduces cracks and keeps the brick more solid. The straw used in the clay mixture is considered an agricultural waste or by-product during the harvest of wheat or rice. It is stored after harvest from local fields to be used in brick casting or as food for animals. The water needed for casting comes from a well approximately 500 m from the site and is transported in barrels using donkey carriages. After the casting process, the bricks are left to dry in the sun as shown in Fig. 9. The total number of bricks needed for the construction of the building is cast before the construction process begins since the whole piece of land is required for casting and drying. The process works in parallel sequences, meaning at a certain moment, preparing the soil mix, casting, and drying happens simultaneously. After the drying process, the bricks are stacked in rows on the periphery of the land until they are used. If nearby transport is needed, donkey carriages are then used to carry the bricks to the building site. The cycle of the extraction and manufacturing processes requires and emits almost zero carbon.

Fig. 9. Sun-dried bricks during the treating process are baked by the sun at the building site.

It can be deduced from site surveys, that the reduced embodied energy in creating the sun-dried clay brick, from manufacturing to demolition and reuse, is minimal. The production of sun-dried clay brick utilises only natural resources, meaning no manufactured products are used in the mud mixture. The energy input for clay brick construction is human labour. The drying process is indirectly fuelled by the sun. After use, the bricks break back down into the earth they came from and can be re-casted as bricks or used as soil for vegetation. Transport of workers and waste products are calculated in this inventory. Based on actual field investigation, waste products are re-incorporated back into the soil in the same location of the building after demolition, so there is no burden due to transportation. Similarly, if local inhabitants cast bricks in building sites near where they live, as is the tradition in the Western Desert, neighbours help each other out with transportation either on foot or through the employment of donkey carriages as shown in Fig. 10. However, it is also possible that bricks are transported to the building site from another location, which would also affect labour and transport costs and emissions. This scenario would be more similar in energy needs to those required for fired bricks.

Fired clay bricks in the Western Desert are either composed of the same type of soil used in sun-dried bricks or using clay and sand that comes from a quarry. The manufacturing and burning processes, as well as the transportation of raw materials, have direct and indirect impacts on carbon emissions, see Fig. 11. Direct CO_2 emissions are high because of the use of machinery and furnaces that use heavy oils or coal as fuel. Generally, there is a significant amount of energy used in transporting raw materials and services

Fig. 10. A typical means for transporting sun-dried bricks to nearby building sites often includes donkey carriages.

to and from building sites. The bricks are mechanically cast using diesel to fuel the machines. The bricks are then burnt in kilns using high temperatures, reaching up to 1000 °C, (typical brick factory shown in Fig. 12). From a site survey, evidence was collected that indicates Mazout (oil waste) or diesel is used as a fuel, meaning about 205 L are burned per 1000 bricks, producing 0.536 kg of CO_2 per litre. Transportation is needed to bring the raw materials to the factory site and to transport the bricks after manufacturing to the construction site (60 km). This transportation is another energy burden as the fuel used in trucks is diesel, which is preferred over benzene for economic reasons. A truck consumes 0.35 L of fuel per km and produces 2.68 kg CO_2 per litre.

The amount of fired brick waste is considerable not only after the building is demolished, but there is also waste produced during the brick manufacturing and building processes. Brick waste cannot be reused and is therefore usually re-burned or incinerated in dump sites. Both solutions pollute the environment. Recently in Egypt, on a very limited scale, construction debris can be re-used in the form of recycled bricks, but such possibilities are not available in the Western Desert region, and even when brick recycling is an option, there is considerable embodied energy and carbon in the recycling process.

The energy required to transport labourers to and from the brick kiln site, based on a 2003 paper by Cole et al., can range from 10 to 80% of the total energy required to construct a building. In this study, the average distance for workers is 15 km. Labour transportation accounts for 9% of the total transportation energy required in brick production, which is rather low. Some workers used means of transportation fuelled by diesel, but the majority of workers came from nearby locations by horse, camel, or a donkey carriage. Interviews with local labourers at the brick kiln made clear that brick manufacturing is physically demanding. Labourers suffered from burns, back injuries, and respiratory illnesses associated with inhaling burning diesel and furnace fumes. The factory, like the majority of factories in the area, rarely use filters in their chimneys, which not only harms the environment, but also affects the health of workers and nearby residents. In terms of humanitarian abuses, child labours have been observed as assistants and are normally overworked and paid less in comparison to their adult co-workers. Other incidents reported include workers losing their balance because of heat stress resulting in death from falling into the fire pit or oven in the burning furnaces.

Looking at the economics of production, from tracing the cost along the whole production process for the two types of bricks. The production cost for 1000 bricks is 340 EGP for sun dried mud bricks compared to 1500 EGP for fired bricks. The difference is big and that shows that sun dried bricks are more economical. The cost of sun-dried bricks might increase in the scenario of using machines for brick production instead of manual casting. It can reach up to 550 EGP for 1000 bricks for the brick casting machine rent. Also, can reach up to 750 EGP for 1000 bricks if transportation is needed. Yet, it is still more economical compared to fired bricks. The production cost for fired bricks can be reduced by substituting the use of fossil fuel in brick furnaces with renewable energy sources. Which consequently will also reduce the emission and negative environmental impacts.

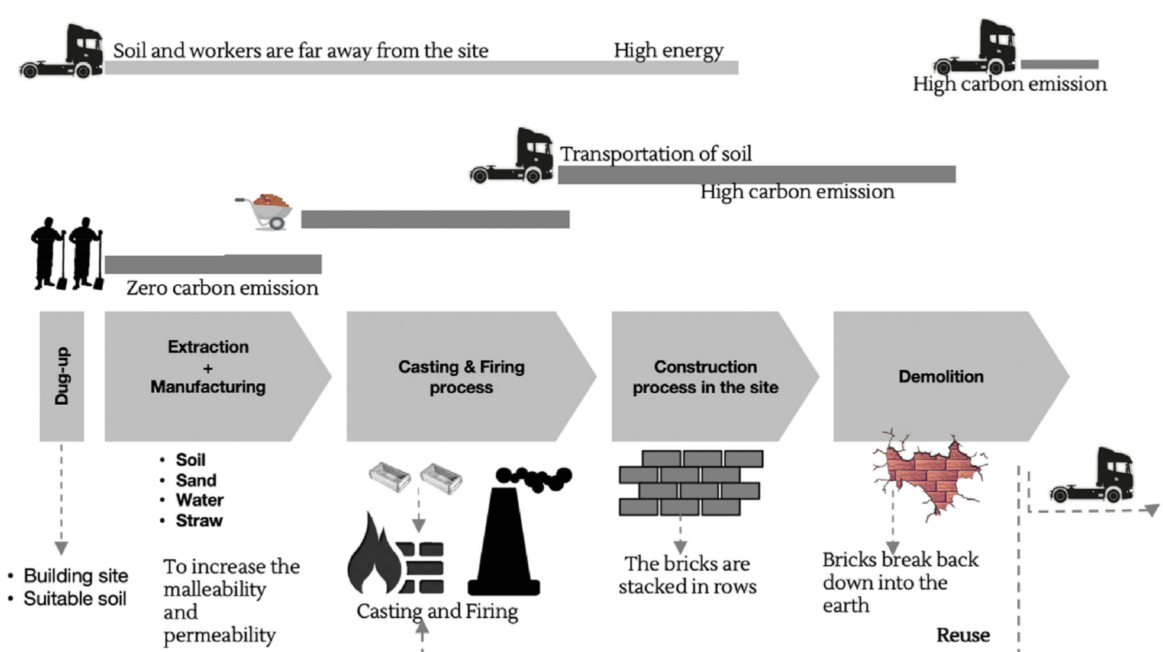

Fig. 11. The process of producing fired clay bricks.

Fig. 12. The brick factory was used as a case study during site investigation. It is representative of typical brick kilns in the Western Desert area.

3.2. Embodied energy and embodied carbon calculations outcomes

The results show that fired clay brick exerts a considerable amount of carbon and energy along its life cycle in comparison to the sun-dried option. If it is substituted with sun-dried clay bricks, there will be minimal environmental impacts from carbon emissions and energy burdens. Fig. 13 shows the embodied energy and carbon emissions for both types of brick. For every 1000 fired bricks produced, the embodied energy calculated for raw material extraction, processing, manufacturing, and delivery of material to the building site is 4250 MJ. The amount of carbon emissions calculated for raw material extraction, the manufacturing process, including firing processes in brick kilns, and the delivery of material to the building site is 5502 kg CO_2e. On the other hand, sun-dried bricks require only 0.033 MJ of embodied energy for raw material extraction, manual manufacturing (casting), and delivery of material to the building site. They emit 0.24 kgCO_2e, which is also calculated based on raw material extraction, manual manufacturing (casting) and delivery of material to the building site. There is minimal embodied energy or carbon emissions associated with disposal for sun-dried bricks. In the demolition phase, locals disassemble buildings constructed from sun-dried bricks using manual tools like axes. The bricks degrade back into nature as soil. However, in comparison, the calculated embodied energy for the demolition of fired bricks is 1025 MJ for every 1000 bricks and the amount of carbon emissions is 405 kg CO_2e/1000 bricks, which includes the energy required for machinery and for transportation to the nearest incineration dump site.

3.3. Comparative assessment between the sun-dried and the fired clay bricks

From the results discussed above, this study indicates a significant difference between both construction techniques, favouring the sun-dried clay brick construction technique. The outcome is consistent with earlier studies that present how material choice may affect both embodied energy and the carbon footprint of building materials (Cabeza et al., 2013; Thormark, 2006). Other studies have also shown the environmental, economic, and energy–efficiency benefits of developing the use of unfired clay bricks in comparison to fired conventional ones (Oti and Kinuthia, 2012).

As indicated in the calculations results, when sun-dried bricks were used instead of fired bricks, a reduction in CO_2 emissions up to 5907 kg CO_2e and 5305 MJ embodied energy for every1000 bricks produced was achieved. The difference relates mainly to the kiln used for fired bricks, and to a lesser extent to the fuel used for transport and machinery. This also means that an option of industrial production of sun-dried bricks could reach a significantly lower $LCCO_2$ level. It should also be noted that the production of fired bricks requires machinery and infrastructure not needed for local on-site sun-dried brick production. These components were left out from this study due to the complexity of connecting the emissions to the final products (as discussed by e.g. Säynäjoki et al., 2017). Nevertheless, their inclusion would lead to a further increase in the difference between the $LCCO_2$ performance of the two alternative materials.

In addition, some studies also stressed the importance of using locally available materials as a way of reducing environmental impacts and burdens from transportation (Morel et al., 2001). Sun-dried bricks can be promoted as an environmentally friendly building material if local consumers are aware of green issues. Using local labour in casting traditional bricks is even preferred over mechanical casting in much of Egypt, as it is cheap and easily produced in remote desert areas. However, the selection and implementation of building materials in a building project should not only have significant implications for long-term costs and performance but should also satisfy locals using the bricks. If the concepts of “product responsibility in the manufacturing ring” and “end-users” are applied, many of the negative impacts of the current cradle to cradle pathway of brick production will be reduced.

Clear and credible information on the environmental impacts of building materials using life cycle calculations can help consumers make more informed choices. It is recommended that other hybrid and indirect energy consumption calculations be considered as the current energy assessments of buildings often analyse only a small fraction of the total energy life cycle while the indirect energy consumption also needs to be considered (Crawford, 2008; Stephan et al., 2011). A complete life cycle energy analysis of buildings is needed, which unfortunately, is rarely undertaken in Egypt. As there is still a knowledge gap in Egypt about the embodied energy in the production and life cycle of building materials, the results that this paper presents will hopefully encourage the use of more durable and recycled materials while promoting low-carbon material production practices. If legislation is introduced across the Western Desert specifically, and in Egypt generally, it should put into effect environmentally friendly building practices. The achieved results can have a strong impact if they are integrated into building construction regulations and policy guidelines.

In Egypt, a detailed life cycle database and correlation with software like SimaPro and GaBi (for a complete LCA calculations) is crucially needed in order to quantify other environmental impacts according to other impact categories for each specific building material. Yet there is still a need for more LCA studies on vernacular and traditional materials (Fernandes et al., 2019). This is particularly important to help understand the environmental impact of materials, to implement improved options in the life cycle of products, and to help in the selection of more sustainable materials (Koroneos and Dompros, 2007; Fernandes et al., 2019). Moreover, additional LCA studies on building materials from Africa are particularly needed. According to Cabeza et al. (2013) and Säynäjoki et al. (2017), most of the LCA studies carried out are done in developed countries, with only a few in Asia and Oceania, and limited cases found from Africa.

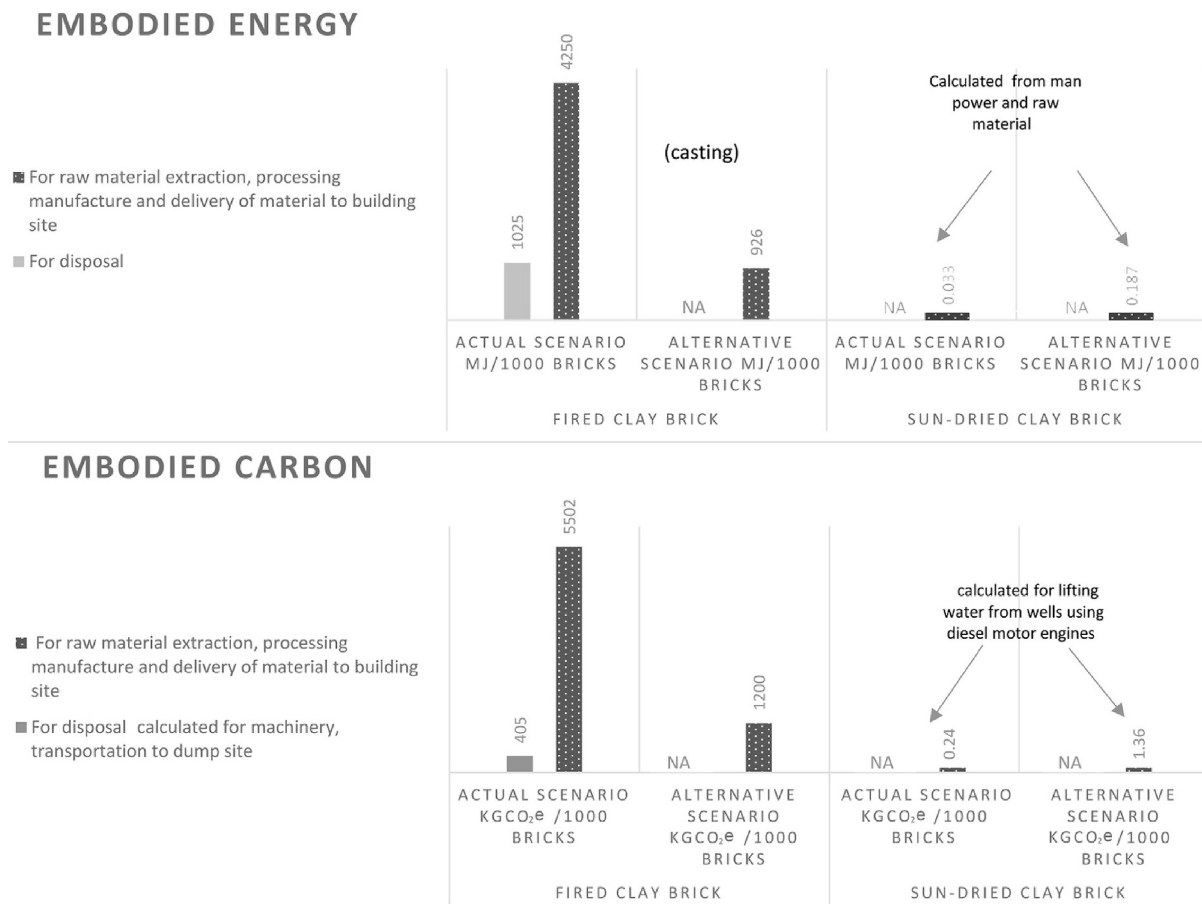

Fig. 13. Differences between sun-dried and fired clay brick in terms of energy burden and CO_2 emissions along the material life cycle.

4. Alternative scenarios and recommendations for improving brick production

Alternative scenarios for both types of bricks are played out. In the case of sun-dried clay brick, it is assumed that raw material might be needed from quarries if the soil recovered from the building site is not suitable for use. In such cases, there will be an increase in the embodied energy and carbon emissions by approximately 0.187 MJ/1000 bricks and 1.36 kgCO_2e/1000 bricks, respectively. Also, additional labour might be needed in order to cast the bricks when homeowners are not physically capable to do so themselves, which will also affect costs depending on the number of workers and days of work required. Even in these predicted scenarios, sun-dried bricks are still lower in impact and more economical in production.

Another possible scenario would be to assume that the bricks would be mechanically manufactured, but naturally dried in the sun, thus reducing their embodied carbon and energy to 926 MJ/1000 bricks and 1200 kg CO_2e/1000 bricks, respectively. In this anticipated scenario, selling clay brick that is not fired, would reduce both the embodied energy and carbon during the burning process and after end-of-life. Unfired bricks can be easily and organically decomposed if no industrial additives are added to the brick mixture.

Another scenario of mass production, which can vary from large-scale production using a bulldozer and grids of brick moulds, to small-scale production with an adze or hoe and a single brick mould or using the geo-polymerization technology for more eco-friendly bricks (Shakir and Mohammed, 2013), includes the use of a pugmill mixer which produces an average of 5000–7000 adobe/day. The second method is the use of a ready-mix truck (Smith, 1981).

Based on the alternative scenario results, it seems possible to replace the usage of fired bricks to a large extent, and extend the use of sun-dried bricks beyond small-scale construction in locations suitable for raw material extraction. This would lead to significant GHG reduction, even in the case of mechanical serial production of sun-dried bricks. Moreover, the drying process could even be supported with technical solutions without losing the key advantages of sun-dried bricks over fired bricks.

Based on the results and discussion provided, this study puts forth some recommendations for improving sun-dried clay brick production and for reducing the negative environmental impacts of fired bricks.

1 In order to increase the water-resistant capacities of sun-dried clay brick, lime is a useful additive in the clay mixture.
2 Local municipalities can offer mixers, manual casting, and hand machines (compressed earth blocks) for rent to local homeowners to help reduce the physical exertion needed in the clay mixing and casting process, which can be burdensome for many builders. Such services would encourage locals to produce better quality uniform bricks with better physical properties at a lower cost. This study has shown that machine casting is no more time-efficient than manual casting as productivity per person per hour is almost the same in both cases.

3 The use of solar PV systems as a renewable power source is encouraged when using electric mixers and brick compressors.
4 The purchase of unfired bricks from brick factories, as shown in Fig. 14 is highly encouraged. However, improving unfired bricks water resistance is recommended. Adding lime to the brick mix is one way to enhance waterproofing properties. These measures will reduce the cost, the amount of energy, and the amount of CO_2 emitted during the burning process and after the end of the brick's life. However, this recommendation will not reduce transportation costs and the carbon emitted from trucks during transportation between the factory and the building site. Transportation will still be an environmental burden but at least the embodied energy and carbon in the burning process, which is the biggest contributor of carbon released into the atmosphere in the brick lifecycle, will be reduced.
5 Using PV solar pumping systems instead of diesel-engine powered water pumps to lift fossil water from water wells will reduce both energy consumption and carbon emissions. Solar PV water pumping is becoming a common practice in the Western Desert for irrigation. The time it takes for such systems to pay off is relatively short and depends on the power production of the system.
6 Using alternative fuel as natural gas for brick kilns instead of diesel will significantly reduce the carbon emissions involved in the burning process.
7 Renewable energy or ecological sources of energy are recommended if firing is needed.
8 Reducing the consumption of natural resources such as clay, sand, and shale in the brick production, and increasing the use of building waste and fibre additives such as sawdust, ash, and sugarcane (which are valuable and more environmentally friendly), is recommended.
9 Clay deposits are being depleted in many countries worldwide. Accordingly, new pozzolanic materials are now being added to brick mixtures, such as waste glass and agriculture waste, which lower the melting temperature, decrease the temperature of firing, and are lighter in weight (Abbas et al., 2017). Consequently, that will decrease the clay content (amount) in the brick mixture and will reduce the brick weight in general.

5. Conclusion

The study showed a comparative $LCCO_2$ calculation for two substitutable building materials, sun-dried bricks and fired clay bricks as a means of evaluating the environmental impact of carbon emissions and the economics of production. This is a first attempt concerning remote rural areas of Egypt to evaluate bricks including the full life cycle and conducting eco-costing in relation to waste from brick production. A case study was presented to demonstrate the real outputs of the two options towards encouraging the use of low carbon building materials. The methodology used is an empirical comparative investigation of the environmental impact of each brick type throughout their respective life cycles.

The results showed that for every 1000 fired bricks produced, the calculated embodied energy is 4250 MJ and embodied carbon 5502 kg CO_2e for raw material extraction, processing, manufacturing and delivery of material to the building site. In comparison, for sun-dried bricks, only 0.033 MJ of embodied energy is needed and 0.24 $kgCO_2e$ are emitted. Therefore, if sun-dried bricks are used instead of fired bricks, a reduction in CO_2 emissions up to 5907 kg CO_2e and 5305 MJ embodied energy for every1000 bricks produced. Discussion on other alternative production options without kiln-firing were also discussed and shown to also lead to significant energy and GHG reductions − while providing opportunities for large-scale utilization of sun-dried bricks.

The significance of this research is that it shows the impacts of industrial building materials like fired bricks and emphasizes how choosing the proper building materials can minimize energy consumption, production costs, and environmentally deleterious effects, such as those caused by CO_2 emissions. Durable materials that use locally sourced raw materials and renewable energy sources for manufacturing can be easily recycled and reused after the end of their lives without producing waste, causing fewer negative impacts on the economy and the environment across their whole life cycle. In addition, the study revealed that phases of energy consumption during manufacturing are significant contributors to buildings' life cycle energy demands. Buildings' life cycle energy demands, and carbon emissions could be significantly reduced by reducing the energy required to manufacture building material.

Fig. 14. Fired clay bricks casted mechanically showing the two possible scenarios. The left image shows bricks before burning and the right image shows bricks after burning in brick kilns.

Using low-tech approaches and passive means in treating bricks and renewable resources for other mechanical purposes will also lead to a reduction in manufactured embodied energy.

The study is also a valuable contribution to the global community. A low $LCCO_2$ option of on-site production of sun-dried bricks is not only relevant in Egypt. Thus, the comparison of this study can be used as a benchmark elsewhere as well. In addition, as mentioned earlier, there are also industrialized production options available for sun-dried bricks in which a major part of $LCCO_2$ reduction, in comparison to fired bricks, could be retained while scaling up production.

At a more in-depth level, this research shows that the calculation of total energy use and carbon emissions during bricks' life cycles is necessary in order to develop strategies for reducing the energy use and environmental impact of building with bricks. Society's perception of using environmentally friendly building materials should not only look at the environmental burdens and drawbacks of using fired bricks but should also look at the building material's thermal performance and energy use across the whole building life cycle. Once that is done, it will become possible to choose materials based on their overall costs and benefits.

CRediT authorship contribution statement

Marwa Dabaieh: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Jukka Heinonen:** Validation, Formal analysis, Writing - review & editing. **Deena El-Mahdy:** Writing - review & editing, Visualization. **Dalya M. Hassan:** Writing - review & editing.

Declaration of competing interest

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

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