FRAMEWORK TO REDUCE EMBODIED ENERGY IN BUILDINGS: A LITERATURE REVIEW

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Abstract: As the building sector is a major contributor to global energy consumption and greenhouse gas emissions, there is a growing focus on achieving significant reductions in energy consumption and greenhouse gas emissions in the building sector. Energy consumption in buildings can be classified into embodied energy and operational energy. Studies have indicated that operational energy contributes to 80%–90% of the total life cycle energy in buildings while embodied energy only contributes to 10%–20%. Though several strategies have been implemented to reduce OE, there has not been enough attention on reducing embodied energy in buildings. Therefore, it is vital to conduct a study on reducing embodied energy in buildings. A comprehensive literature review was conducted by referring to books, reports, theses, journals, magazines, and conference proceedings to identify several practices for reducing embodied energy in buildings as well as barriers to moving towards low embodied energy in buildings. In conclusion, the study showed that reducing embodied energy in buildings is an essential step towards achieving significant reductions in energy consumption and greenhouse gas emissions in the building sector, and a concerted effort is needed to overcome the identified barriers and implement the identified practices.

Keywords: *Embodied Energy, Buildings, Practices, Barriers*

1. Introduction

Despite adding value to society, the construction industry has significant negative effects on the environment (Cabeza *et al.*, 2014). It contributes a larger share of global carbon dioxide emissions and consumes substantial amounts of natural and energy resources (AlSanad, 2015). The building sector is one of the major consumers of energy in many nations (Devi and Palaniappan, 2014). About 40% of the energy supply in the world is used for the construction, operation, and maintenance of buildings (Kolokotsa *et al.*, 2011). Therefore, the effective management and minimization of the energy usage of buildings is a global focus (Li *et al.*, 2022). According to Mariano-Hernández et al. (2021), energy effacement strategies are necessary to address the increasing energy demand in buildings. Analyzing the overall energy consumption of buildings throughout their life cycle is desirable to identify stages with high energy consumption and develop ways to reduce them (Ramesh, Prakash and Shukla, 2010).

The concept of 'Life Cycle Energy' (LCE) encompasses all energy requirements associated with a building throughout its life cycle, from the first stage of production to demolition (Karimpour *et al.*, 2014). The total LCE of a building is constituted of Embodied Energy (EE) and Operational Energy (OE) (Ramesh, Prakash and Shukla, 2010; Dixit *et al.*, 2012). EE in buildings refers to the amount of energy needed for processes related to building completion (Dissanayake, Jayasinghe and Jayasinghe, 2017), including raw material extraction, production, transportation, construction, and end-of-life procedures (Cabeza *et al.*, 2014). On the other hand, OE refers to the energy used to operate different building appliances such as lighting, space conditioning and ventilation, heating, and cooling (Dixit, 2017).

Ramesh et al. (2010) identified that, while OE contributes 80%–90% of the LCE in buildings and EE contributes only 10%–20% of the LCE in buildings. As OE owns a larger share of the total usage of LCE in buildings (Dixit *et al.*, 2010), many research studies have focused on reducing OE during the past decades (Marzouk and Elshaboury, 2022). However, with the adoption of energy-efficient equipment and appliances, and modern effective insulation materials, the demand for OE has decreased relatively (Sartori and Hestnes, 2007). With a significant reduction in OE, EE has become a significant factor in minimizing LCE (Gustavsson and Joelsson, 2010). Further, as stated by Zeng and Chini (2017), over the next 50 years, the effect of EE is expected to increase even more.

Although EE accounts for a smaller share of total LCE than OE, the possibility of reducing EE should not be

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neglected (Kua & Wong, 2012). Therefore, it is crucial to address EE in order to achieve significant future reductions in energy consumption within the building sector (Skillington *et al.*, 2022). Further, according to the World Green Building Council (2019), the attention of the entire world is now being shifted toward the quantification and reduction of the EE impacts of the building sector.

When focusing on the Sri Lankan context, as reported by the Sri Lanka Sustainable Energy Authority (2017), rapid expansion in the Sri Lankan building sector is responsible for about 35% of national energy consumption while resulting in significant carbon emissions. Sri Lanka has already identified the need to focus on the building sector in identifying energy reduction strategies (Kumanayake, Luo and Paulusz, 2018). Further, Fernando and Jayasena (2008) emphasized that even though measures for OE reduction are practiced to a certain extent in the Sri Lankan context, EE has received almost no consideration in terms of building design. This emphasizes the need for increasing the focus on reducing EE in the local context. Considering the lack of comprehensive studies on proposing suitable strategies to reduce EE in buildings in Sri Lanka, the aim of this study is to reduce embodied energy in buildings. To achieve the aim of this study, three (03) objectives have been set up: identify practices for reducing embodied energy in buildings, identify barriers towards the reduction of embodied energy, propose suitable measures to overcome those barriers in buildings, and develop a conceptual framework to reduce embodied energy.

2. Research Methodology

A comprehensive literature detailing the history of the subject and important sources of the literature showing the main issues and improving the meaning of the study (Saunders, 2014). Further elaborating, Mahajan (2018) stated that a comprehensive literature synthesis helps to establish the theoretical roots of the study. Therefore, this paper is based on the findings of a literature analysis conducted to gain a comprehensive understanding of the field of EE.

Accordingly, the literature was critically evaluated to synthesize the findings. A comprehensive literature review was conducted by referring to books, reports, theses, journals, magazines, and conference proceedings to identify the concept of EE, practices to reduce EE, and barriers that occurred when implementing those practices. By using the available search engines of 'Scopus', 'Google Scholar', 'Emerald', and 'Science Direct', the keywords such as 'Embodied Energy', and 'Practices and Barriers to reducing Embodied Energy' were filtered to gather a comprehensive literature synthesis. Finally, based on the findings from the literature, a conceptual framework was developed to facilitate the empirical investigation in the next step.

3. Results & Findings

3.1. LIFE CYCLE STAGES OF BUILDINGS

Different perceptions regarding the building life cycle stages can be identified. According to Pomponi and Moncaster (2016), the building life cycle has been categorized into four (04) stages product stage, construction stage, operational stage, and end life stage, while Ramesh et al. (2010) have categorized it differently as the manufacturing phase, use phase and demolition phase. Further Watson (2003) has identified six (06) stages of the life cycle of buildings as initiation, production, construction, operation, maintenance, and demolition/disposal. However, it is identifiable that most research studies relating to LCE have used BS EN 15978:2011 standards to categorize the stages of the life cycle of buildings (Giesekam et al., 2016). According to BS EN 15978:2011 standards, the building life cycle has been categorized into four (04) main stages including the product stage, use stage, operational stage, and end life stage (Achenbach et al., 2018). An additional stage is identified as 'beyond the system boundary' which includes sub-stages of reuse, recovery, and recycling. Figure 1. shows the building life cycle stages as per BS EN 15978:2011 including main stages and sub-stages.

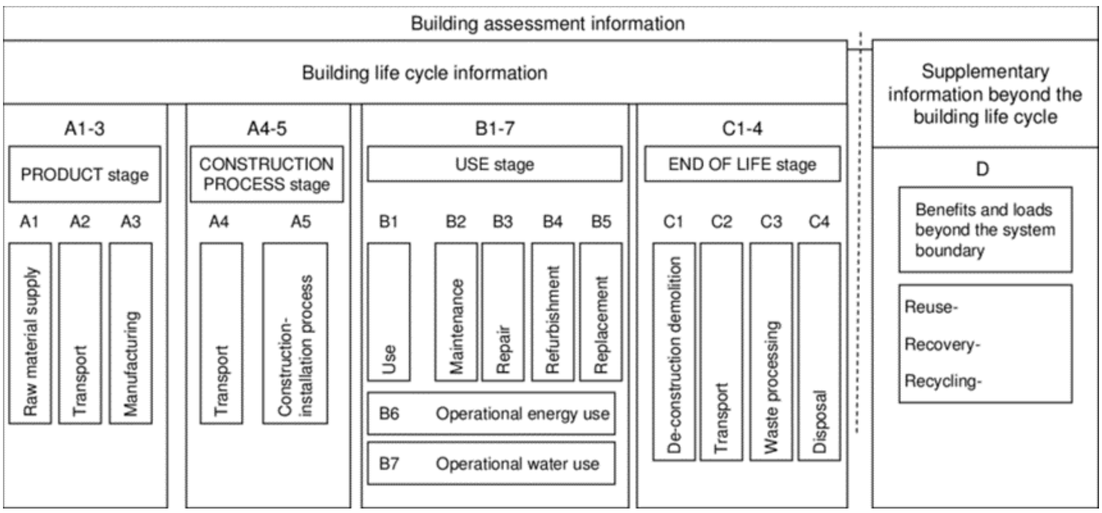

Figure 1, Building life cycle stages as per BS EN 15978:2011 *Source: (Achenbach et al., 2018)*

Though there is a widely accepted standardized categorization for building life cycle stages, it is challenging to identify research studies relating to LCE analysis that have focused on all of the specified life cycle stages because the majority of research studies have only concentrated on a selected few stage (Oregi et al., 2015).

3.2. THE CONCEPT OF EMBODIED ENERGY

According to Chang et al. (2012), still there is no standardized definition for the term EE. As identified through literature, different researchers have given different interpretations and definitions for EE. Table 1 contains various definitions for EE.

Table 1, Definitions for Embodied Energy

Definition	Source of Reference
"The total energy required in the creation of a building, including the direct energy use in the construction and assembly process, and the indirect energy, that is required to manufacture the materials and components of the buildings"	(Crowther, 1999)
"Energy required to provide a product through all processes upstream in both direct and indirect ways"	(Treloar et al., 2001)
"Energy to extract, transport and refine the raw materials and then to manufacture components and assemble the product"	(Fay, Treloar and Iyer-Raniga, 2012)
"Energy used to extract and refine raw materials, manufacture materials assemble components, conduct on-site construction, complete end-of-life processes, and carry out any transportation required between any of these steps"	(Karimpour *et al.*, 2014)
"The total primary energy that has to be sequestered from stock within the earth to produce a specific good or service"	(BRE, 2015)
"The total amount of non-renewable primary energy required for all direct and indirect processes related to the creation of the building, its maintenance, and end-of-life"	(IEA, 2016)
"Energy utilized in manufacture and transport of materials, construction, repair and maintenance demolition and end-of-life management of demolished materials"	(Chastas, Theodosiou and Bikas, 2016)

It depicts that there are significant differences in how different studies interpret the definitions of EE, mainly based on the different life cycle stages that they considered. Recent definitions given by Chastas et al. (2016), IEA (2016), and Karimpour et al. (2014)) provide a comprehensive overview of EE by considering the whole building life cycle during all processes of production, on-site construction, and final demolition and disposal.

3.3. SIGNIFICANCE OF EMBODIED ENERGY

According to Ramesh et al. (2010), OE accounts for 80% to 90% of the total LCE of a building. This indicates that OE consumes a significant portion of LCE throughout the long lifespan of buildings (Li *et al.*, 2020). However, the EE component of LCE has often been overlooked, with most focus given to reducing OE due to its larger proportion (Chang, Rias and Lei, 2012; Azari and Abbasabadi, 2018).

Efforts to minimize OE have involved the implementation of policy-driven initiatives in various countries to promote the construction of energy-efficient buildings (Omrany *et al.*, 2020). Additionally, advancements in construction materials, technologies, and practices have led to the emergence of zero-energy buildings, as highlighted by Zeng and Chini (2017). The enhancement of building energy efficiency has been achieved through effective OE practices, such as optimizing building design and utilizing energy-efficient appliances and technologies (Praseeda, Reddy and Mani, 2015; Marzouk and Elshaboury, 2022).

While OE dominates in countries with adverse weather conditions (Mandley, Harmsen and Worrell, 2015), buildings in tropical climates often have low OE due to their ability to operate without excessive energy requirements (Hashemi, Cruickshank and Cheshmehzangi, 2015). In such cases, EE can become more prominent, as noted by Praseeda et al. (2014). Although OE typically outweighs EE in buildings under normal circumstances, the proportion of EE in the total LCE can range up to 60% depending on the composition of the building (Leoto and Lizarralde, 2019). According to Li et al. (2021), the share of the EE in the LCE of a residential building has increased significantly from 9%–35% to 66%–71% in new residential buildings constructed after 2011. Further, EE accounts for 4%–52% of the LCE in conventional buildings, 9%–50% in retrofit buildings, 19%–60% in low-energy use buildings, and 18%–77% in passive buildings (Dilsiz *et al.*, 2019). Zeng and Chini (2017)predict that the influence of EE will continue to grow over the next 50 years.

Omrany et al. (2020) argue that EE be given priority as, unlike OE, EE cannot be reversed once implemented. Therefore, additional consideration is needed for EE in buildings (Anderson et al., 2022). There is a significant demand to optimize the building performance in terms of EE to reduce energy consumption (Utama and Gheewala, 2009). Therefore, in recent years, there has been an increase in research investigating EE using approaches with numerous detailed case studies of individual buildings developed by researchers (Omrany et al., 2020).

3.4. PRACTICES TO REDUCE THE IMPACT OF EMBODIED ENERGY

According to Treloar and Faniran (2001), the field of EE attracts global attention due to its focus on key aspects of green building design and energy management in construction. This knowledge of EE can inspire the development of products with low embodied energy content, by reducing quantities of serves as inspiration for developing products with lower embodied energy, reducing energy consumption and greenhouse gas emissions during the operational phase (Ding, 2004). By considering that designers, builders, and building materials manufacturers strive to optimize production techniques to minimize energy usage by fully determining the type and level of EE intensity (Azari and Abbasabadi, 2018).

In recent years, research has increasingly concentrated on reducing the environmental impact of building materials throughout their lifecycle, with a specific emphasis on EE. This includes studies conducted by Huberman and Pearlmutter (2008), Venkatarama Reddy (2009), and Ng and Chau (2015). As part of Annex57 (Evaluation of Embodied Energy and CO2eq for Building Construction), a range of case studies has been conducted with the aim of identifying practices to reduce the EE and GHG of buildings (IEA, 2016). The practices have been classified into four categories: substitution of material, reduction of resource use, reduction of construction stage impacts, and designing for the end-of-life stage. The practices identified through literature for reducing the impact of EE are summarized in Table 2.

Table 2, Practices to Reduce the Impact of Embodied Energy

No.	Practices	References
	Substitution of materials	
1	Use natural materials	[01]
2	Use recycled and reused materials and components	[01],[02],[03],[04],[05],[06],[07],[08]
3	Use innovative materials	[01],[04],[07]
4	Use bio-based materials derived from sustainably managed sources	[04]
5	Use alternative materials	[07]
6	Use renewable materials	[06],[08]
	Reduction of resource use	
7	Reuse of building structures	[01],[03],[04],[07]
8	Use Light-weight constructions	[01],[04]
9	Design for low maintenance	[01],[04]
10	Design for service life extension in mind	[01],[04]
11	Optimization of the building form and design of the layout plan	[01],[04]
12	Design for flexibility and adaptability	[01],[04]
	Reduction of construction impacts	
13	Use locally available materials	[02],[04],[06]
14	Avoid the complexity of the manufacturing process	[02]
15	Minimize the quantity of materials used for the construction process	[05],[06]
	Design for end-of-life stage	
16	Design for disassembly	[01],[04]
17	Design for recyclability	[01],[04]
Source: [01]-(International Energy Agency, 2016), [02]-(Chastas *et al.*, 2017), [03]-(Milne and Reardon, 2008), [04]-(Lupíšek *et al.*, 2017), [05]-(Zhao and Haojia, 2015), [06]-(Sattary and Thorpe, 2012), [07]-(Kumanayake and Luo, 2018), [08]- (Venkatarama Reddy, 2009)		

According to Table 2, substitution of material, reduction of resource use, reduction of construction stage impacts, and designing for the end-of-life stage were identified as practices to reduce the impact of EE in buildings. Under the category of 'substitution of materials', practices of the use of natural materials, use recycled and reused materials and components, use of innovative materials, use of bio-based materials derived from sustainably managed sources, and use of renewable materials were identified as alternatives to conventional construction materials. Then the 'reduction of resource use' category was focused on minimizing resource consumption and optimizing the design process. Practices include reusing building structures, using lightweight constructions, designing for low maintenance, designing for service life extension in mind, optimizing building form and design of layout plan, and designing for flexibility and adaptability. Then the 'reduction of construction impacts' category highlights practices that aim to minimize the environmental footprint during the construction phase. These include using locally available materials, avoiding complex manufacturing processes, and minimizing the quantity of materials used for the construction process. Lastly, the 'design for end-of-life stage' category is focused on designing buildings with consideration for their eventual disassembly and recyclability. Practices involve designing for disassembly and ensuring the recyclability of building components. The references support the importance of incorporating these principles into the design process.

3.5. BARRIERS TO THE REDUCTION OF EMBODIED ENERGY

While Zhang and Wang (2013) identified legal barriers, administrative barriers, market barriers, financing barriers, social barriers, and other barriers, Addy et al. (2014) identified social and behavioural barriers, knowledge barriers, policy barriers, market and production barriers and financial barriers as barriers of building energy efficiency. By considering that, Table 3 summarizes barriers that occurred towards the reduction of EE in buildings.

Table 3, Barriers Towards the Reduction of Embodied Energy

No	Barriers	References
	Legal Barriers	
1	Lack of regulations and standard guidelines	[01],[02],[04],[05],[09]
2	Lack of government regulatory body	[03],[05]
3	Lack of subsidies	[05]
4	Political processes and priorities of government	[03]
	Knowledge Barriers	
5	Lack of Experts	[05]
6	Lack of client's knowledge about the benefits	[05],[08]
7	Lack of a complete and standard Database on EE	[01],[02],[04],[10]
8	Information scarcity on EE intensities	[02]
	Financial Barriers	
9	Lack of access to financing sources	[03],[05],[06],[08]
10	High cost of alternative technologies	[05],[07]
11	Lack of access to information on funds	[03]
	Market Barriers	
12	Lack of energy-saving technical evaluation system	[03]
13	Lack of market of energy service systems	[03],[05]
14	Lack of investors in energy-efficient products	[03],[05]
15	Lack of appropriate production technologies	[05]
16	Lack of market transparency	[07]
	Social Barriers	
17	Lack of public awareness	[03],[05]
18	Lifestyle, culture, and behavior of clients	[03],[05]
19	Less priority is given to energy efficiency in buildings	[05]
20	Not having interested in future costs	[05]

Source: [01]-(Marzouk and Elshaboury, 2022), [02]-(Wu *et al.*, 2015), [03]-(Zhang and Wang, 2013), [04]-(Omrany *et al.*, 2020), [05]-(Addy, Adinyira and Koranteng, 2014), [06]-(Painuly *et al.*, 2003), [07]-(Qian, Wu and Chan, 2006), [08]-(Yik and Lee, 2002), [09]-(Dixit, 2019), [10]- (Ding, 2004)

3.6. MEASURES TO OVERCOME THE BARRIERS TO THE REDUCTION OF EMBODIED ENERGY

As depicted in Table 3, the lack of a standard method, incomplete system boundaries, and lack of a standard database are highlighted by many researchers as barriers to analyzing EE which could directly affect for reduction of EE. Overcoming these barriers would involve developing a protocol, standard or correct method for EE calculations, and establishing a robust database (Pullen *et al.*, 2006; Crawford, 2008; Langston and Langston, 2008; Ramesh, Prakash and Shukla, 2010; Dixit *et al.*, 2012).

As there is currently no standardized methodology for accurately and comprehensively determining EE in buildings (Ding, 2004; Stephan, Crawford and Myttenaere, 2012), it is crucial to develop a standardized approach to measuring EE (Ting, 2006). Further, Dixit et al. (2010) emphasized the importance of standardizing the EE measurement process in buildings.

The lack of complete system boundaries is also identified as a barrier, emphasizing the need to standardize the definition of system boundaries for EE calculations (Marzouk and Elshaboury, 2022). Furthermore, the development of building energy standards, policies, and regulatory frameworks is seen as a significant step toward the advancement of energy-efficient measures in many developed countries (Bodach, Lang and Auer, 2016).

Another barrier identified in the literature is the lack of available and reliable data sources, leading research studies to use databases from other countries to calculate EE (Omrany *et al.*, 2020). For instance, Stephan and Stephan (2014) used an Australian database to calculate the EE of a residential building in Lebanon, while Devi and Palaniappan (2014) used a European database to calculate the EE of a residential building in India. Therefore, the data source is an important parameter, its reliability, certainty, and transparency must be considered when calculating EE (Lenzen, 2000).

3.7. CONCEPTUAL FRAMEWORK TO LOWER EMBODIED ENERGY IN BUILDINGS

Through the literature survey, it became apparent that there is a pressing need to minimize EE consumption in buildings to create designs that prioritize energy efficiency. To lower EE buildings, it is crucial to establish a comprehensive framework that outlines practices to reduce EE in buildings, barriers towards, and measures to overcome those barriers. Figure 2 illustrates the conceptual framework developed to lower EE in buildings.

A pivotal component of this research involved the identification of specific practices to reduce EE in buildings. Therefore, through the review of the literature, four (04) distinct categories of practices were identified. These practices, which focus on mitigating the impact of EE, were subsequently integrated into the conceptual framework under the designation of 'practices to reduce the impact of embodied energy' in the conceptual framework. In addition to identifying effective practices, this study also revealed six (06) categories of barriers to the reduction of EE in buildings. These barriers were thoughtfully incorporated into the conceptual framework as 'barriers towards the reduction of embodied energy'. By acknowledging and addressing these obstacles, the framework aims to provide comprehensive guidance for lowering EE buildings. Lastly, the research identified specific measures that can be employed to overcome the identified barriers. These measures, which have been recognized as effective solutions, were encompassed within the conceptual framework as 'measures to overcome barriers'. By incorporating these measures, the framework seeks to facilitate the successful implementation of EE reduction strategies in building design.

Overall, this study presents a comprehensive conceptual framework that not only identifies practices to reduce EE in buildings but also addresses the barriers associated with such reductions. By incorporating measures to overcome these barriers, the framework offers valuable insights and guidance to promote the design for lowering EE in buildings.

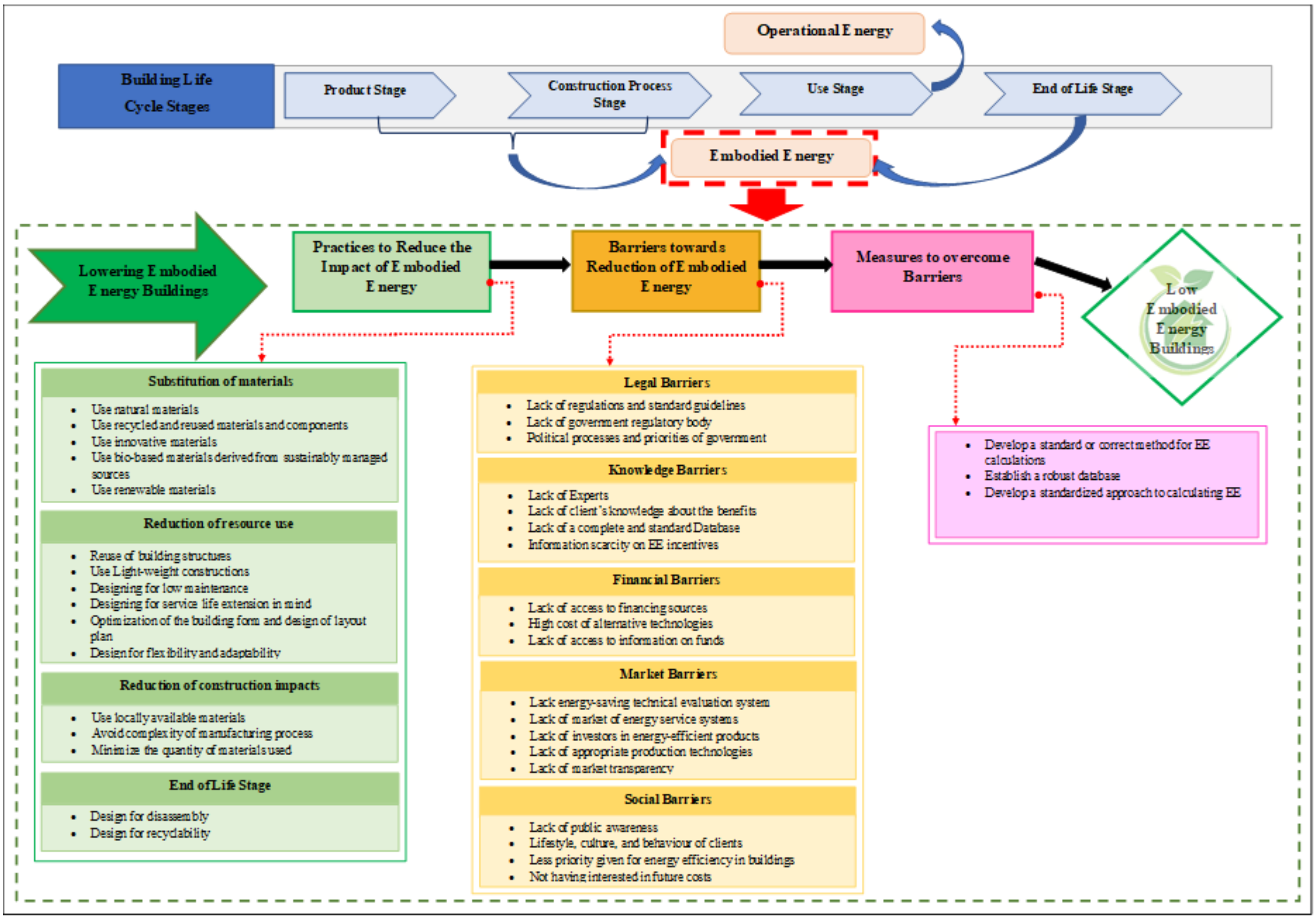

Figure 2, Framework to Lowering Embodied Energy in Buildings

4. Conclusion

Accordingly, the literature analysis first discusses the practices to reduce EE in buildings. Then, the discussion points out the barriers to the reduction of EE in buildings and a few strategies to overcome those barriers. Finally, a framework was developed based on literature findings as a preliminary framework to design low EE buildings.

This research study basically contributes to the knowledge in terms of the reduction of EE in buildings. Further, the following key contributions to knowledge are made through this research study.

- A detailed literature review on the concepts of EE was presented by referring to previous research studies in a particular area.
- Since there was no detailed discussion on practices to reduce EE in buildings, barriers towards reduction of EE, and suitable measures to overcome those barriers, the findings of this study contribute to knowledge in that area.
- Since there was no framework developed based on the reduction of EE in buildings, this study contributes to that area of knowledge.

The outcome of the research would be beneficial for industry practitioners to design energy-efficient buildings by reducing EE at the design stage. Considering that important outcome, the following recommendations can be made.

- As was highlighted, prior concern should be given to the reduction of EE, as same as the reduction of OE, industry practitioners are encouraged to give more prominence to reduce the EE in the building design stage. Further, they are required to convince clients about the importance of moving towards the low EE buildings.

- Industry practitioners are encouraged to follow the framework developed as guidance for lowering EE buildings since it identifies the key aspects of lowering EE buildings.
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This research provides a preliminary analysis of literature focusing on practices to reduce EE in buildings globally. The next step in this research would be to conduct a detailed survey to determine the practices to reduce EE in buildings in Sri Lanka.

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