ID 71

The Embodied Energy Assessment of Various Building Assemblies in Residential Building Construction

Abdul Rauf[1*], Daniel Efurosibina Attoye[1] and Robert Crawford[2]

[1] United Arab Emirates University, Al Ain, UAE
[2] The University of Melbourne, Melbourne, Australia
a.rauf@uaeu.ac.ae

Abstract

Energy consumption in the construction and building industry is associated with significant depletion of natural resources, release of greenhouse gases emissions and related environmental impacts worldwide. An understanding of the direct and indirect, operational, and embodied, as well as life cycle consumption patterns due to building architecture plays a major role in reducing the negative impact of buildings. A review of existing literature shows that there is much less research on the impact of embodied energy and there is a need to provide a clear basis to substantiate its veracity. Previous studies on embodied energy have mainly focused on the overall embodied energy of different building types. However, there is limited focus on the embodied energy associated with various assemblies in a building. In efforts to reduce the embodied energy of buildings, it is important to understand the energy associated with various assemblies in a building. Therefore, this research was conducted to investigate the life cycle embodied energy (LCEE) consumed by various building assemblies in a residential building to provide relatable data for professionals. The findings indicate two levels of interest; firstly, life cycle embodied energy of the case study was found to be 13096.47 GJ with the initial embodied energy being 7390.5 GJ (56%) and the recurrent embodied energy was 5690.01 GJ (43%). Secondly, the study presents the embodied energy impacts of various building assemblies and revealed that while the wall assembly was highest, responsible for 25% of the LCEE, the floors contributed 18% and the roof, 6%. The study reveals the significance of embodied energy consciousness in envelope design, as well as the design and specification of building assemblies.

Keywords

Life cycle embodied energy; initial embodied energy; recurrent embodied energy; Building Assemblies; Building materials; Input Output Hybrid Analysis

1. Introduction

In the last decade, it was predicted that global energy demand will rise by 36% between 2008 and 2035 at an average of 1.15% per year (Birol, 2013). Another prediction suggests that by 2050, global energy demand will rise to 50% (EIA, 2019). In general, energy consumption has a monumental impact on the environment and is frequently associated with environmental damage and global warming.

However, building construction, operation and related activities accounts for a significant percentage of this impacts. In 2017, 36% of global energy was consumed by buildings and also accounted for to 40% of energy-related carbon dioxide (CO2) emissions (IEA & UNEP, 2018). Using the United Arab Emirates as the context of study, this paper sheds light on subtle and overlooked aspects of this situation., It is easy to understand that building impact can be negative and problematic, on the other hand, global population is on the increase and thus, more buildings are needed. Between 2005 and 2010, the UAE population rose by from about 4.1 million to 8.3 million (UAE Federal Competiveness and Statistics Authority, 2020), and by 2019, about 9.8 million (Department of Economic Studies, 2020). Comparatively, the UAE has contributed over $443bn of awards towards building and infrastructure projects since 2004, it ranks as the highest contributor in the Gulf Corporation Countries (GCC) accounting for nearly 41 per cent of the value. Thus, as population rises, investments in the construction industry rises. The world population is predicted to rise to 9.7 billion by 2050 (United Nations et al., 2019),and it is expected that 230 billion m^2 of new building floor area will be added by (IEA & UNEP, 2018). Since buildings involve multiples stakeholders, both technical and non-technical stakeholders in the building industry need to be engaged in developing and promoting strategic solutions to improve building sustainability accompanied by the reduction of negative environmental impacts.

There are multiple studies which have focused primarily on the reduction of the operational energy consumed by buildings (Birgisdottir et al., 2017; Mirabella et al., 2018), leading to a clear understanding of how to reduce the impact of buildings in this regard by improving research accuracy in related calculations and design. As an example, a Danish study reports that about 70% reduction in operational energy has been achieved (Danish Government, 2014). Also, multiple studies report the achievement of NetZero designs based on operational energy reduction (Crawley et al., 2009; Kolokotsa et al., 2011). Conversely a survey of research databases, shows that there are fewer studies which give detailed focus on the embodied energy consumed in building construction. This gap in literature requires more focus on embodied energy analysis due to the fact that some studies have reported the significant and critical role which embodied energy plays (Crawford, 2014; Rauf, 2016).

In previous studies, we have assessed embodied energy based on material replacement and maintenance activities over a building's service life (Crawford, 2014; Crawford et al., 2010; Rauf & Crawford, 2015). Recently, we carried out a detailed investigation of the initial, recurrent and life cycle embodied energy of a villa in the UAE. The aim of the current paper, however, is the broader discussion regarding the veracity of this research area, and along with two key considerations. Firstly, this paper explores this embodied energy of building assemblies such as the roof, walls and floors -this is the technical focus of the paper. Secondly, the paper presents the calculated embodied energy data as a starting point to facilitate stakeholder engagement and interactions by providing market-ready practice oriented data on the topic.

1.1 Life cycle embodied energy analysis

The process used in quantifying embodied energy across a building's life cycle is called life cycle embodied energy analysis (LCEA). The approach draws its merit from the fundamentals of life cycle energy analysis, covers a cradle to site (Lolli et al., 2017; Resalati et al., 2020) or cradle to cradle (Rauf, 2016; Rauf & Crawford, 2015) scope and helps researchers to investigate multiple aspects of energy consumption across the building lifespan (Rauf & Crawford, 2013).

There are strategic benefits associated with the application of this approach in view of the potential improvements which it provides for both building and component design, as well as material selection and specification, and potentially, building construction. This is because the definition of the system boundary for the calculation process for life cycle embodied energy analysis covers associated energy demand from manufacturing, construction and maintenance and as well as the demolition phases of the building (Dixit et al., 2014). In specific terms, it incorporates the initial embodied energy used for construction, the recurrent embodied energy associated with replacement and maintenance of components or materials, and the demolition embodied energy required in demolition and disposal of materials.

1.1.1 Embodied energy assessment methods

Some studies have applied software or online tools in the calculation process (Azzouz et al., 2017; Dascalaki et al., 2021; Wen et al., 2015); these tools draw from three fundamental methods used in the systematic process applied in the quantification of a building's embodied energy. These are the process analysis, input-output analysis, and hybrid analysis (R. Crawford, 2011; Rauf, 2016). In this section, focus is given to these fundamental approaches as backbone of embodied energy calculation. The methods have different system boundaries and energy inputs applied in the analysis process (Dixit, 2017), as well as unique strengths and weaknesses.

The application of process analysis approach comprises a combination of process, product, and location-specific data which is used in the evaluation of environmental flows and effect which makes it the most accurate method. This approach starts with the energy input required from manufactures at the last stage and walks backwards to account for each energy input calculated. Computation results however, then to be incomplete due to the fact that detailed data for many of core production process are unaccounted for and the upstream supply chain in inherent with certain complexities (Treloar et al., 2001). To substantiate this, one study conducted by Crawford [15] reports that a 59% truncation error is associated with the use of this approach (Crawford, 2008).

Input–output analysis on the other hand, uses economic data as its basis; tracing, quantifying, and ordering the energy required in production of product. The availability of inter-industry transactions (input–output tables) which are periodically reported in some countries is used in defining the energy flows for respective national economies. This is aligned with monetary flows between various sectors, drawn from fuel tariffs and are used to create an energy-based input–output model. Although this approach is systemically complete -providing energy flows within an entire supply chain, it creates a combination of dissimilar products, sort of a procedural black box in individual economic sectors (Baird et al., 1997; Crawford, 2011). In some cases, product price estimation/assumptions, usage of economic data, and multiple or double counting of energy embodied in delivered fuels may lead to different errors in computation (Dixit, 2017; Treloar, 1998).

The third approach is called the hybrid analysis which combines process and input-output analysis approaches, and allows researchers to use both methods simultaneously; to maximize their strengths, and minimize their limitations (Crawford, 2011; Treloar & Crawford, 2010). The hybrid approach, however, can be a process-based hybrid analysis or an input-output hybrid analysis. In process-based hybrid analysis, the calculation uses delivered quantities for each material, using product and input-output data to complete the upstream system boundary (Treloar, 1998). Due to the fact that many direct inputs to the process under review may be omitted, the system boundary tends to be incomplete and this hybrid approach has similar weaknesses with process analysis (R. Crawford, 2011). On the other hand, input–output-based hybrid analysis resolves these truncation issues by using input–output data to fill missing data and complete the system boundary (Crawford et al., 2010; Rauf, 2016).

1.2 Building assemblies in construction

In construction, major decisions are made during the early design phase where stakeholder engagement reveals subjective choices in design decision-making. One aspect of construction work which has a definitive impact comprises of the various building assemblies such as wall, roofs and floors used in the construction. The choice of appropriate building materials for these assemblies is thus, considered as an important step in design development due to its potential impact on building performance. As a design variable, Nassar et al (2003) studied building assemblies such wall, roof, floors, windows in line with various performance metrices. This study developed a practice tool with facilitates the designer's decision-making process and information regarding trade-offs beginning with an assembly-based abstract representation of the building. Although this study did not consider embodied energy in the elaboration of performance metrics research shows the importance of this consideration (Nassar et al., 2003). For example, a study by Mayer & Bechthold (2018) reported that embodied energy assessment plays a vital role in building assembly design decisions (Mayer & Bechthold, 2018).

Furthermore, in comprehensive energy performance study by Crawford et al (2015) the authors reported the development of a tool to be used at early design stage, which helps in minimizing life cycle energy demand of building assemblies. The tool considers the significant role of embodied energy considerations along with heating and cooling loads (Crawford et al., 2015). However, this tool is based on comprehensive energy performance data for different assemblies for Australian climate zones only and cannot be used in other countries. Therefore, it is important to study the significance of embodied energy associated with different building assemblies around the world, including UAE.

A study by Silvestre et al (2014) presented a broad understanding of the environmental impact of buildings; asserting that it is associated with material characteristics such as their initial embodied energy. The authors also referenced a previous review on LCA investigations and reported that only 63% of reviewed studies carried out an evaluation of the embodied energy (Silvestre et al., 2014). The aforementioned studies, connectively, indicate that there is a significant merit in evaluating embodied energy of building assemblies. Although it is important to note the significant role played by operational energy in determining energy demand, extensive research has explored this area but much less have focused on embodied energy impacts of building assemblies (See Figure 1).

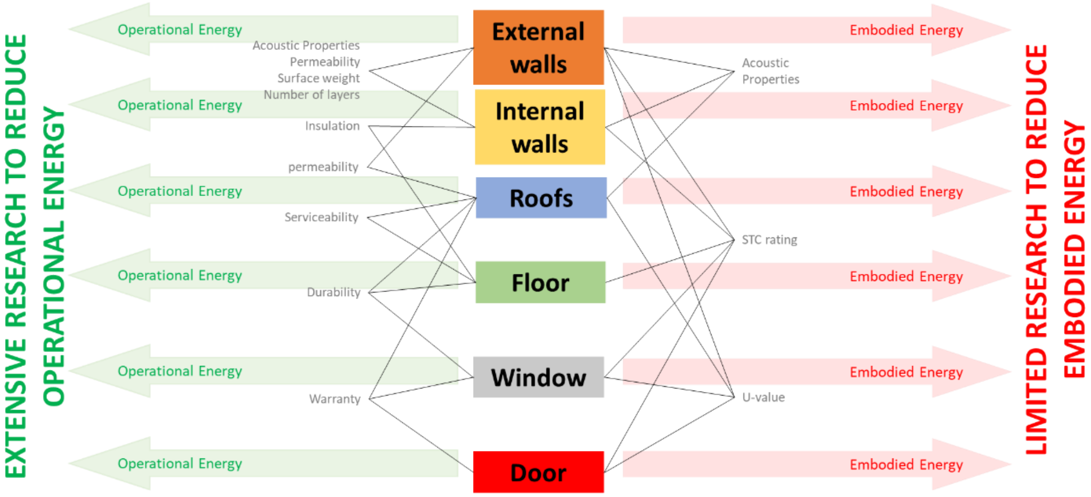

Fig. 1. Design metrics for building assemblies showing limited research on embodied energy aspects (Adapted from (Nassar et al., 2003; Rauf, 2016; Rauf & Crawford, 2015)

2. Method

To conduct this study, a case study UAE residential villa was used to simulate a real exploration of the embodied energy associated with the various building assemblies used in the construction. The use of a real case provided actual figures and material quantities from the Bill of Quantities associated with the architectural design which were then used to calculate the initial embodied energy and recurrent embodied energy values.

The selected representative case study villa is located in Al Ain, UAE (See Figure 2). The two storey house has a total floor area of 532m^2, a concrete column and beam superstructure, concrete solid and hollow blocks, double glazed aluminum windows and a concrete roof. Wall, floor, and roof assemblies are evaluated as a composite element which comprises both the structure and the finishes which were respectively made of ceramic tiles and paint, marble and ceramic, as cement tiles only. The door assemblies were primarily made of hardwood (teak) and were composed of both the door frame, while the double glazing with aluminum frame was used for the window assemblies. A detailed bill of quantities was used to quantify the life cycle embodied energy of the house. The building's structure is made up of concrete columns and beams, while the external floor is assumed to be covered with outdoor stone interlocking paving blocks,

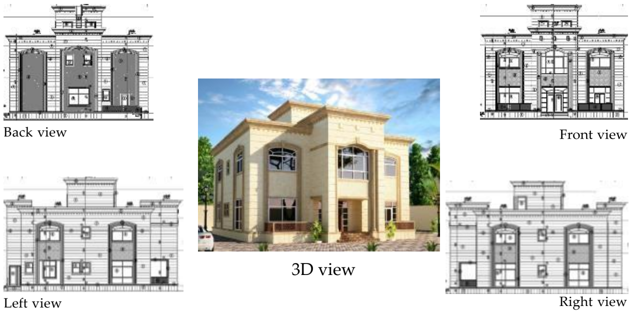
Back view
Front view
3D view
Left view
Right view

Fig. 2. 3D view and Elevations of the case study villa

2.1 Calculation procedure for initial and recurrent embodied energy

The Initial embodied energy of the case study villa was calculated by using the input-output-based hybrid analysis approach. The following calculation approach was used for each material/component:

$$A \ x \ B = C \tag{1}$$

Where:

A is the Delivered quantities of materials (in kg, LM, m^3 or m^2)

B is the Hybrid embodied energy (in GJ)

C is the Process-based hybrid embodied energy (in GJ)

In addition, energy embodied consumed by non-material inputs such as the provision of finance, insurance, transport etc. necessary to support the construction process was calculated to complete the system boundary. This result, referred to as the remainder of energy inputs was then added to the process-based hybrid embodied energy figure. Further explanation of the input-output-based hybrid analysis approach is available elsewhere (Rauf & Crawford, 2015).

To calculate the recurrent embodied energy of the villa, the replacement period or the number of times each individual material/component would likely be replaced with was used to extrapolate the additional energy consumed over the assumed building lifespan of 50 years. In other words, values of the initial embodied energy, delivered material quantities, replacement periods, and embodied energy coefficients were combined with direct and indirect energy associated with the induvial material manufacture. As before, non-material inputs related to material replacement over the lifespan was added. The embodied energy, multiplied by the number of replacements for each material was summed to find the total recurrent embodied energy for the case study villa. For the number of replacements required for each material the applied approach was by dividing the service life of the house by the service life of the material, then subtracting 1 which represents the material used in initial construction at Year Zero. Next, this was rounded up to the nearest whole number in order to complete the computation and infer those materials can only be replaced in whole numbers. Previous research shows further details that explains the application of the input-output-based hybrid analysis (Rauf & Crawford, 2015).

As stated earlier in the Introduction, this investigation is an extension of previous studies that applied the steps listed above. These studies broadly used the bill of quantities to calculate the life cycle embodied energy in various scenarios; however, the current emphasis is the "Building Assemblies". This is targeted at promoting the presentation and communication of the need for embodied energy research, and the results of the study to professionals in the building construction industry.

3. Results and Discussion

Broadly summarizing the results, the assessment showed that the embodied energy associated with the initial construction of the case study villa was found to be 7390.5 GJ (13.9 GJ/m^2). This value includes the energy embodied associated with material manufacturing, transportation, initial building construction, as well as supporting services. Additionally, the recurrent embodied energy consumed over the 50-years building service life was found to be 5690.01 GJ (10.7 GJ/m^2). The sum of these values gives the life cycle embodied energy of the case study villa which was found to be 13096.47 GJ (24.62 GJ/m^2). Thus, the initial and recurrent embodied energy were found to constitute 56% and 43% of the life cycle embodied energy, as shown in Figure 2.

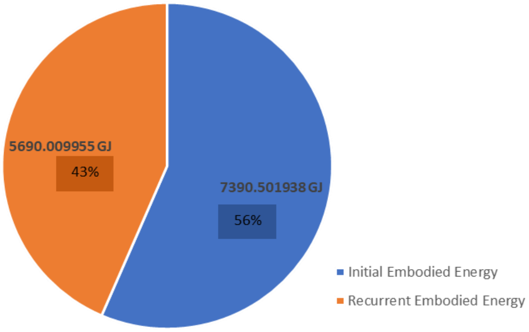

Fig. 3. Proportion of initial and recurrent embodied energy

Figure 3 suggests that material replacement over the building life span can consume almost as much embodied energy as that which was used in the initial construction. This finding reflects the need for proper design and material selection to minimize life cycle energy costs. Alternative building designs, materials specifications, and components installed may thus help in long-term life cycle expenses.

Figure 4 below shows the embodied energy associated with the various building assemblies used in the construction of the villa. For the initial embodied energy, the highest value was 2322.31GJ which was consumed by the Walls while the lowest was 330.38 GJ consumed in constructing the building's Frame Structure. This shows that although both assemblies are critical to the integrity of the construction, they do not have the same life cycle impact, and also suggests that the walls play a much larger role in both initial and recurrent embodied energy impacts. Although this may be due to a much larger area along with need to paint them many times during the life of building.

For recurrent embodied energy the assembly with the highest value was the Floor, which was 1193.2 GJ, although the Other building aspects -electrical, AC and sanitary consumed more (2254.58GJ). The assembly with the lowest recurrent embodied energy was the Frame Structure of the building which was considered as zero due to the fact that the building frame is presumed to last as long as the building service life and thus requires no replacement. There is therefore clear evidence to suggest that materials with longer service life have much less impact or contribution to recurrent embodied energy. This makes a case for material durability and longer lifespans without the need for replacement and repair.

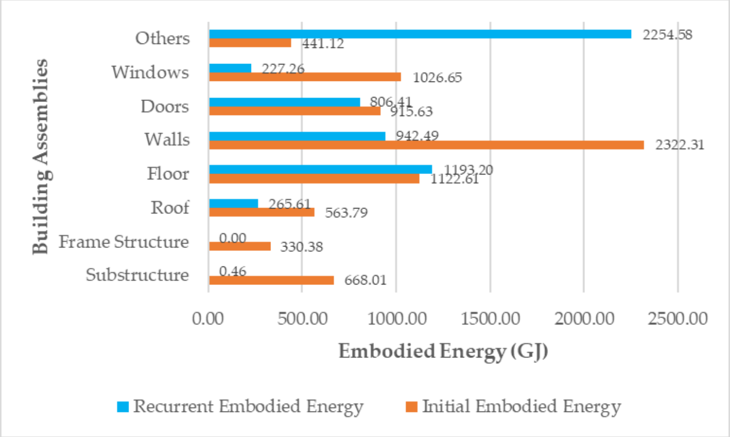

Fig. 4. Comparison of Initial vs Recurrent embodied energy of the case study house based on Building Assemblies

The current study focuses on only initial and recurrent embodied energies to approximate the life cycle embodied energy as other studies show the demolition embodied energy may be as low as 1% of the LCEE (Rauf, 2016;). Figure 5 below shows the LCEE for the villa in three comparative charts: for the initial, recurrent, and the life cycle embodied energies. Specifically focusing on the LCEE, the figure shows that of all the Building Assemblies, the highest consumer of embodied energy is the Walls (25%), followed by Floors (18%) and then Doors (13%).

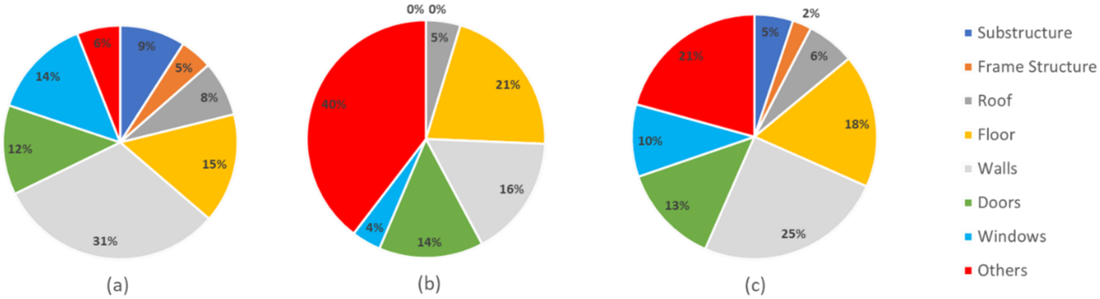

Fig. 5. (a)Initial, (b)Recurrent and (c) Life cycle embodied energy of the case study villa based on Building Assemblies

The results of the LCEE indicate that walls consume a significant amount of embodied energy, which warrants deeper investigation. Considering the area per square metre, the walls cover $1902.4m^2$ which is significantly more than the other assemblies, for example the total floor area was $532m^2$. However, the floors are responsible for 18% of the LCEE while the Walls are responsible for 25%. Thus, although the Wall area is almost 3 times the floor area, the LCEE contribution of the Walls is less than double LCEE of the Floor. The cause of this results may lie with the type of material used on the construction of both assemblies. Thus, this makes a case for further research to examine the embodied energy associated with materials which make up building assemblies. These results, however, clearly suggest that the Wall assembly provides the greatest opportunity to reduce life cycle embodied energy.

4. Conclusions

This research was conducted to assess the life cycle embodied energy impact of building assemblies in UAE villas, and to provide market-ready data that can be used in communicating the importance of embodied energy to practice professionals in the construction industry. A case study residential villa in the UAE was used in this investigation. The input-output hybrid analysis method was used in this study, as it is considered the most comprehensive and reliable embodied energy assessment method. Based on the building's architectural design, the findings show that the initial embodied energy was 56% of the LCEE and the recurrent embodied energy was 43%. The study also shows that comparing the life cycle embodied energy of the building assemblies, Walls were responsible for highest embodied energy (25%). The findings also showed that the floor and door assemblies were responsible for 18% and 13% respectively. This study helps in defining the focus for design review and remediation; showing professionals which components have the greatest impact in the long term and providing a guide to design specification for both the building and building assemblies.

References

Azzouz, A., Borchers, M., Moreira, J., & Mavrogianni, A. (2017). Life cycle assessment of energy conservation measures during early stage office building design: A case study in London, UK. Energy and Buildings, 139, 547–568.

Baird, G., Alcorn, A., & Haslam, P. (1997). The energy embodied in building materials-updated New Zealand coefficients and their significance. Transactions of the Institution of Professional Engineers New Zealand: Civil Engineering Section, 24(1), 46–54.

Birgisdottir, H., Moncaster, A., Wiberg, A. H., Chae, C., Yokoyama, K., Balouktsi, M., Seo, S., Oka, T., Lützkendorf, T., & Malmqvist, T. (2017). IEA EBC annex 57 'evaluation of embodied energy and CO2eq for building construction.' Energy and Buildings, 154, 72–80.

Birol, F. (2013). World energy outlook 2013. International Energy Agency Paris.

Crawford. (2008). Validation of a hybrid life-cycle inventory analysis method. Journal of Environmental Management, 88(3), 496–506.

Crawford, R. (2011). Life cycle assessment in the built environment. Routledge.

Crawford, R. H. (2014). Post-occupancy life cycle energy assessment of a residential building in Australia. Architectural Science Review, 57(2), 114–124.

Crawford, R. H., Czerniakowski, I., & Fuller, R. J. (2010). A comprehensive framework for assessing the life-cycle energy of building construction assemblies. Architectural Science Review, 53(3), 288–296.

Crawford, R. H., Czerniakowski, I., & Fuller, R. J. (2015). An early-stage design decision-support tool for selecting building assemblies to minimise a building's life cycle energy demand. Living and Learning: Research for a Better Built Environment: 49th International Conference of the Architectural Science Association, 457–466.

Crawley, D., Pless, S., & Torcellini, P. (2009). Getting to net zero. National Renewable Energy Lab.(NREL), Golden, CO (United States).

Danish Government. (2014). Strategy for energy renovation of buildings The route to energy-efficient buildings in tomorrow's Denmark. https://ec.europa.eu/energy/sites/ener/files/documents/2014_article4_en_denmark.pdf

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

Department of Economic Studies, U. A. E. (2020). THE ANNUAL ECONOMIC REPORT 2020 (No. 28; pp. 1–103).

https://www.moec.gov.ae/documents/20121/302471/English%20Version%20_MOE_Annual%20Report.pdf/e89802b5-b321-126f-ccae-62c2103cac5b

Dixit, M. K. (2017). Life cycle embodied energy analysis of residential buildings: A review of literature to investigate embodied energy parameters. Renewable and Sustainable Energy Reviews, 79, 390–413.

Dixit, M. K., Culp, C. H., Lavy, S., & Fernandez-Solis, J. (2014). Recurrent embodied energy and its relationship with service life and life cycle energy: A review paper. Facilities.

EIA. (2019). EIA projects nearly 50% increase in world energy usage by 2050, led by growth in Asia—Today in Energy—U.S. Energy Information Administration (EIA). https://www.eia.gov/todayinenergy/detail.php?id=41433

IEA, & UNEP. (2018). 2018 Global Status Report: Towards a Zero-Emission, Efficient, and Resilient Buildings and Construction Sector. Global Alliance for Buildings and Construction. Https://Www. Worldgbc. Org/Sites/Default/Files/2018% 20GlobalABC% 20Global% 20Status% 20Report. Pdf.

Kolokotsa, D., Rovas, D., Kosmatopoulos, E., & Kalaitzakis, K. (2011). A roadmap towards intelligent net zero- and positive-energy buildings. Solar Energy, 85(12), 3067–3084. https://doi.org/10.1016/j.solener.2010.09.001

Lolli, N., Fufa, S. M., & Inman, M. (2017). A parametric tool for the assessment of operational energy use, embodied energy and embodied material emissions in building. Energy Procedia, 111, 21–30.

Mayer, M., & Bechthold, M. (2018). Development of policy metrics for circularity assessment in building assemblies. ECONOMICS AND POLICY OF ENERGY AND THE ENVIRONMENT, 2017, 57–84.

https://doi.org/10.3280/EFE2017-001005

Mirabella, N., Roeck, M., Ruschi Mendes SAADE, M., Spirinckx, C., Bosmans, M., Allacker, K., & Passer, A. (2018). Strategies to improve the energy performance of buildings: A review of their life cycle impact. Buildings, 8(8), 105.

Nassar, K., Thabet, W., & Beliveau, Y. (2003). A procedure for multi-criteria selection of building assemblies.

Automation in Construction, 12(5), 543–560. https://doi.org/10.1016/S0926-5805(03)00007-4

Rauf, A. (2016). The effect of building and material service life on building life cycle embodied energy [PhD Thesis].

Rauf, A., & Crawford, R. H. (2013). The relationship between material service life and the life cycle energy of contemporary residential buildings in Australia. Architectural Science Review, 56(3), 252–261.

Rauf, A., & Crawford, R. H. (2015). Building service life and its effect on the life cycle embodied energy of buildings.

Energy, 79, 140–148.

Resalati, S., Kendrick, C. C., & Hill, C. (2020). Embodied energy data implications for optimal specification of building envelopes. Building Research & Information, 48(4), 429–445.

Silvestre, J. D., de Brito, J., & Pinheiro, M. D. (2014). Life-cycle impact 'cradle to cradle'of building assemblies.

Proceedings of the Institution of Civil Engineers-Engineering Sustainability, 167(2), 53–63. Treloar, G. J. (1998). Comprehensive embodied energy analysis framework. Deakin University.

Treloar, G. J., & Crawford, R. H. (2010). Database of embodied energy and water values for materials. Melbourne: The University of Melbourne.

Treloar, G. J., Love, P. E., & Holt, G. D. (2001). Using national input/output data for embodied energy analysis of individual residential buildings. Construction Management and Economics, 19(1), 49–61.

UAE Federal Competiveness and Statistics Authority. (2020). UAE Numbers (No. 2; pp. 1–48). https://fcsa.gov.ae/en- us/Documents/UAE%20Numbers%20En%202019.pdf

United Nations, Department of Economic and Social Affairs, & Population Division. (2019). World population prospects 2019—Highlights.

Wen, T. J., Siong, H. C., & Noor, Z. Z. (2015). Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: Case studies of residential buildings in Iskandar Malaysia. Energy and Buildings, 93, 295–302.