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Evaluating the impact of material service life on embodied energy of residential villas in the United Arab Emirates

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Abdul Rauf and Daniel Efurosibina Attoye
Department of Architectural Engineering, United Arab Emirates University, Al Ain, United Arab Emirates, and
Robert H. Crawford
Faculty of Architecture, Building and Planning, The University of Melbourne, Parkville, Australia

Abstract

Purpose – Recently, there has been a shift toward the embodied energy assessment of buildings. However, the impact of material service life on the life-cycle embodied energy has received little attention. We aimed to address this knowledge gap, particularly in the context of the UAE and investigated the embodied energy associated with the use of concrete and other materials commonly used in residential buildings in the hot desert climate of the UAE.

Design/methodology/approach – Using input–output based hybrid analysis, we quantified the life-cycle embodied energy of a villa in the UAE with over 50 years of building life using the average, minimum, and maximum material service life values. Mathematical calculations were performed using MS Excel, and a detailed bill of quantities with >170 building materials and components of the villa were used for investigation.

Findings – For the base case, the initial embodied energy was 57% (7390.5 GJ), whereas the recurrent embodied energy was 43% (5,690 GJ) of the life-cycle embodied energy based on average material service life values. The proportion of the recurrent embodied energy with minimum material service life values was increased to 68% of the life-cycle embodied energy, while it dropped to 15% with maximum material service life values.

Originality/value – The findings provide new data to guide building construction in the UAE and show that recurrent embodied energy contributes significantly to life-cycle energy demand. Further, the study of material service life variations provides deeper insights into future building material specifications and management considerations for building maintenance.

Keywords Embodied energy, Recurrent embodied energy, Material service life, Building service life, United Arab Emirates (UAE), Life-cycle assessment

Paper type Research paper

1. Introduction

The environmental impacts of building materials are significant; the entire life cycle of a building is directly or indirectly affected by the building materials used (Arrigoni *et al.*, 2017; Huang *et al.*, 2020; Rauf, 2016). These impacts occur locally and globally, ranging from those

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caused by quarrying to those caused by carbon dioxide during manufacturing, and directly and indirectly affect the health of building occupants (Harris, 1999; Sahlol *et al.*, 2021; Sözer and Sözen, 2020). In general, the impact of buildings on the environment depends on their design, construction, use, and location (Bredenoord, 2017; Harris, 1999). Ede *et al.* (2017) argued that traditionally, little attention has been paid to the environmental impact of building materials. However, more emphasis has recently been placed on reducing negative impacts and ensuring waste recovery (Amaral *et al.*, 2020; Walach, 2021), while prioritising the choice of high-performing construction materials (Habert *et al.*, 2012; Walach, 2021).

Although many principles and strategies exist to reduce these negative impacts and achieve design sustainability, some are generally agreed upon. Energy use reduction, minimal material/resource use, and maximum effort towards recyclability are crucial for ensuring sustainable design (Bogdanov *et al.*, 2021; Fernando *et al.*, 2021; Mankoff *et al.*, 2007; Thormark, 2007). Significant research efforts have been made to reduce the operational energy of buildings (Gao *et al.*, 2020; Shoubi *et al.*, 2015); researchers have identified factors which affect operational energy, such as building location, size, conservation policy, occupant behaviour, and room occupancy distribution patterns (Abuimara *et al.*, 2021; Akande, 2015; Macknick *et al.*, 2012; Rickwood, 2009).

However, studies have shown that operational energy as well as embodied energy must be reduced to minimise the energy footprint and associated environmental impacts of buildings (Giordano *et al.*, 2015; Mourao *et al.*, 2019; Shadram and Mukkavaara, 2018). Although existing literature confirms the significance of both energy aspects, knowledge and understanding of the total energy embodied in the replacement of materials over a building's life are limited (Janjua, 2021; Rauf, 2016). For example, although thermal insulation and additional materials are often used to reduce energy consumption by reducing operational energy, Abbasi and Noorzai (2021) reported that this is only effective at a certain point. Their study sought to find a trade-off between embodied and operational energy, and argued that when embodied energy impacts are considered, the total life-cycle energy actually increases, further complicating the situation further (Abbasi and Noorzai, 2021).

Embodied energy considerations in the construction industry are multidimensional. Buildings consume large quantities of materials and energy during their lifespan (Crawford *et al.*, 2010; Fay *et al.*, 2000; Rauf, 2016), leading to high environmental impacts (Brophy and Lewis, 2012; Kim, 1998). Conversely, this implies that understanding and reducing the use of energy-intensive materials can help reduce energy demand and assuage-associated environmental effects such as greenhouse gas emissions (Cabeza *et al.*, 2013; Rauf, 2016). Sufficient knowledge of the embodied energy composition of specified building materials may inform the reselection or preference of low-embodied energy materials among professionals in the industry (Ding, 2004). There is comparatively less research which focuses on embodied energy in contrast to operational energy studies; thus, researchers have called for a comprehensive focus on life-cycle energy investigation (Dixit, 2017), and recognition of embodied energy research as a key component of sustainable global energy transition (Cottafava and Ritzen, 2021).

In a recent review of studies which focused on embodied energy, Cabeza *et al.* (2021) reported that only 70 of 1,003 related studies presented the embodied energy or carbon values of the materials. The review also asserts that the majority of the studies focus either only on a "cradle to gate" (i.e. initial embodied energy) in their calculations, or do not specify this crucial parameter (Cabeza *et al.*, 2021). Few researchers have focused on the recurrent embodied energy associated with building maintenance, a critical and necessary activity once a building is occupied until it is demolished (Crawford *et al.*, 2010; Fay *et al.*, 2000; Rauf, 2016). Some studies suggest that over a building's lifespan, maintenance activities, either repairs in the building which are carried out on materials or components, are determined by the service life of the materials (Janjua, 2021; Rauf, 2016). However, there is little case-based evidence in the literature and significantly less in the UAE context to clarify the importance of material service life linked with recurrent embodied energy, as it relates to the life-cycle energy demand of a building.

1.1 The case of the United Arab Emirates

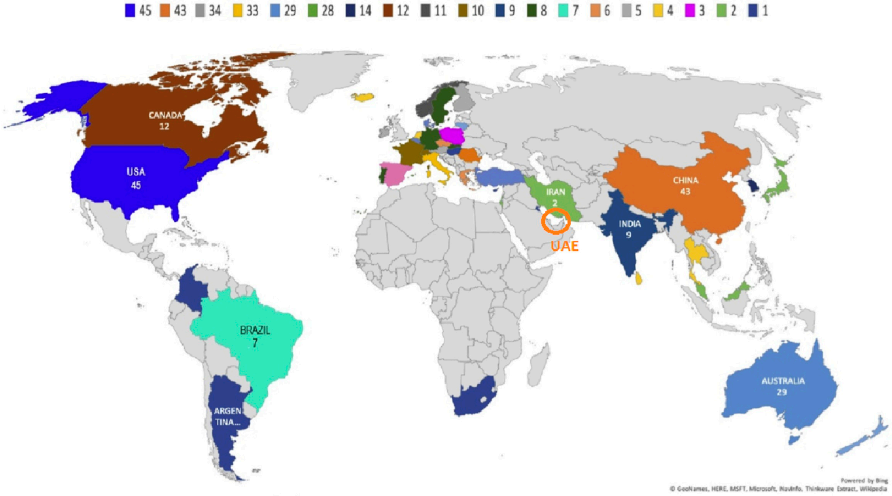
The rapid urbanisation of the United Arab Emirates over the last 50 years has had a significant effect on various aspects of the country. From major cities such as Abu Dhabi and Dubai to others such as Al Ain and Sharjah, the country has witnessed urban development at an unprecedented scale which has impacted its microclimate (Bande *et al.*, 2020), urban heat island (Mohammed *et al.*, 2020), water resources (Shanableh *et al.*, 2018), and social costs related to desalination, carbon, and power (Saleh *et al.*, 2019). This is particularly noteworthy, as approximately nine out of ten people in the UAE live in urban areas (Statista, 2021). The UAE's total CO_2 emissions doubled between 1994 and 2005, increasing from 74,436 $kTCO_2$ eq. to 161,134 $kTCO_2$ eq (MOEW, 2015). The UAE Government has set many ambitious targets to reduce energy consumption and related emissions to help achieve the Sustainable Development Goals (SDGs) in line with the United Nations 2030 agenda (FCSA, 2020).

To reduce these environmental impacts and change the status quo, it is crucial to reduce the energy consumption of buildings. Some studies report that the average operational energy may be as high as 273.36 $kWh/m^2/yr$ for a villa (Abu-Hijleh and Jaheen, 2019; AlQubaisi and Al-Alili, 2018; Bande *et al.*, 2020; Giusti and Almoosawi, 2017). It is important to note that in 2020, residential buildings in the UAE were the second highest consumers of energy (32.8%), next only to commercial buildings (39.8%), and significantly higher than industrial buildings (16.5%) (FCSA, 2020). Buildings in the UAE consume more than 70% of the total energy generated compared with the global average of 40%, with energy for cooling and heating in the harsh desert climate being as high as 70% in some cases (Lin *et al.*, 2018; UAE Government, 2019). However, beyond the discourse on operational energy, there have been few studies on the embodied energy of residential buildings in the UAE. To reduce energy consumption and its related impacts, it is necessary to reduce both operational and embodied energy consumption.

The results of embodied energy assessments in the literature cannot be generalised simply because of the varying influences of multiple factors, such as location, climate, and fuel source (Dixit, 2017). This implies that there is a need for localised knowledge regarding the life-cycle embodied energy of buildings. In a bibliometric study on the extent of research on embodied energy and environmental impacts in different parts of the world, Hu and Milner (2020) showed that the United States, China, and the United Kingdom dominated research publications between 1996 and 2019 (Hu and Milner, 2020). As shown in Figure 1, UAE is among those regions that lack recorded investigations on this topic. Therefore, there is a need to take a targeted look at the UAE construction sector and explore how energy is consumed, both directly and indirectly, in building construction processes. Furthermore, it is vital to study building maintenance activities with respect to the replacement and repair of materials, assemblies, and components during building use or occupancy. These needs are critical in this region because they are essential for achieving the goal of environmental sustainability. Furthermore, current trends seem to favour the design and construction of high-performing buildings with lower operational energy, with little concern for the embodied energy impacts in the UAE.

1.2 Aim of the study

The localised life-cycle embodied energy data and knowledge in the UAE may help ensure that across their life cycles, UAE buildings do not consume as much energy as they are reported to (Lin *et al.*, 2018; UAE Government, 2019). In addition, a lack of knowledge



Source(s): Hu and Milner (2020)

Figure 1. The number of publications on embodied energy research between 1996 and 2019, distributed by country and region -based on the publications found in WoS

regarding the relationship between the material service life and life-cycle embodied energy demand of buildings has been identified. Therefore, the objective of this study was to provide case-based evidence and quantify the life-cycle embodied energy associated with a representative residential villa in the UAE. Furthermore, this study defines the effect of the service life of building materials specified by designers on the associated life-cycle energy demand of residential buildings in the UAE context.

2. Building materials and energy

2.1 Life-cycle analysis

Energy consumption in buildings can be quantified by carrying out a life-cycle energy analysis (LCEA) to provide a holistic life-cycle understanding. Examples of this type of assessment in residential, commercial, and institutional buildings have been conducted to compute life-cycle energy demands (Azzouz *et al.*, 2017; Lolli *et al.*, 2017; Rauf, 2016). LCEA is closely related but different from standard life-cycle assessment (LCA); it is a streamlined variation which focuses only on aspects related to energy during the building lifespan (Omrany *et al.*, 2020). The LCEA is a construct which sums a building's embodied energy and its operational energy. It is important to state that this assessment can be heavily influenced by the completeness and reliability of available data and analysis method (Omrany *et al.*, 2020). Building information modelling (BIM) accelerates the data inventory and digitalisation of construction processes, thereby improving decision-making for built asset design, construction, and management (Eastman *et al.*, 2008; Shafiq and Afzal, 2020). More recently, BIM has also been used in life-cycle energy assessment studies (Antwi-Afari *et al.*, 2023; Apostolopoulos *et al.*, 2023; Rad *et al.*, 2021) to integrate an evaluation of both embodied and operational energies (Allacker, 2010) along with the environmental aspects of building impact (Muazu *et al.*, 2021).

Nevertheless, evaluation methods for operational energy are well established in research and practice, and less attention and effort have been given to detailed assessments of the embodied energy associated with buildings. The assessment methods for addressing this gap are underdeveloped and sometimes not well understood (Rauf and Crawford, 2012). This assertion was confirmed by a study on building energy which reported that the total life-cycle energy increase may have been caused by unintended increments in embodied energy, although a relative drop in operational energy was achieved (Dara *et al.*, 2019; Omrany *et al.*, 2020). Thus, the LCEA evaluates energy inputs across different building life-cycle stages and processes, from manufacturing and construction of the buildings to operation, maintenance, and demolition stages of the building (Omrany *et al.*, 2020; Rauf, 2015). Figure 2 shows these building life stages as stated by BS EN 15978, which is a European Standard closely related to the sustainability of construction works and is relevant to the current study.

2.2 Life-cycle embodied energy

Embodied energy refers to the onsite and offsite energy used directly or indirectly during building construction and related processes, including the extraction and manufacture of building materials and equipment. Three components constitute the life-cycle embodied energy (LCEE). The first is the initial embodied energy (IEE) which refers to the energy used during material production and includes raw material procurement as well as the manufacturing and delivery of the building material to the site. This refers to the energy consumed from manufacturing to construction. The second is recurrent embodied energy (REE) which refers to the energy expended during a building's useful life that is specifically related to maintenance, repairs, or refurbishment processes. Finally, the demolition and disposal embodied energy (DDE) refers to the energy used in deconstruction and disposal when a building reaches its end-of-life. This extends to the amount of energy required in various stages of demolishing, waste sorting, and hauling (Dixit *et al.*, 2010, 2014). Connecting the above to BS EN 15978 provides a holistic overview of construction works that identifies several stages: the product and construction phases relate to IEE in this study, the use phase relates to REE, and the end-of-life phase is connected to DDE. Thus, an analysis of the LCEE provides a holistic means of assessing all the energy related to the use of a building material across its life cycle, from cradle-to-grave, or from cradle-to-cradle (Dixit *et al.*, 2014; Venkatraj and Dixit, 2021).

Generally, building materials with high embodied energy tend to have higher energy consumption and large-scale impacts during construction (Bribián *et al.*, 2011; Jiang *et al.*, 2020; Li *et al.*, 2019), increased environmental and carbon footprints, and higher greenhouse gas emissions (Florentin *et al.*, 2017; Kumanayake *et al.*, 2018; Rajpu and Tiwari, 2020) across their lifespan. Studies have shown that the direct relationship between building material selection and embodied energy is a vital component of holistic life-cycle energy assessments. Reddy and Jagadish (2003) and Huberman and Pearlmutter (2008) studied the embodied energy of both common and alternative construction materials. They discovered that a reduction in embodied energy up to 20% (Huberman and Pearlmutter, 2008) and 50% (Reddy and Jagadish, 2003) is possible if alternative materials are considered. Another study by Dabaieh *et al.* (2020) found that using sun-dried bricks instead of fired bricks in building construction led to a reduction of approximately 5,907 kg CO_2eq and 5,305 MJ of embodied

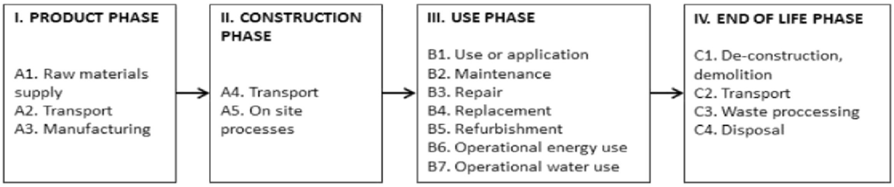


Figure 2.
Life-cycle stages and activities associated with buildings

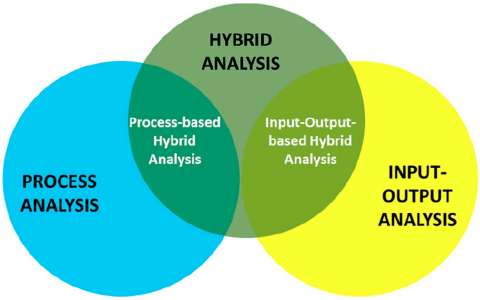
Source(s): European Committee for Standardization (CEN) (2011) energy per 1,000 bricks (Dabaieh *et al.*, 2020). Thus, the significance of choosing materials with lower embodied energies is apparent.

2.2.1 Embodied energy assessment. Fundamentally, it has been stated that life-cycle energy assessment methods which include embodied energy considerations, provide a more comprehensive approach to mitigating indirect and direct energy demands (Chen *et al.*, 2019; Grazieschi *et al.*, 2021; Minunno *et al.*, 2021). However, some studies have raised concerns that embodied energy calculation procedures or methods of assessment are not sufficiently understood in the literature or in practice (Rauf, 2016; Rauf and Crawford, 2014). A review which focused on this topic suggested that the calculation approach embarked upon by several studies was reported in only one of the three studies (Dixit, 2019). To ensure the credibility of the results, the calculation method, database of the materials used, and system boundaries should be explicitly stated, consistent, and valid (Dixit, 2019; Feng *et al.*, 2016; Omrany *et al.*, 2020). In a previous study, the life-cycle embodied energy proportion of the life-cycle energy for a case-study building was as high as 60%, which confirms its importance in understanding building life-cycle impacts and sustainability in design (Rauf and Crawford, 2013). Some authors have reported embodied energy percentages of the primary energy consumed for different building classes: 35% in advanced retrofit homes (Koezjakov *et al.*, 2018), 67% in NetZero Energy Buildings, and approximately 32% in a conventional buildings (Giordano *et al.*, 2017). The ensuing consensus of similar studies is that, when high-performance buildings are compared with basic or standard constructions, the embodied energy may be higher because more materials are used (Azari and Abbasabadi, 2018; Thormark, 2007).

Several approaches have been used by researchers to estimate embodied energy, the most common of which are process, input–output, and hybrid analyses (Dixit, 2019; Rauf, 2015; Su *et al.*, 2020). These methods have particular differences in approach (Crawford, 2011), which can lead to variations in results, sparking a call for an international standardisation of the approach for calculating embodied energy (Dixit, 2019). Common methods (Figure 3) and their differences are outlined below.

1. Process analysis

This approach draws locational data which represent the statistics and data-related information of both processes and products to describe key issues, such as environmental flows which help define a product’s embodied energy and approximate energy aspects (Baird *et al.*, 1997). This approach can also be used to assess practices and process sustainability (Crawford, 2011; Rauf, 2016) in the manufacturing sector (Escobar and Laibach, 2021; Fan *et al.*, 2021). However, researchers have argued that this approach has certain limitations. For example, it has been reported that the manufacturers’ databases used in the calculations



Source(s): Authors own work

Figure 3. Assessment methods for embodied energy calculations

sometimes contain missing information (Crawford, 2011; Dixit, 2019; Rauf and Crawford, 2015; Treloar, 1997). Consequently, it is impossible to comprehensively define production processes which add to other complexities impacting reliability within upstream supply chains (Dixit, 2019; Rauf, 2015). Fan *et al.* (2021) also argued that this method is time-consuming, and because of the numerous steps required, it tends to focus only on major inputs (Fan *et al.*, 2021). Ultimately, this can lead to truncation errors and reported incompleteness or uncertainties in the definition of system boundaries (Suh *et al.*, 2004; Treloar, 1997).

2. Input–output analysis

This assessment method is based on an approach which simultaneously traces and aggregates both financial transactions and energy flows simultaneously. To systematically boost its completeness, this dual-track system is applied across the entire supply chain (Baird *et al.*, 1997; Crawford, 2011). Recently, Malik *et al.* (2021) argued that this method may serve as an alternative to life-cycle analysis because it adopts impact inputs from the supply chain and avoids voluminous data collection (Malik *et al.*, 2021). However, over time, it has been argued that although it is comprehensive in its approach, this method has certain limitations. An advantage of this approach is that energy and economic data on a national scale can be collated and compared; however, unplanned mismatches may occur because of product dissimilarities in the combined evaluation of different sectors (Baird *et al.*, 1997). Other authors agree that this mismatch creates a "black box", which negatively impacts the data collected and the results (Cellura *et al.*, 2013; Dixit, 2019; Rauf and Crawford, 2013). These authors note that there are critical challenges due to this approach which relate to "homogeneity, proportionality, and inadequate considerations of the economies of scale" (Rauf *et al.*, 2021). Thus, the potential for producing questionable and unreliable results is due to the unintended double counting of the enumerated energy input (Dixit, 2019).

3. Hybrid analysis

This method adopts a combination of both the process and input–output methods into one calculation method (Lenzen and Crawford, 2009) in a way that attempts to address their limitations (Crawford *et al.*, 2018). This makes the hybrid approach significantly more robust, and it has been reported as the most comprehensive embodied energy assessment approach for computing life-cycle inventories (Allende *et al.*, 2020; Crawford, 2011). This is because bottom-up industrial process data are combined with input–output large-scale, top-down economic data. There are two versions of hybrid analysis: process-based hybrid analysis (PBHA) and input–output-based hybrid analysis (IOBHA).

In principle, process-based hybrid analysis tracks the embodied energy of individual materials, products, or components used directly in the manufacturing process or building construction under review. The result is added to the extrapolated energy intensity for each, as sourced from the input–output analysis (Crawford, 2004; Treloar, 1997). Therefore, embodied energy results from the process analysis are added to "the difference between the total energy intensity of the input-output path of the basic material, and then multiplying it by the total price of the basic material" (Crawford, 2004).

Input–output-based hybrid analysis (also known as the path exchange hybrid approach) aims to address the limitations of process analysis/process-based hybrid analysis (Treloar, 1998). Some authors have suggested that embodied energy calculations are limited by the lack of a database, which also applies to input–output hybrid analysis (Allende *et al.*, 2020; Mao *et al.*, 2013). However, it has been argued that the completeness of the system boundary used in this approach is more reliable because of the combination of energy data aggregated from the process analysis, hybrid data which represent material energy intensities, and input–output data (Crawford, 2011; Rauf, 2016). Additionally, the adoption of integrated processes associated with input–output data applied at the material level creates hybrid material energy coefficients (Crawford, 2011).

2.3 Service life of building materials and recurrent embodied energy

In a practical sense, the service life of building materials is an important consideration in embodied energy studies. This is because, when both building materials or components are reviewed, their service lives have a direct impact on the building's recurrent embodied energy (Chau *et al.*, 2007; Chen *et al.*, 2001; Cole, 1996; Winistorfer *et al.*, 2005). A longer service life for materials and components equates to fewer replacements over the building life, resulting in lower recurrent embodied energy (Chau *et al.*, 2007; Chen *et al.*, 2001; Scheuer *et al.*, 2003). Conversely, a higher recurrent embodied energy is due to the frequent need to change or the service aspects of the building, which is sometimes the result of specifying building materials with a low initial embodied energy or relatively poor quality (Cole, 1996). Consequently, research-based practice recommendations embrace life-cycle energy reduction by selecting long-service-life materials and components (Dixit *et al.*, 2014).

Material service life is affected by a number of factors, including geographic and climatic conditions, and other factors such as the type of building components or construction materials, size, architectural and structural designs, functional requirements, quality of workmanship, internal and external exposure conditions, and subsequent damage mechanisms, as well as the quality of maintenance (Janjua, 2021). This strengthens the argument for appropriate material selection and service-life considerations relative to the building lifespan at the design or renovation stages (Rauf, 2016). Building renovation, refurbishment, and retrofit studies have also shown that the selection of materials may be driven by goals such as sustainability standards (Bande *et al.*, 2022; ElKaftangui and Mohamed, 2015), energy and economic impacts (Abu-hijleh *et al.*, 2017) and multi-criteria assessment (Belpoliti *et al.*, 2020). Therefore, the selection process could be objective, subjective, or both. Nevertheless, the environmental impact of this choice can be significant from an LCA viewpoint (Tokede *et al.*, 2023) and should be driven by sustainability (Asdrubali *et al.*, 2023).

Janjua (2021) recently reported that a complex relationship exists between the service life of materials and buildings, which has another relationship with the environmental performance of a building. For example, excessive replacement of low-quality nonstructural elements and building components may increase the building's lifespan, but ultimately increase the building's environmental impact. This study argues that the benefits of a longer building service life must be accompanied by fewer replacements (i.e. a longer material service life) to ensure environmental sustainability and reduced wastage (Janjua, 2021). This consideration of "number of replacements" is known as the "replacement factor" and is defined as the number of times a building element is replaced over its life cycle. It is calculated by dividing the building service life by that of the building component material, assembly, or system. Consequently, as the building service life increases, recurrent embodied energy increases (Dixit, 2017).

3. Research approach

The focus of this study was to examine the extent to which life-cycle embodied energy could be influenced by variations in material service life. To achieve this, the life-cycle embodied energy of a representative residential villa was calculated as a case study of the status quo. In phase one, the initial and recurrent embodied energies and the embodied energy associated with end-of-life demolition and disposal were calculated. For recurrent embodied energy, the lifespan of this villa was assumed to be 50 years.

In phase two of the investigation, a sensitivity analysis was conducted using three alternative scenarios in which the service life of all building components and construction materials was varied, and the impact of these variations on the villa's life-cycle energy demand was assessed. In the sensitivity analysis in this study, the alternative scenarios assessed were based on the average, minimum and maximum material service lives, measured in years. The values applied for these scenarios were deduced from secondary data found in the available literature as well as the current living situation in the study context. In other studies, carried out by the authors, the sensitivity analysis focused on variations based on the adoption of a rooftop Solar System as an alternative energy source. The impact on the LCEE was an 11.5% increase, and impact on the life-cycle operational energy (LOPE) was 9–11.5% (Rauf *et al.*, 2022). In another study, a sensitivity analysis focused on variations in the building service life in relation to the assessment period (AP). The reported impact relative to the BSL was 50%, and for 100 and 150 years it was up to 275% (Rauf, 2022).

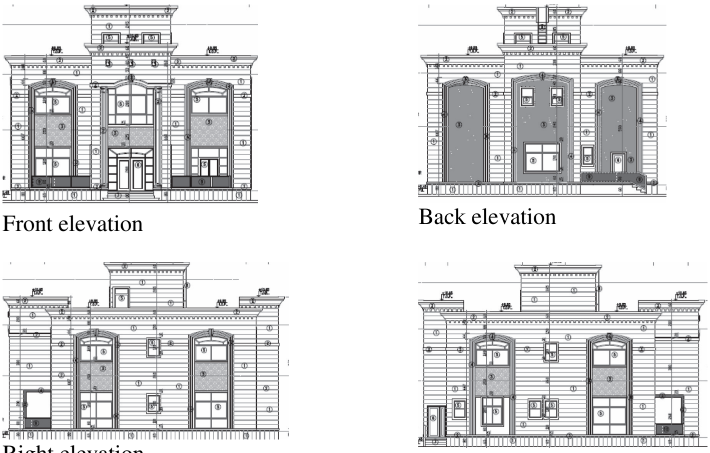
In this study, the embodied energy was measured in gigajoules (GJ) and calculated for a 50-year building lifespan. Other energy metrics used were the embodied energy per square metre (GJ/m^2) of the building's gross floor area (GFA), annual embodied energy (GJ/year), and annual embodied energy per m^2 (GJ/m^2/year).

In line with the referenced literature (See Section 2), the input–output hybrid approach (Path Exchange hybrid approach) was selected to calculate the embodied energy using a MS Excel spreadsheet with the appropriate mathematical formula (See Section 3.2). These calculations often rely on a robust material database; however, the current study found a lack of sufficient data on the embodied energy of building materials in the UAE. This critical information provides a clear definition of the system boundary for assessment, because it includes the embodied energy coefficients and intensities of each material or component used in villa construction. To compensate for this, an Australian material database which has been reviewed and used in several other studies (Allende *et al.*, 2020; Crawford *et al.*, 2019, 2022; Rauf *et al.*, 2021) called the Environmental Performance in Construction (EPiC), was used to assess the villa's embodied energy.

3.1 Representative case-study building

In the UAE context, villas are the most common type of residential property built for citizens and their families, either personally or by the government. The typical UAE Emirati family prefers these spacious houses (villas) which are available with several bed types, ranging from 3 to 10-bedrooms (Abuimara and Tabet Aoul, 2013; Giusti and Almoosawi, 2017). The selected case-study building is a detached villa located in Al Ain, UAE. Summers in Al Ain are long, sweltering, and arid, whereas winters are short, comfortable, dry, and clear. Minimum and maximum temperatures in summer (May to September) range from 35 °C to 50 °C in the daytime, while in winter (December to February) the range is between 25 °C and 35 °C (Haggag *et al.*, 2017) with a yearly average global horizontal irradiance in excess of 20 MJ/m^2/day (Taleb, 2015). Average annual precipitation reported in the city is 72 mm while the average annual temperature is about 27.8 °C (Elmahdy *et al.*, 2020).

The selected case-study villa represents a cross-section of the residential building typology in all parts of the UAE for a typical Emirati (UAE citizen) family. The total gross floor area of this two-story, five-bedroom villa was 532 m^2 (Figure 4). This villa was constructed using common building materials found in the study context: the floor and roof were made of conventional reinforced concrete slabs, and the walls were made of hollow concrete block walls layered with plaster. Additionally, it had a plasterboard ceiling, floor tiles made of ceramic, and ceramic tiles combined with oil and acrylic paint in different portions that were used for the wall. The windows were double-glazed with aluminium frames, while the doors were made of and framed using teak.



Front elevation

Back elevation

Right elevation

Left elevation

Source(s): Authors own work

Figure 4.
Case-study building

3.2 Calculating life-cycle embodied energy

The considerations and components for assessing embodied energy are explained in Section 2. While some researchers have focused only on the initial embodied energy (cradle-to-site) assessment (Dixit and Singh, 2018; Lolli *et al.*, 2017), others have addressed the cradle-to-grave assessment which considers both recurrent and demolition-embodied energy (Giordano *et al.*, 2017; Rauf and Crawford, 2013). This study defines the system boundary by considering both the initial and recurrent embodied energy over a 50-year assumed life span of the building. The demolition-embodied energy is assumed, based on literature, as 1% of the life-cycle energy owing to limited data. LCEE is the sum of IEE, REE, and DDE. The procedure for calculating the LCEE components is detailed below.

3.2.1 Initial embodied energy. The review of various assessment methods in Section 2.2.1 guided the selection of the IOBHA to evaluate the IEE of the selected villa. The IEE associated with the villa construction was calculated using a detailed quantity bill. An extract of the BOQ is provided in Table 1, but given the high volume, entire list is given in the Supplementary Table of this paper, which is available online. The BOQ lists over 170 building materials and components used in this study. The excluded items included electrical and plumbing pipes and fittings owing to a lack of data at the time of inventory.

The delivered quantity (in kilograms or cubic metres) of each material was multiplied by its corresponding embodied energy coefficient, as obtained from the EPiC Database (See extract in Table 2). This table shows the wide variations in embodied energy and emissions across these common materials, which is of particular importance when considering that these materials have similar building functionalities.

The following formula was used (Crawford, 2004) to calculate IEE:

$$IEE_b = \sum_{m=1}^{M} (EC_m \, x \, Q_m)$$

where IEE_b = initial embodied energy of the building;

EC_m = embodied energy coefficient of material; and

Table 1.
Extract of detailed BOQ

S.No	Item	Unit	Qty	Wastage factor	Delivered quantity	EI GJ/unit
2	*Excavation and substructure work*					
	2.10 Excavation	M^3	500			
	2.11 Backfilling	M^3	400			
	2.12 Filling of imported soil materials	M^3	150			
	2.13 Blinding concrete 10 cm thick footing and solid block	M^3	18	1.15	20.7	2.404
	2.14 Blinding concrete 5 cm thick T/beam	M^3	7	1.15	8.05	2.404
	2.15 Reinforced conc. foundation for footing	M^3	106	1.15	121.9	2.404
	2.16 N/column and, T/beam	M^3	27	1.15	31.05	2.404
	2.17 RCC for graded slab with 10 cm thick	M^3	24	1.15	27.6	2.404
	2.18 Anti-termite control in ground slab level	L.S	1			
	2.19 Polythene sheet 1,000 g	L.S (m^2)	249	1.2	298.8	0.0123
	Total					
3	Superstructure work					
	3.10 Columns	M^3	21	1.15	24.15	2.404
	3.11 Beams	M^3	26	1.15	29.9	2.404
	3.12 Staircase and entrance steps	M^3	16	1.15	18.4	2.404
	3.13 Lintels and arches	L.S				
	3.14 Solid Slabs 25 cm thick	M^3	112	1.15	128.8	2.404
	3.15 Solid Slabs 18 cm thick	M3	5	1.15	5.75	2.404
	3.16 Dome	M^3	0			
	3.17 Parapet	M^3	30	1.15	34.5	2.404
	Total					
4	Blocks work					
	4.10 20 cm solid block-60 m^2 @425 kg/m^2	KG	25,500	1.05	26,775	0.0026
	4.11 20 cm hollow block with insulation - 440 m^2	KG	121,000	1.05	127,050	0.0026
	4.11 20 cm hollow block with insulation - 440 m^2	KG	660	1.05	693	0.0026
	4.12 20 cm hollow block-620 m^2 @275 g/m^2	KG	170,500	1.05	179,025	0.0026
	4.13 10 cm hollow block-150 m^2 @275 kg/m^2	KG	41,250	1.05	43312.5	0.0026
	Total					

Source(s): Authors own work

Q_m = quantity of delivered material

The system boundary for the assessment also included the energy associated with nonmaterial inputs. For example, the construction process is carried out on-site, material transportation, and other inputs related to project finances and insurance coverage. These were computed based on their contributions and impacts on the construction of the case-study villas. These nonmaterial inputs or *reminder* were then added to the calculated initial value. To calculate this *reminder,* an input–output model based on a disaggregated energy pre-assessment was applied. The formula for this procedure is as follows (Crawford, 2011):

Building material	Embodied energy (MJ/kg)	Embodied emissions ($kgCO_2eq$)	Building function			
			Foundation	Structure	Envelope	Finishing
Concrete block	2.6	0.24	☒	☒	☒	
Concrete roof tile	4.3	0.39			☒	
Brick	3.5	0.32	☒		☒	☒
Ceramic tile	18.9	1.3			☒	☒
Air-dried hardwood*	13,632	944	☒	☒	☒	☒
Cold rolled steel	51.7	3.7			☒	☒
Water-based Paint	111	6.8				☒
Solvent-based paint	124	6.3				☒
Single glazing flat glass**	444	2.2			☒	
Double glazing flat glass***	1,441	115			☒	
Aluminium Composite panel	1,196	102				☒
Aluminium sheets*	4,800	434				☒

Note(s): * per m^3
** per m^2 values for 6 mm
*** per m^2 values for 6:12:6 flat glass
Source(s): Crawford *et al.* (2019)

Table 2. Comparison of common building materials

$$EE_i = \sum_{m=1}^{M} (EC_m \, x \, Q_m) + \left[TER_n - \sum_{m=1}^{M} (TER_m) \right] x C_b$$

where EE_i = total initial embodied energy of the building;

TER_n = total energy requirement of the building construction-related input–output sector in GJ per currency unit

TER_m = total energy requirement of the input–output pathways representing the material in GJ per currency unit; and

C_b = total cost of the building in currency units.

A further explanation of the procedure for the analysis process used in the computation of embodied energy in this study can be found in the literature (Rauf, 2016).

3.2.2 Recurrent embodied energy. To calculate recurrent embodied energy, it is important to approximate the frequency of replacement during the building lifespan for each item in the bill of quantities, including both materials and components. Based on the literature review, assumptions were made regarding the service life of each material or assembly used in the construction of the villa and the service life of the building itself. The mathematical equation for this calculation is as follows:

$$REE_b = \sum_{m=1}^{M} \left[\left[\frac{SL_b}{SL_m} - 1 \right] X \, (EC_m \, x \, Q_m) \right]$$

where $REEb$ = recurrent embodied energy of the building;

Qm = the delivered quantity of material;

SLb = service life of the building; and

SLm = service life of the material, m.

As mentioned earlier, the initial embodied energy was used to calculate the embodied energy of nonmaterial inputs or the *remainder* to ensure a complete definition of the system boundary. Finally, for each material, component, or assembly, the product of its embodied energy and the number of possible replacements were calculated. This was performed for each material across the total lifespan of the building and then added together. This sum provides the total recurrent embodied energy of the villa. It is important to note that the number of replacements is related to the assumed 50-year building lifespan. Thus, we divided the lifespan of the villa (50 years) by the specific service life and subtracted one (in this case, one represented the quantity of material consumed when the villa was initially constructed). The results were then rounded for ease of calculation and practicality. The formula for calculating the REE of the building is as follows:

$$REE_b = \sum_{m=1}^{M} \left[\left[\frac{SL_b}{SL_m} - 1 \right] X \left[(EC_m \, x \, Q_m) + (TER_n - TER_m - TER_{i \neq m}) \, xP_m \right] \right]$$

where $TER_{i \neq m}$ = total energy requirements associated with those processes that were not associated with the replacement of each individual material.

3.3 Sensitivity analysis: material service life scenarios

As a further step, different possible scenarios were used to assess the embodied energy of the case-study villa which depicted alternative material specifications or the service life of materials, components, or assemblies. This helps develop a more comprehensive understanding of the effect of material service life (MSL) on the recurrent and life-cycle embodied energy of buildings, and ultimately, its potential impact on the environment. Thus, a reinvestigation of the villa's LCEE was conducted by selecting the minimum (MSL-MIN), average (MSL-AVE), and maximum (MSL-MAX) material service life scenarios. These alternative MSL values were selected based on the literature (Rauf, 2016) to reflect the extent of possible variability in the service life of the building materials used to construct the villa and their impact on the LCEE.

Based on the foregoing, the recurrent and life-cycle embodied energy of the villa were recalculated for the minimum and maximum scenarios in relation to its useful life or occupancy. In these simulated scenarios, the initial embodied energy at the original construction stage of the building is assumed to remain unchanged throughout the service life of the materials. As a reference, Table 3 shows examples of some common materials as well as the alternative material service life values used to define the scenarios.

4. Results and discussion

In line with the research objective, this section presents the results of IOHBA for the case-study villa as a vital component of its life-cycle energy. It focuses on two aspects: first, the life-cycle embodied energy analysis, and second, the variations in life-cycle embodied energy due to the alternative material service life scenarios.

4.1 Initial embodied energy (IEE)

By following the sequential steps for the IOBHA, the IEE calculated was 7,390.5 GJ (13.9 GJ/m^2). A comparison with other studies shows that this value is close to, but marginally higher than those of other investigations. Treloar *et al.* (2000) and Rauf (2016) studied residential buildings in Australia. They found their initial embodied energy to be 11.7 GJ/m^2 and 13 GJ/m^2, respectively. To explain these results, we infer that the use of energy-intensive materials in the case-study building may have been responsible for this variation. The use of concrete rather than timber for roof construction and concrete blocks rather than clay blocks or timber for walls in this study are two examples. Furthermore, compared with studies that used other embodied energy analysis methods, this study reflects a much higher embodied energy demand. This assertion is evidenced by recent studies using process analysis, where initial embodied energy in a study in Greece was found to be 5.6 GJ/m^2 (Dascalaki *et al.*, 2021). The other study found that the initial embodied energy values for two Iranian residential buildings were 2.86 GJ/m^2 and 5.09 GJ/m^2 respectively (Pakdel *et al.*, 2021). These results may be due to the comprehensive nature of the IOBHA approach, which provides a more complete system boundary.

4.2 Recurrent embodied energy (REE)

As stated in Section 3, it was assumed that a building would have a lifespan of 50 years; thus, the REE was first calculated for this duration using the average service life of building materials, assemblies, and components. Using the IOBHA, the result of the REE assessment was 5,690 GJ (10.7 GJ/m^2). Comparatively, a study by Rauf (2016) on a residential building in Melbourne, Australia found the recurrent embodied energy over the same assessment period to be 8 GJ/m^2. Thus, the results of the current study were approximately 25% higher, although the latter study also used the IOBHA approach. This higher value may be due to a few reasons, such as the relatively frequent material replacement periods in the UAE owing to issues of poor workmanship in some cases or sporadic building servicing as a result of the new tenant's request.

As stated earlier, the EPiC database and some secondary data were used for the REE calculations in the case study. The international applicability of this database has been confirmed by other non-Australian studies. This latter speculation is based on the reported findings that expatriates in the UAE tend to change houses every three to four years (Attoye, 2020). Considering that a building's service life is assumed to be 50 years and that expat workers make up 80% of the UAE population (Muysken and Nour, 2006), the multiplied impact of this trend is significant and requires further investigation which lies outside the focus of the current study.

4.3 Life-cycle embodied energy

The sum of both the IEE in Section 4.1, and the REE in Section 4.2, gives the life-cycle embodied energy associated with the villa under review for the 50 years assumed life span.

Material	Minimum	Average	Maximum	Source
Concrete	Life-time	Life-time	Life-time	Seiders *et al.* (2007) *Tiles Conder (2008) *Wall
Stucco-wall/cement-based plaster	17	55	100	Canada Mortgage and Housing Corporation and IBI Group (2000), Conder (2008), Seiders *et al.* (2007)
Windows – aluminium	10	25	40	Chapman and Izzo (2002), Conder (2008), Seiders *et al.* (2007)
Door – solid wood	25	32	40	Carre (2011), Chapman and Izzo (2002), Fay *et al.* (2000), Treloar (1998)
Paint – exterior	7	11	15	Carre (2011), Conder (2008), InterNACHI (2012), Seiders *et al.* (2007)

Source(s): Rauf (2016)

Table 3. Materials service life scenarios for some common building materials

An additional 1% of the LCE demand was added to represent the energy associated with end-of-life demolition and disposal (DDE). Because operational energy (OPE) was not the focus of this study, secondary data (Abu-Hijleh and Jaheen, 2019; AlQubaisi and Al-Alili, 2018; Bande *et al.*, 2019; Giusti and Almoosawi, 2017), was used to approximate the operational energy, as explained in a previous study (Rauf *et al.*, 2021). By summing up the IEE, REE and OPE, the DDE was calculated as 1% of the result. The life-cycle OPE of the villa was approximated based on the above reference as 26,177.91 GJ; the DDE was thus found to be 392.58 GJ and the life-cycle embodied energy over 50 years was 13,473 GJ (25.3 GJ/m^2). Thus, for this representative case study, the proportions of the life-cycle energy calculated over the villa's 50-year lifespan were 34% for the embodied energy and 66% for the operational energy.

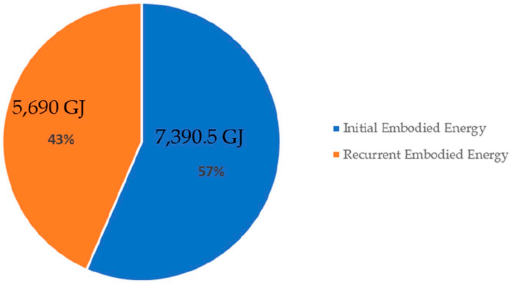
Figure 5 below shows that the IEE (43%) and the REE (57%) make up the life-cycle embodied energy demand. This not only shows the significance of REE, but we may also assume from previous studies (Rauf, 2016), that if a building's service life is increased from 50 to 75 or 100 years, it would play a comparatively greater role. This demonstrates the importance of the appropriate selection of materials and service life considerations when designing and constructing buildings.

4.4 Material service life alternatives

Thus far, the average values of the service life of materials and components have been used to calculate the recurrent embodied energy of the villa. These values were sourced from data available in the literature (Table 3). In this study, we focused only on varying the recurrent embodied energy value for each material service life scenario, while the initial embodied energy remained untouched. Thus, REE is a critical component which would invariably lead to variations in the magnitude of LCEE. To accomplish this part of the assessment, the potential material service life impact on the LCEE was assessed by applying alternative scenarios: minimum and maximum values for all material service life values. Accordingly, this section reports the recalculation of the recurrent and life-cycle embodied energies presented in Sections 4.2 and 4.3.

The results of the calculations performed using minimum and maximum MSL scenarios were significantly different from the findings which resulted from the average MSL values. Figure 6 compares the three scenarios (minimum, average, and maximum). It shows that when the minimum value was used, REE was 14995.3 GJ (28 GJ/m^2) but when the maximum value was used, the REE was 1651.8 GJ (3.1 GJ/m^2).

The findings confirm that a decrease in material service life (MSL-MIN) causes an increase in the recurrent embodied energy due to a greater frequency of material replacements. Compared to the results with average material service life values, there was a 163.5% increase in recurrent embodied energy when using minimum material service life



Source(s): Authors own work

Figure 5.
Comparing the initial versus recurrent embodied energy over 50-year lifespan for the Villa

values and a 71% reduction in recurrent embodied energy when maximum material service values (MSL-MAX) were used.

Similarly, when life-cycle embodied energy was checked, the results were similar to the findings for recurrent embodied energy. When a decrease in material service life was applied, it led to an increase in the life-cycle embodied energy; however, an increase in service life led to a decrease in the life-cycle embodied energy compared with the results when average material service life values were used. The analysis showed that for minimum and maximum service life alternatives, the LCEE value was 22871.5 GJ (43 GJ/m^2) and 9394.5 GJ (17.7 GJ/m^2), respectively, as shown in Figure 7.

Compared to the life-cycle embodied energy result with average material service life scenario, there was a 69.7% increase when using minimum values of the material service life and a 30.2% reduction when maximum material service life values were used. As explained earlier, these variations are due to variations in the replacement cycle, durability, maintenance requirements of materials, components, and other factors (Asdrubali *et al.*,

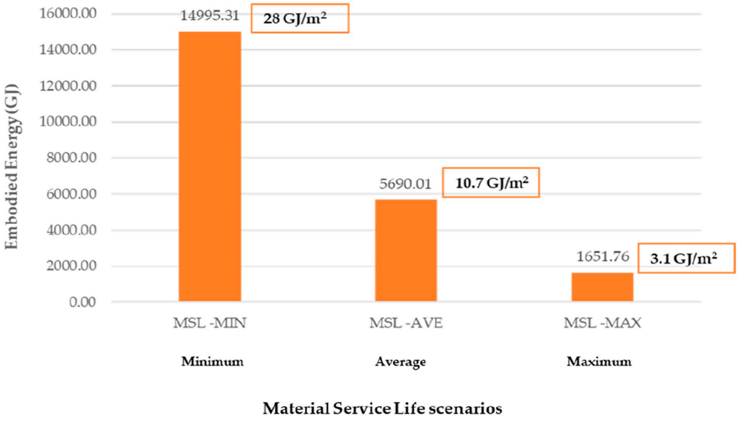


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Figure 6.
Alternative material service life scenarios with corresponding recurrent embodied energy values

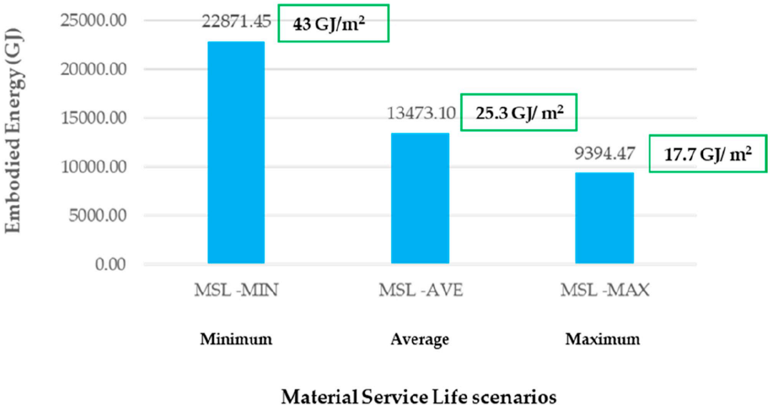

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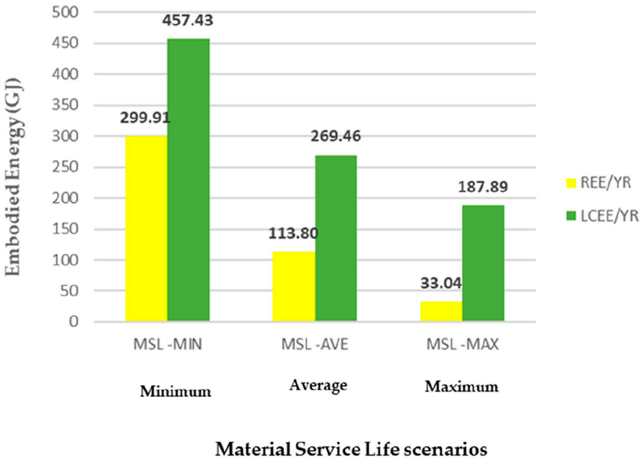
Figure 7.
Alternative material service life scenarios with corresponding life-cycle embodied energy values

2017; Dixit, 2019; Huberman and Pearlmutter, 2008). The wide variations recorded suggest that the service life of a building material may have a significant effect on its recurrent and life-cycle embodied energies. This suggests that the embodied energy due to the minimum material service life alternative is over 1.5 times more for an average material service life over a 50 years building lifespan. Similarly, the embodied energy decreases significantly when the maximum values are used instead of the average material service life values over the same period.

Two considerations are critical for elaborating these variations. First, we reviewed the annual recurrent embodied energy impact for each material service life alternative and the impact of extending not only the material but also the building service life. In Figure 8, the annual impact of these alternative material service life scenarios are presented in relation to REE and LCEE.

The figure shows that for minimum material service life (MSL-MIN), the annual recurrent embodied energy value was 300 GJ/yr (0.56 GJ/m^2/yr) while the annual life-cycle embodied energy was 457.4 GJ/yr (0.86 GJ/m^2/yr), meaning that annually the REE is 65.6% of the LCEE. This finding affirms that it is critical to consider recurrent embodied energy in life-cycle energy analysis and confirms the need for its consideration in the decision-making process, particularly during the early building design phase. For the average material service life (MSL-AVE), computed results were 113.8 GJ/yr (0.21 GJ/m^2/yr) and 269.5 GJ/yr (0.51 GJ/m^2/yr) for the recurrent and life-cycle embodied energy, meaning that the annual REE is 43.9% of LCEE. For the maximum material service life (MSL-MAX), annual recurrent and life-cycle embodied energy was 33 GJ/yr (0.06 GJ/m^2/yr) and 187.9 GJ/yr (0.35 GJ/m^2/yr), meaning that annually, the REE is only 15% of the LCEE. This suggests that improving the service life of the materials reduces the associated recurrent embodied energy.

When comparing the relative difference between annual LCEE results for minimum and average material service life values, a difference of 188 GJ was found, which reflects a 69.7% increase from the average MSL. The difference in annual LCEE between the average and maximum material service life values was 81.6 GJ. This reflects a 30.2% decrease in the average MSL. Similarly, the results showed a comparative difference of 269.5 GJ (143.5%) between annual embodied energy results for minimum in relation to the maximum material service life values. These findings defend the assertion that using materials with longer



Source(s): Authors own work

Figure 8.
Annual recurrent and life-cycle embodied energy of case-study villa with minimum, average and maximum material service life values over 50 years

service lives can lead to a significant drop in the magnitude and impact of the total life-cycle embodied energy. Extending the longevity of building materials reduces the need for frequent replacements, thereby reducing resource extraction, manufacturing, and energy consumption of new materials. Consequently, resource usage, carbon emissions, and waste generation were minimised. The findings of this study are important for the refurbishment of old buildings. While extending building lifespans via refurbishment appears to be more sustainable than new construction, continual material reuse can still affect energy use and the environment. Insights from such studies can help in making informed decisions in material selection, striking a balance between service life and environmental impact throughout a building's extended duration. These results are particularly important in the context of residential buildings in the UAE, where there is a drive towards sustainability. It also provides a strong argument to curb practices in which the service life of residential building materials is relatively low owing to the use of unskilled labour in the construction process or weathering effects due to extreme temperatures.

5. Limitations and future research

As one of the first studies in this region, the current study did not have multiple options for similar studies in the context of a review as a guide. Documented data on the actual material service life in the region required to develop a full inventory for analysis are difficult to assess. A bill of quantities, literature, and personal experiences of the authors was used. The research design assumed that the materials used in replacements over the building lifespan would have the same dimensions and properties as the materials used in construction. Changes in taste, occupancy, and policies may lead to the selection of different materials.

Future research should focus on these limitations to aid the development of a context-specific database as well as embark on a longitudinal study to examine changes in the material specified relative to the initial specifications. This could focus on renovation projects and the motivations for material selection. Further studies are required to explore embodied energy in hot climates and draw lessons for policymakers. There is a need to study strategies to reduce the initial and recurrent embodied energy in buildings, the impact of renewables on embodied energy and hybrid power systems, and the use of decision-making systems to compare alternative embodied energy material options and designs. Other areas could be the relation between LCEE and carbon emissions, as this applies to various stakeholders' demographics, perceptions, and social life in relation to LCEE. Comparative studies on other building typologies, alternative construction systems, and alternative methodologies can also be explored using simulation software and mixed methods to account for the motivation behind current and future material selection over the building life cycle.

6. Conclusion

This study was conducted to investigate the potential impact of changes in the service life of common building materials used in residential buildings in the UAE on the embodied energy associated with construction from a lifecycle perspective. To achieve this aim, a case study of villas in the UAE was selected and analysed using an input–output-based hybrid analysis to calculate the initial, recurrent, demolition, and disposal embodied energies using average material service life values. Next, two alternative scenarios with different service-life values of materials drawn from the literature were used to recalculate the recurrent and life-cycle embodied energy by substituting the average with the minimum and maximum service-life values for all materials and components.

Based on the results of this study, increasing the service life of building materials is a critical strategy for reducing a building's embodied energy and the related environmental impacts. This is mainly attributable to the resulting decrease in the recurrent embodied energy owing to fewer material replacements. Reduction in recurrent embodied energy was found to be in the order of 71% when maximum material service life values were used over average values. However, the magnitude of this reduction was 907.8% when maximum material service life values were used over with minimum material service life values.

In conclusion, the findings of this study show that with a building lifespan of 50 years, the recurrent embodied energy due to the replacement of building materials is substantial and worth considering as much as the initial embodied energy used in the construction. This may become even more significant if the service life of the building increases. In this study, minimum, average, or maximum material service life of materials resulted in recurrent embodied energy percentages of 67%, 43.5%, and 18.3% of the life-cycle embodied energy, respectively. This shows the importance of material service life considerations when selecting materials for a building at the design stage, as well as material replacement throughout a building's life.

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Supplementary File

The supplementary material for this article can be found online.

Corresponding author

Abdul Rauf can be contacted at: a.rauf@uaeu.ac.ae