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Title:

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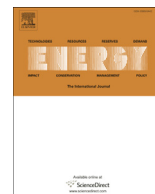
2015

Citation:

Rauf, A. & Crawford, R. H. (2015). Building service life and its effect on the life cycle embodied energy of buildings. *Energy*, 79 (1), pp.140-148. <https://doi.org/10.1016/j.energy.2014.10.093>.

Persistent Link:

<https://hdl.handle.net/11343/313677>



Building service life and its effect on the life cycle embodied energy of buildings



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ARTICLE INFO

Article history:

Received 23 April 2014

Received in revised form

26 September 2014

Accepted 31 October 2014

Available online 4 December 2014

Keywords:

Building service life

Life cycle embodied energy

Recurrent embodied energy

Life cycle energy analysis

ABSTRACT

The building sector is responsible for significant energy demands. An understanding of where this occurs across the building life cycle is critical for optimal targeting of energy reduction efforts. The energy embodied in a building can be significant, yet is not well understood, especially the on-going 'recurrent' embodied energy associated with material replacement and building refurbishment. A key factor affecting this 'recurrent' embodied energy is a building's service life. The aim of this study was to investigate the relationship between the service life and the life cycle embodied energy of buildings. The embodied energy of a detached residential building was calculated for a building service life range of 1–150 years. The results show that variations in building service life can have a considerable effect on the life cycle embodied energy demand of a building. A 29% reduction in life cycle embodied energy was found for the case study building by extending its life from 50 to 150 years. This indicates the importance of including recurrent embodied energy in building life cycle energy analyses as well as integrating building service life considerations when designing and managing buildings for improved energy performance.

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1. Introduction

In recent decades, buildings have become a critical factor in efforts to reduce global greenhouse gas emissions. The building sector is responsible for significant energy demand globally which results in greenhouse gas emissions along with the depletion of energy resources. Buildings account for 30–40% of energy use and greenhouse gas emissions in many countries around the world with a significant share of this attributable to residential buildings [1,2]. This situation is further exacerbated with the use of fossil fuels as the main source for energy production around the globe. All fossil fuels emit carbon dioxide to the atmosphere when burned. The carbon dioxide helps trap heat in the atmosphere, a main contributor to the potential warming of the Earth [3]. The previous decade was one of the warmest in recorded history and carbon dioxide concentrations have now reached over 401 ppm (parts per million) [4], well above what is considered to be the upper safety limit for atmospheric CO₂, of 350 ppm. In the last century, world population has grown rapidly along with an increase in life expectancy and per capita energy use [5]. It is expected that this trend

will continue. It is therefore of critical importance that energy demand within the built environment is addressed to avoid further degradation of the natural environment.

These impacts are not limited to the energy use associated with building operation, but also include energy use associated with all stages of a building's life. Previous studies have shown the significance of the energy required for the operation of buildings as well as the energy embodied in initial building construction [6–9]. Fewer studies have analysed the recurrent embodied energy involved in maintenance and refurbishment activities over a building's life [10–13]. Recurrent embodied energy associated with the replacement of building materials and components is directly affected by the service life of building materials as well as the service life of buildings themselves. However, the significance of building service life and recurrent embodied energy on the life cycle energy of a building is not well understood. The aim of this study was to determine what effect variations to the service life of buildings has on their life cycle embodied energy demand. It was hoped that this would provide new evidence of the importance of integrating building service life considerations in the initial design process and facilities management phase, in order to select the most appropriate construction materials and methods to reduce energy demand over the building life cycle.

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2. Background

2.1. Life cycle energy analysis

The approach used to quantify the energy demand of a building across its life is known as LCEA (life cycle energy analysis). This approach is based on the general principles of LCA (life cycle assessment) as outlined in ISO 14040 [14] and is used to quantify the effects of a product or process on the environment during the different stages of its life cycle [15]. The system boundary for a life cycle energy analysis of a building typically includes the energy demand associated with the manufacturing, construction, operational and end-of-life phases of the building. This includes the initial embodied energy (i.e. the energy required to manufacture, supply and install the materials in a building's initial construction) along with the energy embodied in subsequent replacement and maintenance of components or materials throughout a building's life (known as its recurrent embodied energy). Previous studies have shown the importance of embodied energy as well as operational energy. In a study by Huberman and Pearlutter, embodied energy of a reinforced concrete building was found to represent 60% of its overall life cycle energy demand [16]. Another study by Crawford [10] on residential construction assemblies shows that the energy embodied in material replacement of each assembly can represent between 7 and 110% of their initial embodied energy.

While methods and tools for the quantification of building operational energy requirements are well established and understood, there is much less consensus and understanding on the techniques that can and should be used for quantifying embodied energy. Process analysis, I–O (input–output) analysis and hybrid analysis are the most commonly used methods. There can be considerable difference between embodied energy values calculated using each of these methods, mainly due to the extent of system boundary completeness and source of inventory data. As outlined by Treloar and others [7,17–21], each of these methods has its own strengths and limitations, but hybrid analysis is generally considered the preferred approach for embodied energy analysis due to its systemic completeness and use of reliable data, where available [20]. In a hybrid analysis, process and I–O data are combined to take advantage of the strengths while minimising the limitations of each approach. Process data is used to maximise reliability and I–O data to maximise completeness [22]. A hybrid approach provides a more reliable assessment than a pure I–O analysis as it relies on process specific data for the processes for which it is available. Process-based hybrid analysis involves the calculation of delivered material quantities for an individual product and the completion of the upstream system boundaries associated with these materials with I–O data [17,23]. Process and I–O data are integrated at a material level to form hybrid material energy coefficients [18,26]. The system boundary of a process-based hybrid analysis or hybrid material energy coefficients has similar limitations to those of a process analysis as many of the direct inputs to a process (such as construction) can be excluded [24]. An I–O-based hybrid analysis addresses the truncation issues associated with a process-based hybrid analysis by using I–O data to fill in any remaining data gaps [23,25]. I–O-based hybrid analysis is considered more complete and less data and labour intensive [26]. A study by Crawford [17] on a residential building and other household products shows that the process analysis values can be up to 87% lower than equivalent I–O-based hybrid analysis values. The hybrid model used within this study is based on process data sourced from the Australasian SimaPro LCI database [27] and an I–O model of the Australian economy based on data from the Australian Bureau of Statistics [28,29].

2.2. Building service life

Building service life is the period of time in which a building is in use. Building service life data can help to decide the type and frequency of activities required to maintain, repair and replace building materials and systems [30]. It can also affect the extent of recurrent embodied energy required over the building's life. By increasing the service life of a building, the number of replacement cycles for materials is increased resulting in an increase in recurrent embodied energy. On the other hand, a reduction in the service life of a building may result in more frequent replacement of the whole building which will increase the initial embodied energy demand over a specific period of time [31]. Studies have shown that different assumptions made for the building service life may affect the most appropriate selection of materials. For example, a building designed for 100 years or more may warrant the use of highly durable and long-lasting materials. In situations where a building is designed for a much shorter life (for temporary or semi-permanent structures, for example) the use of highly durable materials may be seen as an over-investment in embodied energy and a more appropriate focus may be on design for deconstruction to maximise material reuse and/or recyclability [32]. In a study of the environmental impacts of the heating and ventilation systems in residential buildings, Blom et al. found that extending the service life of these systems can help in reducing the energy required in their replacement [33]. However, they also found that the ability to replace it with a system of much higher efficiency sooner, might be a more preferred option in some cases. This may especially be the case where technological advancements over time can result in considerable operational efficiency improvements. This reinforces the need to consider building energy demand from a life cycle perspective.

Due to the potential importance of building service life on the life cycle energy demand of buildings, service life planning must play a vital role in achieving more sustainable buildings. There are several approaches to predict the service life of a building or its components. The first approach involves the use of structural engineering to estimate a material's structural integrity and fatigue in relation to physical loading, on-going chemical reactions and degradation over time [34]. However, this approach often excludes the effect of human activities on the service life of a material or building component (e.g. frequency of maintenance).

The ISO 15686-1 [35] and ISO 15686-2 [36] standards deal with service life planning and address the service life of a building or a building component. These standards assist in the decision processes relating to value engineering, cost planning, maintenance planning and minimising environmental impact. They prescribe a factorial approach, known as the 'factors method', to determine the potential service life of a building or component, based on knowledge about materials and building technology. The factors method is a method by which knowledge on service life from a known reference condition is transferred to a project specific condition [37]. This approach starts with a reference service life and is based on the following seven factors that are considered to be the key factors determining the service life of a building: quality of materials; design level of a component's or an assembly's installation; installer skill level; indoor environment (e.g. whether the component will be utilised in a wet area such as a bathroom or kitchen, or in a relatively stable indoor environment); outdoor environment (e.g. coastal climate, hot and dry climate etc.); in-use condition and maintenance level. However, due to the subjective nature of qualitative descriptions of factors quantities, many have questioned the accuracy and objectivity of this approach [34].

The service life of a building may also be effected by various sociological, economic and cultural factors including urban

development plans and policies [31,38]. The changing needs of occupants or owners over time may result in the demolition of a building, ending its service life before it would otherwise cease to be serviceable. Several other factors such as heritage considerations or tougher regulations for new construction can also force decision makers to prolong the service life of a building through significant refurbishment and repairs. In this scenario, use of empirical data is arguably considered as a reliable approach to service life prediction. However, the approach of using empirical data can present challenges in terms of the time and cost involved as well as the relevance of data over time [34].

3. Research approach

In order to determine what effect a variation in service life would have on the life cycle embodied energy demand of a residential building, the total life cycle embodied energy associated with a selected case study building was quantified. This involved calculating and combining the initial and recurrent embodied energy of the

building. A number of building service life scenarios were developed and the life cycle embodied energy demand of the selected case study building was recalculated. The service life scenarios considered ranged up to 150 years, considered to be around the maximum likely life expectancy of the case study building. The functional unit used for the study is GJ of energy for the provision of housing over 150 years. A variety of metrics have been used for this functional unit, including: GJ of energy over 150 years, GJ of energy per m² GFA (gross floor area) over 150 years, GJ of energy per annum over 150 years and GJ of energy per m² GFA per annum over 150 years.

3.1. Case study building

A 291.3 m² single-storey detached house located in Melbourne, Australia was used as the case study for this analysis (Fig. 1). The house consists of a concrete slab floor and brick veneer external walls. The structural framing is of traditional timber stud construction clad with plasterboard internally. Wall finishes include ceramic tiles in all wet areas and paint to all plasterboard. The roof



Fig. 1. Floor plan and front elevation of the case study house.

is timber-framed with softwood trusses, and clad with concrete roof tiles along with steel gutters, down pipes and fascias. The windows are double-glazed and aluminium-framed. Floor coverings for bedrooms and main living areas are nylon carpet and all other areas are finished with ceramic tiles. A breakdown of the main material quantities for the house is provided in [Appendix A](#).

3.2. Calculating life cycle embodied energy

3.2.1. Initial embodied energy

An I–O-based hybrid analysis was used to quantify the embodied energy associated with the initial construction of the case study house. Delivered quantities of materials used in the construction of the house (Q_m) were multiplied by the hybrid embodied energy coefficient of the respective material (EC_m), obtained from [18] and compiled according to [26], to determine the process-based hybrid embodied energy of the house. To complete the system boundary, the energy embodied in non-material inputs (i.e. the energy associated with the on-site construction process, transport of materials to site and the provision of finance, insurance etc. needed to support the construction process) was calculated, referred to as the remainder of energy inputs. This remainder was calculated with the use of a disaggregated energy-based I–O model of the Australian economy as no easily accessible process data exists for these processes. Developed by Treloar [23], this model provides values for the specific energy requirements associated with each and every individual product and process within each of Australia's economic sectors. The material-related I–O pathways (TER_m) covered by the material energy coefficients (EC_m) were identified within the I–O model and subtracted from the total energy requirement of the residential building sector (TER_{rb}) (0.01063 GJ/\$1). The remaining I–O pathways were converted from GJ/\$1 to GJ for the entire house based on the estimated construction costs of the house, as described in [18], and added to the process-based hybrid embodied energy figure.

$$IEE_h = \sum_{m=1}^M (Q_m \times EC_m) + \left(TER_{rb} - \sum_{m=1}^M TER_m \right) \times C_h \quad (1)$$

where IEE_h is the Initial embodied energy of the house, in GJ; Q_m is the Quantity of material, m ; EC_m is the Hybrid embodied energy coefficient of material, m , in GJ per unit; TER_{rb} is the Total energy requirement of the Residential building sector, in GJ per dollar; TER_m is the Total energy requirement of the I–O pathways covered by the material energy coefficients, in GJ per dollar; and C_h is the cost of the house, in dollars.

3.2.2. Recurrent embodied energy

The recurrent embodied energy of the house was calculated based on the number of times each individual material would likely be replaced during the service life of the house. Average material service life figures from the literature were assumed for the analysis (see Table 1 in [13]).

The embodied energy associated with the materials being replaced over the life of the house was calculated as per the initial embodied energy of the house. The delivered material quantities (Q_m) associated with each replacement were multiplied by the respective material embodied energy coefficients (EC_m). To complete the system boundary, the remainder was then calculated as per the initial embodied energy calculation, for each material being replaced. As only specific processes are required for the replacement of individual materials (as opposed to the broader range of processes associated with the materials in the initial construction of the house), it was also necessary to subtract energy requirements

associated with those processes that were not associated with the replacement of individual materials ($TER_{i \neq m}$) when calculating the remainder. This was to avoid including the embodied energy of materials and processes that are required for the initial construction of the house, but not for on-going maintenance and repair (inputs of steel or concrete when carpet is replaced, for example). The remainder then includes only energy for those inputs actually required for material replacement. Energy associated with the removal of old materials is not included as numerous studies have shown that these requirements are insignificant.

The energy embodied in each material was then multiplied by the number of replacements for that material over the life of the house, and summed to determine the total recurrent embodied energy associated with the house. The exact number of replacements required for each material was determined by dividing the service life of the house (SL_h), by the average service life of the material (SL_m), subtracting 1 (representing the material used in initial construction at Year Zero) and rounding up to the nearest whole number (to reflect the fact that materials can only be replaced in whole numbers). Credit for any embodied energy value that remains in any materials after their replacement or at the end of the life of the house is given to the building in which those materials are eventually reused.

$$REE_h = \sum_{m=1}^M \left[\left(\left\lceil \frac{SL_h}{SL_m} \right\rceil - 1 \right) \times [(Q_m \times EC_m) + (TER_{rb} - TER_m - TER_{i \neq m}) \times C_m] \right] \quad (2)$$

where REE_h is the Recurrent embodied energy of the house, in GJ; TER_m is the Total energy requirement of the I–O pathway representing material m , being replaced, in GJ per dollar; $TER_{i \neq m}$ is the Total energy requirement of all I–O pathways not associated with the installation or production process of material m , being replaced, in GJ per dollar; and C_m is the cost of the material, m , in dollars.

3.3. Building service life scenarios

A building service life range of 1–150 years was used for the building service life scenarios (i.e. 150 scenarios) to analyse the effect of variations to building service life on the life cycle embodied energy of the case study house. These building service life scenarios can be considered to represent the potential effect of different climatic and geographic conditions on the service life of a building. The recurrent embodied energy for each scenario was calculated by replacing SL_h in (2) with the service life value (1–150).

Selection of an appropriate AP (assessment period) for the life cycle embodied energy assessment is necessary to determine the effect of building service life on life cycle embodied energy associated with the provision of housing over a longer period of time than the service life of one individual building. Comparison between initial and recurrent embodied energy of the case study house over a specific assessment period assists in identifying the ideal building service life, and the time at which energy associated with maintenance becomes so high that demolition becomes a potentially preferred option. An assessment period of 150 years was selected for this study. In the case of a building service life of one year over an assessment period of 150 years, it is assumed that the building will be demolished and rebuilt one year after its initial construction. Therefore, in this case, the total initial embodied energy requirement for the provision of housing for a period of 150 years would be 150 times the initial embodied energy of the house. In the case of a building with a service life of 50 years over an

assessment period of 150 years, it is assumed that the building is demolished and rebuilt 50 years after its initial construction. In this case, the total initial embodied energy requirement for the provision of housing over a period of 150 years would be three times the initial embodied energy of the house (AP/SL_h). Building materials and components with a service life of less than the building service life will be replaced during the life of the building, resulting in a requirement for recurrent embodied energy. The number of replacements will depend upon the actual service life of each material.

3.4. Assumptions and uncertainty

The accuracy and reliability of results from the I–O-based hybrid embodied energy analysis is dependent on a number of factors including the age, source and completeness of process and I–O data used. Although this approach provides a systemically complete analysis of the embodied energy of the main construction materials, it is prone to random and systemic errors. This problem is not limited to the errors associated with the embodied energy data used to represent current practice, but also the likelihood that the energy intensity, energy mix and manufacturing processes are likely to change over the next 150 years. As such, the embodied energy associated with materials used in the future is unpredictable and likely to be significantly different than for those materials used today. Therefore, the following assumptions were made:

- Energy mix and intensities were considered constant over the next 150 years.
- Standard building construction methods and materials were assumed to be the same over the next 150 years.
- Embodied energy associated with demolition and removal of building materials was assumed to be insignificant, based on [39], and excluded from the study.
- The service lives for the structural components were assumed to be equal to the service life of the house.

In order to account for the potential errors associated with the data used within the study, standard error ranges were used to conduct a sensitivity analysis and provide an indication of the likely variation in the findings. Process data is typically considered to have an error range of ± 20 per cent with I–O data varying by as much as ± 50 per cent, compared to reality [18]. Because the results of the study are based on hybrid figures, containing both types of data, (3) was used to determine the overall uncertainty associated with the study findings.

$$AUH = SP \times AUP + SIO \times AUIO \quad (3)$$

where AUH is the average uncertainty of the hybrid embodied energy figures; SP is the share of process data within the hybrid embodied energy figure (%); AUP is the average uncertainty of process data (20 per cent); SIO is the share of I–O data within the hybrid embodied energy figure (%); and AUIO is the average uncertainty of I–O data (50%). SP and SIO are based on the extent of process data available for each material and the embodied energy value of each material as a proportion of the total embodied energy of the house. The process data available for each material differs and depends on the comprehensiveness of the individual material's system boundary within the LCI database. To determine SP, all individual material quantities within the house were multiplied by their respective process-based energy coefficient from the Australasian SimaPro LCI database. These values were then summed and divided by the total hybrid embodied energy of the house to

determine SP. SIO is the remaining proportion of the hybrid embodied energy value (i.e. $SP + SIO$ is equal to 100%).

4. Results and discussion

This section presents the results of the life cycle embodied energy analysis of the case study house for each of the building service life scenarios to demonstrate the effect of building service life variability on the life cycle embodied energy demand of a building.

4.1. Initial embodied energy

The embodied energy of the initial construction of the case study house was found to be 3891 GJ (13.4 GJ/m^2). The floor assembly (concrete slab on ground, carpet and ceramic tiles) accounts for the highest proportion (45%) of the initial embodied energy followed by wall (external bricks, softwood timber studs and plasterboard) and roof (concrete roof tiles, softwood timber trusses, fibreglass insulation and plasterboard ceiling) assemblies with a share of 16% and 13%, respectively.

The initial embodied energy of the house for each of the building service life scenarios from 1 to 150 years was calculated over an assessment period of 150 years. For a building service life of one year, the accumulated initial embodied energy over a period of 150 years was found to be 583,717 GJ (2004 GJ/m^2), which assumes the house is completely replaced each year. For a building service life of 25, 50 and 100 years, the cumulative initial embodied energy over 150 years was found to be 23,349 GJ, 11,674 GJ and 7783 GJ, respectively. At the other extreme, a building service life of 150 years results in a total initial embodied energy over 150 years equal to the initial embodied energy of the house (i.e. 3891 GJ). Fig. 2 shows the total initial embodied energy of the case study house for the building service life range of 1–150 years for the assessment period of 150 years. It is important to note that values in this graph must be considered in the context of this study alone as the values will vary depending on the assessment period used. However, the trend is important to note due to the considerable difference in values for different building service life scenarios. For example, there is a dramatic drop in the cumulative initial embodied energy demand over the first 10 years and beyond around 30 years there is a limited benefit in prolonging the service life of a building to minimise the embodied energy associated with its initial construction. However, while 150 year cumulative initial embodied energy is higher for buildings with a lower service life, it is expected that their recurrent embodied energy will be lower than for a building with a longer service life.

4.2. Recurrent embodied energy

The recurrent embodied energy associated with the case study house was calculated for each building service life scenario, from 1 to 150 years. All as-built materials were assumed to be replaced with the same materials at the end of their service life. For the assessment period of 150 years and a building service life of 75 years, recurrent embodied energy was calculated for the building service life and multiplied by the number of building service life periods within the assessment period ($\downarrow(AP/BSL)$). In the case where the number of building service life periods was not a whole number, recurrent embodied energy for the remaining years was also added. This process was repeated for each building service life scenario.

For the building service life range of 1–10 years, none of the materials of the house were replaced resulting in no recurrent embodied energy demand (i.e. all materials had an assumed service life of at least 10 years). For a building service life of 11 years,

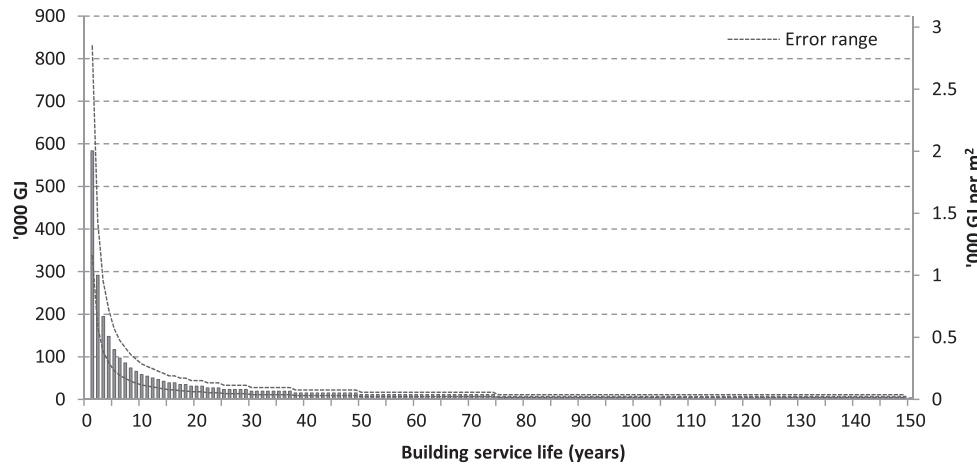


Fig. 2. Cumulative initial embodied energy of the case study house, by building service life over a period of 150 years.

recurrent embodied energy was found to be 3991 GJ over 150 years (Fig. 3). For a building service life of 11–20 years, total recurrent embodied energy decreases each year with 2149 GJ required at a service life of 20 years (paint and carpet, with an assumed service life of 10 years, are the only materials with a service life less than 20 years). At a building service life of 21 years recurrent embodied energy jumps dramatically to 5624 GJ. At a building service life of 101 years, recurrent embodied energy was found to decrease to 7123 GJ from 9090 GJ just one year earlier. Recurrent embodied energy remains unchanged for the next four years due to no material replacements during this time. This suggests that if the house reaches the age of 101 years, embodied energy value can be maximised by prolonging the building service life to 105 years. This phenomenon is visible at many other points throughout the assessment period and suggests that decisions regarding complete building replacement should be made immediately before rather than after any material replacement occurs. The specific building service life at which phenomenon like this occur will vary in reality for this and other buildings based on a number of factors, not least of which is the predicted and most importantly, actual service life of materials.

While the proportion of recurrent embodied energy by material varies between service life scenarios, an example of this breakdown is shown in Fig. 4 for building service lives of 50, 100 and 150 years.

This shows that paint and carpet represent the highest proportion of recurrent embodied energy requirements for the house, mainly due to the high frequency of replacement compared to other materials. ‘Other’ includes items such as appliances, sanitary ware, heating system, hot water system, light fittings and exhaust fans. As expected, in most cases the recurrent embodied energy associated with each material increases as the service life of the house increases. While minimising this recurrent embodied energy is of considerable importance, it must be considered in the context of its effect on the building’s initial embodied energy. A reduction in recurrent embodied energy will often be the result of the use of more longer-lasting, durable materials and this can come at the expense of a higher energy requirement for initial material manufacture in some cases (for example, aluminium-framed windows require less on-going maintenance and thus recurrent embodied energy than timber-framed windows, but also require more embodied energy in their initial manufacture).

4.3. Life cycle embodied energy

Life cycle embodied energy was calculated by adding the initial and recurrent embodied energy of the house for each service life scenario, over a period of 150 years. For a building service life of 1 year, the life cycle embodied energy associated with the provision

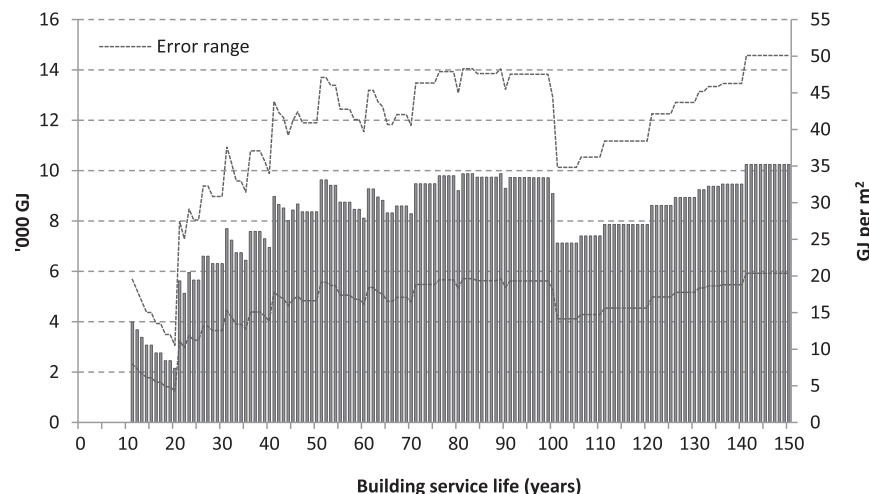


Fig. 3. Recurrent embodied energy of the case study house, by building service life over a period of 150 years.

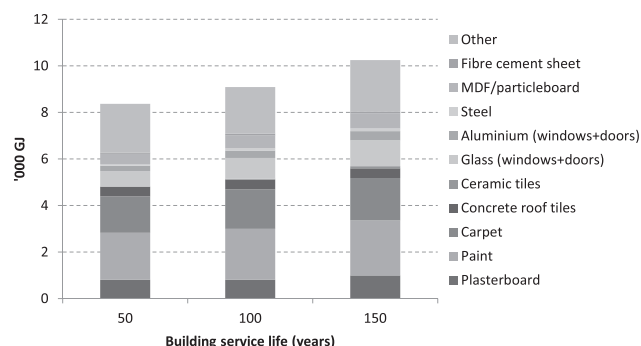


Fig. 4. Recurrent embodied energy of the case study house for a 50, 100 and 150 year building service life over a period of 150 years, by material.

of housing over a period of 150 years was found to be 583,717 GJ (2004 GJ/m²), based on the complete replacement of the house every year. Life cycle embodied energy decreases at a significant rate as the service life of the house increases to 40 years, down to 22,518 GJ. It then continues to decrease, but at a much slower rate before trending upwards again after a building service life of 105 years, due to an increasing demand for recurrent embodied energy. For a building service life of 150 years, the life cycle embodied energy of the house was found to be 14,139 GJ (48.5 GJ/m²). This represents a dramatic difference (a 98% reduction) in embodied energy requirements over a 150 year period attributable to variations in building service life alone (Fig. 5).

The variation in life cycle embodied energy for building service life scenarios greater than 50 years is relatively insignificant considering the error range associated with the findings ($\pm 42\%$). Despite the potential errors, there is still a downward trend in life cycle embodied energy for a building with a longer service life.

Fig. 6 shows the annual life cycle embodied energy of the case study house, which was calculated by dividing the life cycle embodied energy value by the corresponding building service life value. This shows that the annual life cycle embodied energy of the house decreases with an increase in service life up to a building service life of 105 years at which point it begins to increase gradually through to a building service life of 149 years. These increases are relatively insignificant though considering the potential variation in values demonstrated by the error range.

Although operational energy was not included in the scope of this study, the findings from a study by Crawford [40] based on the

same house, provide evidence of the significance of embodied energy as a proportion of the total life cycle energy of the house. In the study, annual primary operational energy was calculated based on actual energy bills over three years and found to be 86 GJ per annum. This results in life cycle embodied energy accounting for 60% of the total life cycle energy of the house over a period of 50 years. For a building service life of 100 and 150 years, life cycle embodied energy was found to account for 54% and 52% of total life cycle energy, respectively. The smaller decrease in the proportion of embodied energy from a building service life of 100–150 years is due to an increasing demand for energy for maintenance and replacement during this time.

5. Conclusion

This study aimed to determine what effect variations in the service life of buildings would have on their life cycle embodied energy demand. A case study house located in Melbourne, Australia was used for this analysis. The life cycle embodied energy of the house for a building service life range of 1–150 years over a period of 150 years was calculated using a comprehensive I–O-based hybrid assessment approach.

The study has shown that a variation in the service life of buildings can have a significant effect on their annual and life cycle embodied energy demand. Compared to the building service life of 50 years, annual and life cycle embodied energy demand decreased by 14%, 16%, 18% and 29% for the building service lives of 75, 100, 125 and 150 years, respectively. This shows that despite the additional recurrent embodied energy requirement (a 22% increase for a building service life of 150 years compared to one of 50 years), the longer a building lasts, the lower its annual life cycle embodied energy demand. This is a result of the considerable reduction in initial embodied energy demand associated with a decreasing number of whole building replacements. Initial embodied energy associated with the complete replacement of a building represents a large demand for energy within a very short period of time. The study shows that this situation can be avoided by maximising the life of the existing building and its constituent materials as long as possible. The decrease in annual life cycle embodied energy demand for building's with a longer service life was also found in a study by Fay et al. [11]. They found that for a residential building with a service life of 75 years, annual life cycle embodied energy decreased by 15% compared to a building service life of 50 years. The decrease was 25% for a service life of 100 years.

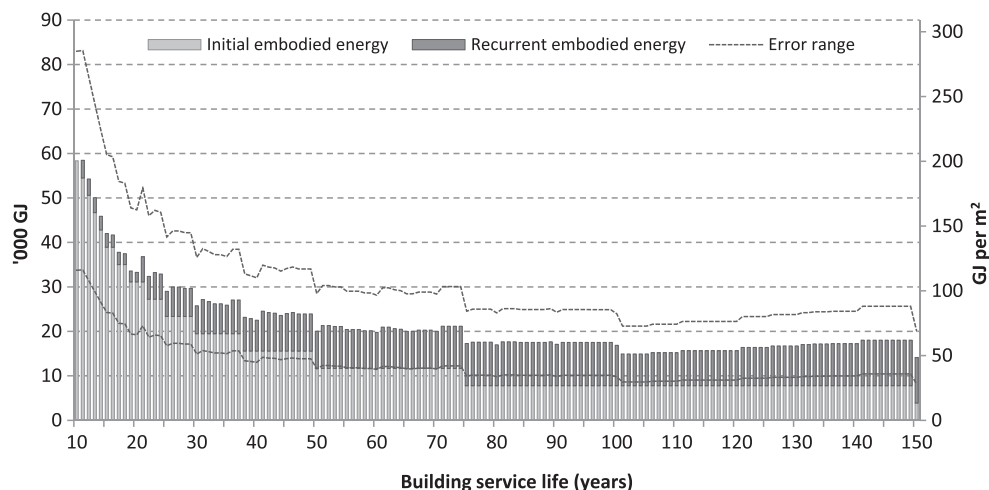


Fig. 5. Life cycle embodied energy of the case study house, by building service life (10–150 years) over a period of 150 years.

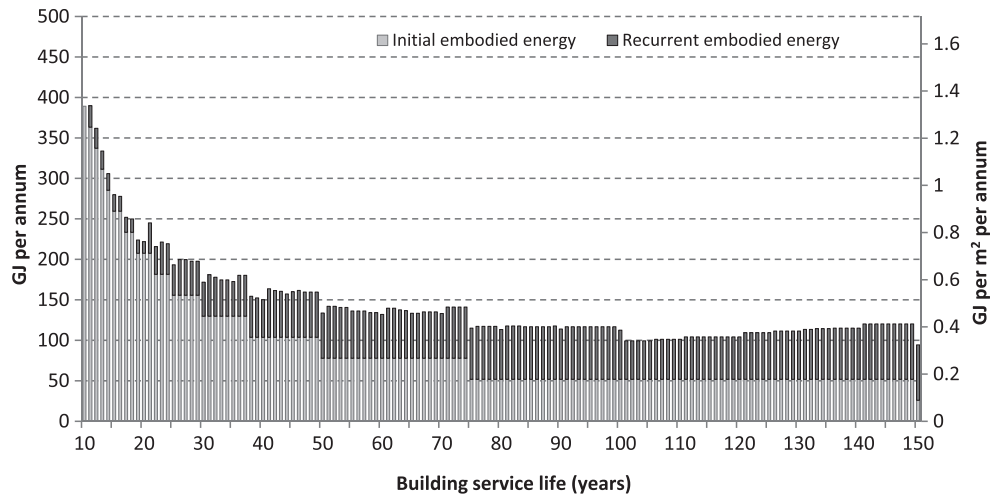


Fig. 6. Annual life cycle embodied energy of the case study house, by building service life (10–150 years) over a period of 150 years.

Another major finding of this study is the significance of the embodied energy proportion of the life cycle energy associated with the house. The 50–60% of life cycle energy attributable to embodied energy is considerably higher than the range of 10–20% found for 46 studies of residential buildings presented by Ramesh [41]. The use of the I–O-based hybrid approach for the calculation of embodied energy, with its broader system boundary, is one of the main reasons for this higher embodied energy proportion. The other major reason for this is that the energy bills for the house indicate that it is being operated much more efficiently than the typical house built to current energy efficiency regulations. The way in which occupants use a building and the type and efficiency of the equipment used can have a considerable influence on its total operational energy demand. Other reasons include the difference between the scope and location of these studies and the materials and service life values used.

The integration of building service life considerations in the design process, including the appropriate selection of materials and timely maintenance and repair, is critical for ensuring that the embodied energy demands of buildings and associated environmental consequences are kept to a minimum. To better inform environmental decision-making by building designers, owners and managers, there is also a need for knowledge on how the service life of individual building materials affects the life cycle embodied energy and environmental performance of buildings and further research in this area is needed.

5.1. Limitations

This study focusses solely on the embodied energy implications of variations to building service life. While it does briefly highlight the relationship to operational energy demand for the case study house, it is crucial that any decisions made that aim to reduce the energy demand of buildings be based on a life cycle approach, considering all demands for energy across the building life cycle. This is important to ensure that energy demands aren't inadvertently shifted from one area to another.

The location of a building, construction materials and systems used, material manufacturing processes, fuel type and source and other factors will influence its total energy demand and variations in any of these factors has the potential to vary the findings of this study. The applicability of the study findings to other buildings is hence limited to providing useful direction in minimising energy

demand rather than identifying how energy is being used across the various life cycle stages of these buildings.

Acknowledgements

The authors acknowledge the anonymous reviewers of previous versions of this paper and their contribution to improving the quality of the final paper.

Appendix A. Material quantities, embodied energy coefficients and service life values for the case study house

Material	Measured quantity	Embodied energy coefficient (GJ/unit)	Service life (years)
Concrete 20 MPa	51.78 m ³	4.44	Lifetime
Steel	5.18 t	85.46	Lifetime
Concrete roof tiles (20 mm)	378.83 m ²	0.251	40
Clay bricks	92.58 m ²	0.56	Lifetime
Glass (4 mm)	96.99 m ²	1.73	25
Aluminium (windows)	0.28 t	252.6	25
Hardwood timber	0.78 m ³	21.33	Lifetime
Softwood timber	19.19 m ³	10.93	Lifetime
Carpet (nylon)	141.41 m ²	0.683	10
Paint (water-based)	1350.90 m ²	0.096	10

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