Assessment of Embodied Energy: The Missing Piece -The Recurring Embodied Energy

TamilSalvi Mari
Ed.D., Senior Lecturer., School of Architecture, Building & Design, Taylors's University, Lakeside Campus,
Petaling Jaya, Selangor, Malaysia.
TamilSalvi.Mari@taylors.edu.my

Sivaraman Kuppusamy
Ed.D., Lecturer., School of Built Environment,
University of Reading Malaysia, Iskandar Puteri,
Johor Darul Takzim, Malaysia.
s.kuppusamy@reading.edu.my

Sujatavani Gunasagaran
Ed.D., Senior Lecturer., School of Architecture, Building & Design, Taylors's University, Lakeside Campus,
Petaling Jaya, Selangor, Malaysia.
sujatavani.gunasagaran@taylors.edu.my

Abstract **- The existing buildings account for approximately 40% of the world's total primary energy consumption and 24% of the world's CO^2 emissions. Buildings demand energy in their life cycle right from its pre-construction to end use phase. Studies on the total energy use during the life cycle are needed to identify phases of major energy use and to develop strategies for its reduction. Energy consumed by building are in two main categories, operational energy and embodied energy. The embodied energy is the total of initial and recurring embodied energy. The embodied energy is significant from a life-cycle perspective and there are substantial amount of studies conducted to evaluate the embodied energy in residential buildings but most of these studies concentrates on assessment of the initial embodied energy, while assuming the recurring embodied energy as insignificant. Therefore, this study discusses the obvious gap in the Life Cycle Energy Assessment literature, in that much of it only focuses at initial embodied energy and pays little or no attention to recurring embodied energy associated with the continual replacement and maintenance of buildings. As such, this paper presents a study on embodied energy analysis considering both the initial and recurring embodied energy in typical linked double story terraced houses over a 50 years' building service life. The findings from the study provided an insight into embodied energy the houses and the significance of recurring embodied energy in contributing towards the energy demand. The embodied energy of the houses ranged from 8.05 to 9.85GJ/m², with the average of 8.95GJ/m² while, the recurrent embodied energy ranged from 2.37 to 3.49GJ/m² with the average of 2.93GJ/m². The average recurrent embodied energy equates to 33% of total embodied energy and this component can significantly influence the life cycle embodied energy. The study also identified building materials with significant potential for reduction in embodied energy demand.**

Keywords: Embodied energy, recurring embodied energy, life cycle assessment

I. INTRODUCTION

The existing buildings account for approximately 40% of the world's total primary energy consumption and 24% of the world's $C0^2$ emissions [1]. The environmental impact from this sector is significant and globally efforts are being taken by industry professionals, researchers, and academia to mitigate the impact. The situation is the same for Malaysia, with most of its population concentrated in cities. In the year 2016, the Malaysian construction sector recorded moderate growth at 7.4% [3].

This is due the rapid rate of urbanization that has increased the demand in housing and energy and it is a significant factor in increasing the impacts of global warming. While accommodating its population growth and the issues associated with housing needs, Malaysia is committed to reducing its carbon emission up to 40% by the year 2020 [4]. At present, Malaysia is ranked 30th in the world for countries that have the highest amount of carbon emission. Most of the energy consumed by the construction and building sector, be primary or secondary energy are generated using fossil fuels mainly coal and natural gas. In working towards the 2020 carbon emission reduction, in the construction industry particularly, efforts are being taken by industry professionals in reducing energy consumption in the housing sector by promotion of improved architectural designs, use of passive building elements and low energy materials and application of energy efficient equipment. The building life cycle demands energy throughout its life cycle starting from pre-construction phase, to construction, operation, and end use phase. In understanding, the demand of energy and its impacts life cycle energy assessment (LCEA) is often used. Application of LCEA for building is significant for formulating strategies to achieve reduction in primary energy use of the buildings and to control emissions [5].

Most studies in energy and building often concentrates on energy used in the operational phase of a building ignoring the fact that a significant amount of energy consumed during the pre-construction and construction phase. The energy required to operate a building over its life greatly overshadows the energy attributed to the products used in its construction and the focus in energy conservation efforts are more towards the building operating systems [6], [7]. The existing energy studies are focused more on operational energy for different climatic zones whilst, studies on embodied energy has received much lesser attention [8]. The embodied energy (EE) is significant from a life-cycle perspective and there are substantial amount of studies conducted to evaluate the embodied energy (EE) in residential buildings or houses, however most of these studies concentrates on assessment of the initial embodied energy (EE_i)

whilst, assuming the recurring embodied energy (EE_r) as insignificant. Though embodied energy contributes only 10–20% to life cycle energy, opportunity for its reduction should not be ignored [9]. Similarly, most of the building studies in Malaysia are mainly focused on the impact assessment of different materials and the benefit of integration of an industrialized building system (IBS) to a conventional construction system [10]. There are substantial amount of studies that have revealed the significance of the building operational energy and energy embodied in initial building construction [10]. Somewhat, fewer studies have been conducted to analyze the recurrent embodied energy that occurs due to maintenance and refurbishment activities throughout the service life of a building [11]. Mari [6] conducted a study on five types of terraced houses with common building materials in Malaysia, to identify materials that contributed significantly to the embodied energy and suggested alternatives for it. However, the study had limitations due to it only considered the initial embodied energy (EE_{mi}) of materials. Recurrent embodied energy (EE_r) is the quantity of energy associated with manufacturing the materials and products that are needed for the replacement, maintenance and repair of building materials and components throughout a building's service life and is directly affected by the service life of building materials [11], [12]. However, the significance of EE_r is still less understood and analyzed. There are limited number of studies that have reported on EE_r [10]. Therefore, the significance of EE_r in embodied energy during a building's life span should be further investigated. The purpose of this study is to contribute towards a better understanding of initial embodied energy of a building that occurs during the construction of the building and the recurrent embodied energy that occurs due to repair and maintenance of building materials or components during the life span of a typical double story terraced link houses in Malaysia. The main objective of this study is to

- estimate the embodied energy (EE) for the main building materials including the recurring embodied energy (EE_r) and the construction energy (E_c) that used in the construction of terraced link houses
- identify and rank building materials studied from the embodied energy (EE) perspective
- to evaluate building materials with significant potential for reduction in EE demand.

The study also aims to raise the awareness of the designers to the embodied energy implications of material choices and to suggest alternatives in materials specification of residential buildings. The findings from the study provide an insight into embodied energy of residential buildings locally.

II. PREVIOUS INVESTIGATIONS

There are numerous investigations pertaining to embodied energy of buildings globally, while very few studies focuses on recurrent embodied energy that is associated with replace, repair and maintenance of building materials or components [13], [10]. Treloar et al. [10] has stated that EE_r associated with material or component replacement and periodic maintenance can represent up to 32% of its EE_i. Whilst [13] stated that amount of EE_r depends on the service life of individual building materials and the frequency of maintenance. Crawford [13] analyzed a house Melbourne, reported a figure of 2319GJ (8GJ/m^2) as the EE_r associated with maintenance and refurbishment over the 50-year life of the house. This figure equates to 60% of $EE_{i,}$ it is comparatively higher to the 32% figure suggested in [10], and the total life cycle embodied energy of the house was 6210GJ (or 21.3GJ/m^2*)*. Thormark [14] reported the total of EE_{mi} and EE_r for 50 years for three different designs of 20 apartments ranges between 6.1-7.6GJ/m^2, nevertheless this figure did not include the E_c. A study in Brazil [15] stated an EE of 7.2GJ/m^2 with the EE_r component at 50% of the EE_i. Contrasting, to before mentioned studies, a study on residential buildings in India [9] stated that the EE_r component accounted for only 9% of the EE_i. A Nigerian study [16] reported EE_r of 46.5% of the 7.38GJ/m^2 of EE for a multistory residential building. Buchanan and Honey [17] suggested a figure of 2.32-5.53GJ/m^2 for a 94m^2 house, whilst another study [18] on load bearing houses with 1 and 2 story and a 4 story RC frame structure documented EE_i of 3-5GJ/m^2. Monahan and Powell [19] compared the embodied carbon in a low energy of affordable house constructed in the UK, reported the EE_i figure of 5.7-8.2GJ/m^2. Reddy and Jagadish [20] examined embodied energy of typical conventional urban houses with RC frame structure and masonry infill walls, reported an EE_i in the range of 3.8-4.25 GJ/m^2 (excluding E_c). A study in the UK [21] reported the average embodied energy of the 14 real-world case studies to be 5340 MJ/m^2. The above literatures clearly describe the significance of EE, EE_i and EE_r to the energy profile of a building thus, the study explores the significance of EE_i and EE_r in local typical houses.

III. METHOD

The chosen houses are of double-story link terraced intermediate units located at Klang Valley. These houses are typical urban prototypes consists of four bedrooms and three bathrooms, with the gross floor area (GFA) of approximately 130-150m^2. Built up area of the chosen houses (H1 and H2) are 137m^2 and 145m^2 respectively. These houses were constructed according to the standard plans and approved specifications by the local authorities.

A. Analysis Method

The EE_i and EE_r demand of the two houses was quantified for a service life of for 50 years. The common materials included in the scope of the embodied energy analysis are listed in Table I below. Building materials service life assumptions and replacement factors are indicated in Table II below. The items included in the embodied energy analysis are the all materials and components required in the construction of the house excluding landscaping, fences, driveway and paths, furniture and other non-fixed household items. The analysis did not include any white goods and furniture that may be fitted to the houses (for example, stove, dishwasher, air-conditioner, microwaves, toasters, etc.).

TABLE I. COMMON BUILDING MATERIAL CHICH CHARACTERIZE THE HOUSES.

Building Component	Construction Materials	
	H1	H2
Structure	RC Concrete 25	RC Concrete 25
Formwork	Plywood	Plywood
Door panels	Timber with paint	Plywood with paint
Wall Int. and Ext.	Clay and Cement sand	Clay and Cement sand
Wall finishes	Plaster, Paint and Ceramics	Plaster, Paint and Ceramics
Floor finishes	Marble and Ceramic	Ceramic tiles
Glazing	4mm clear float glass.	4mm clear float
Roof Truss	Timber	Timber
Roof Covering	Concrete Roof tiles	Concrete Roof tiles
Doors frames	Timber	Timber
Windows frames	Extruded aluminum	Extruded aluminum

The quantity of each material was determined from the bill of quantities provided by the builder and analysis of the plans and specifications of the house. An existing model in [5] was adapted in determining the EE for the case study houses. The calculation and analysis of the EE was done manually using the excel spreadsheet. The total EE calculated in this study is divided into two parts, mainly the EE_i inclusive of the energy required for the construction and installation of building component during construction phase (E_c) and the EE_r that occurs due to replacement and maintenance of building materials or components during the use phase of the houses.

B. Initial embodied energy (EE_i)

The EE_i of a building is the sum of the energy embodied in all the building materials used in its construction. The EE_i that occurs during the material production and on-site construction life cycle stages, is influenced by material embodied energy coefficient (EC_m), material mass (Q_{mi},), transportation distance, construction methods and context of application. Process based analysis was used to quantify the embodied energy associated with the construction of the case study houses. Delivered quantities of materials (Q_{mi},) used in the construction of the houses building were multiplied by the embodied energy coefficient (EC_m) of the respective materials, obtained construction materials database from [22] and [23], where the EC_m were determined based on cradle to gate production processes. This is due to the controlled access of locally available Life Cycle Inventory Database, which requires the database to be purchased. However, the study is limited major building materials or components of the houses that has the most effect in the construction. Emmanuel [24] and [8] stated that the EC_m of building materials differs from one country to another, subject to the energy sources used in the manufacturing and production building materials and components. Therefore, the limited availability of data on EC_m of building materials was another reason limiting the types materials analyzed. An existing model in [5] was adapted to calculate the EE_i is expressed as below:

$$EE_i = \sum Q_{mi}\, EC_m \qquad + \qquad E_c \tag{1}$$

Where Q_{mi} is the quantity of the building materials used in the initial construction of the house; were multiplied by their respective embodied energy coefficient (EC_m). The sum of these results gives the total process-based embodied energy for the houses (EE_{mi}.) These values were then added to energy used at site for construction (E_c) or installation of the building and components during the construction phase to determine the EE_i.

C. Construction Energy (E_c)

The E_c is the energy required for the erection of the building and its components involving a range of processes and activities for instance drying and drainage, the lighting of sheds and of the building itself, electricity operate for machinery, and so on. Past investigations have documented a figure of 7-10% of the EE_i of a building for the energy used during the construction process [25]. Bardhan [8] reported an average figure of 0.2GJ/m^2 as construction associated energy based on a study conducted on a construction site using top-down and bottom–up method. The author stated that using top-down approach, the energy computed energy for building construction was about 0.22GJ/m^2, while using the bottom-up approach was 0.18GJ/m^2 and he suggested an average figure of 0.2GJ/m^2 as the energy consumed during the construction phase. The energy data pertaining to the various construction processes and activities was collated from [26]. Though, some energy will be consumed during the repair, replace and maintenance processes, most of these activities and processes will consume more of manual energy (labour), hence this manual energy is not considered and captured in the study. Calculated E_c using the energy data for the construction activities and processes is 0.18GJ/m^2 and 0.20GJ/m^2 for house for H1 and H2 respectively. The averaged value of E_c for the study is 0.19GJ/m^2, which is comparable to average energy reported by [8]. However, the average E_c for the case study houses is only 3.3% of the EE_i, which is lesser than the 7-10% suggested in [25]. The reason for this can due to local E_c calculation does not include heating that is required for sheds and construction objects, due to the difference in the climatic zones.

D. Recurrent Embodied Energy (EE_r)

Recurring embodied energy (EE_r) is the sum of the energy embodied in the materials used to maintain and replace worn out materials and components and to rehabilitate a building over its service life. The recurrent life cycle embodied and operational energy depend on a facility's service life [7]. Additionally, individual building material and component holds differing service lives, which also affects the amount of EE_r of a building [27]. The building's use phase includes the processes of building operation as well as repair, replacement, and maintenance activities, which consume energy and resources [28]. These activities uses building materials and includes energy intensive construction processes [29]. Each of these activities or processes contribute to the EE_r [7] [30]. The EE_r of a material is highly influenced by several factors for instance, its service life, the replacement factor, and nature and frequency of maintenance. The EE_r was calculated based on the number of times each individual material would possibly be replaced during the useful life of the building [11]. The EE_r, was computed using replacement factors (Rf) for materials or components in the case study houses. The sum of the embodied energy of the materials, used in the repair, replacement and maintenance, EE_r can be expressed as:

$$EE_r = Q_{mi}\, EC_m\, [(Sl_h / Sl_{mi}) - 1] \tag{2}$$

Where EE_r is the recurrent embodied energy of the house, in GJ; Sl_h is the service life of the house (50 years); Sl_{mi} is the service life of the material, m; Q_{mi} is the delivered quantity of material, m; EC_m is the embodied energy coefficient of material, m; Sl_h / Sl_{mi} is the replacement factor of building materials and components over a buildings life span. 1 is subtracted from the equation representing the first time the materials was used in the construction.

E. Service life of building materials (Sl_{mi}) and building service life (Sl_h)

The average service life for building materials was derived from various literatures [11], [31] and [32] refer to Table II below.

TABLE II. THE SERVICE LIFE OF VARIOUS COMMON BUILDING MATERIALS AND COMPONENTS EXTRACTED FROM [11], [31],[32]

Building Components/Materials	Service life of building materials and components			
	min	max	average	assumed
Concrete roof tiles	30	life time	40	30
Bricks		life time, 100+		50
Water-based paint	5	15	10	5
Solvent based paint				5
Aluminum frame	15	40, 20	25	25
Timber	15	25	20	20
Plaster	30	50	20	30
Timber roof truss		life time		50
Marble			100+	50
Ceramic tile	75	100		50
Concrete Systems	lifetime			50
Window Glazing			10+	10
Door (plywood)			15	15

Service life is the period after construction during which a building or its components meet or exceed performance requirements (33). Service life is often predicted from recorded performance over time (experience) or can be obtained from the building materials manufacturers. The S_{lm} influences the number of times a material will be replaced over the life of a building. The lower the Sl_m, the greater the quantity of materials required for ongoing repairs, replacements, and maintenances, consequently the EE_r will be greater throughout the building's life. As it is typically fossil fuel-based, this additional demand for energy may have considerable effect [11]. The period of analysis chosen for this study is 50 years and it does not suggest that the houses would be unfit for further use, after 50 years. The average life span of the case study houses are assumed as 50 years based on earlier studies on energy consumption in buildings [20], [34]. This figure was then used to determine the replacement factors (Rf) of the materials.

F. Replacement factor (Rf)

A replacement factor is the ratio of service life of a built facility to the average service life of a building material or a component, is essential in assessing the amount of EE_r [7] [27]. The replacement factor provides a means to compare the durability of the building materials. It is an indication of the number of times (including first installation) that resource input is needed for installation of the material or component within service life of the house [27]. Table II, above shows the service life of various common building materials and components extracted from [11], [31] and [32]. The collated SL_m was used to estimate the Rf, which is then used to calculate the embodied energy (EE_r) associated with the replacement of materials over its life. Table III below shows the calculated Rf for this study based on assumed Sl_m as shown in Table II and average service life of house (50 years). The Rf, of each of the materials or components was determined by application of the following formula, namely:

$$RF = Sl_h / Sl_{mi} \tag{3}$$

TABLE III. CALCULATED REPLACEMENT FACTOR (Rf) FOR BUILDING MATERIALS OF THE CASE STUDY HOUSES

Building Components/Materials	Calculated Rf	Building Components/Materials	Calculated Rf
Concrete roof tiles	1	Timber roof truss	0
Bricks	0	Marble	0
Water based paint	9	Ceramic tile	0
Solvent based paint	9	Poured-Concrete	0
Extruded Aluminum	1	Window Glazing	4
Timber door panels	2	Door (plywood)	2
Plaster	1		

G. Embodied energy (EE)

Embodied energy (EE) of a building is the energy content of all the materials used in the building and technical installations (EE_i), energy consumed for the erection and installation of building materials and components, (E_c) and energy incurred for the materials and components that is used for repairs, replacements, and maintenances of the building (EE_r). The objectives of carrying out embodied energy analysis for these houses are to compute the amount of EE_i within building materials, identify the total EE content of different building materials and, to determine the significance of EE_r in influencing the EE of houses with 50 years of service life. Thus, the model to analyze EE in this case study is adapted from [5], expressed as:

$$EE = \sum EE_{mi} + E_c + \sum EE_r \tag{4}$$

IV. RESULTS AND DISCUSSION

The following section presents the results of the EE assessment for both of the case study houses, that includes initial embodied, construction and recurrent embodied energy requirements.

A. Initial embodied energy (EE_i)

The total EE_i associated with initial construction of the houses was 778.11GJ and 922.15GJ for houses H1 and H2 respectively. On a per square meter basis the EE_i figures are 5.68GJ/m^2 and 6.36GJ/m^2, this figures compares closely with a previous Malaysian study [6] which reported EE_i that ranged between 4.12GJ/m^2 and 5.38GJ/m^2. The earlier figure [6] was slightly lesser as the E_c was not included in the study. The study findings are also closely comparable with findings in [19]. A study in India [20], reported an EE_i in the range of 3.8–4.25GJ/m^2, this figure is comparable, yet lesser than the figure in this study as it too did not include the $E_{c.}$ The EE_i figures from this study conforms with a study in the UK [21] which reported the average EE of 14 real-world case studies is 5340MJ/m^2.

On a material or component basis, the extruded aluminum used for window frames represents the greatest share of the EE_{mi} of the houses (28.26%). Despite the use of this material being limited for the window frames, the EE_{mi} is large due to its high embodied energy coefficient (EC_m). The current trend to use aluminum for doors and windows frames can however contribute significantly to the energy input into a building [20]. The study findings also corresponds with study in [6], which suggested timber as an energy efficient substitute for aluminum. The subsequent significant EE_{mi} demand ranges from 9.67% to 11.11% for building materials, which include cement sand bricks, reinforcement, timber truss, and concrete. These materials make up most part of the structure of the houses and are large in quantity, though the EC_m for these materials are much lower to EC_m for extruded aluminum. The total EE_{mi} of the materials used for the structure of the houses is 54.8%. Figure 1 below shows the average embodied energy of building materials (EE_{mi}) of the case study houses.

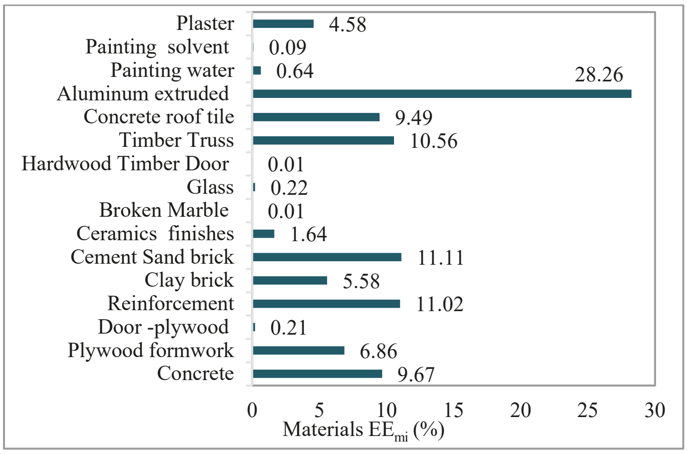

Figure 1: Average embodied energy of building materials of case study houses.

B. Recurring Embodied Energy (EE_r)

The materials used for the structure of both case study houses (H1 and H2) represent the largest components of the EE_{mi}, 63% and 48% respectively, but do not contribute to EE_r. Meanwhile, the finishing materials of HI and H2 demand lesser EE_{mi} of 37% and 52% respectively, but are the core contributor to the EE_r. The EE_r of the materials used for the structure of the case study houses is zero as the structural components are assumed to last as long as the houses. The EE_r over the 50-year life of both the houses was found to be 324.95GJ (2.37GJ/m^2) and 505.74GJ (3.49GJ/m^2), the average EE_r of both H1 and H2 is 415.35GJ (2.93GJ/m^2). This figure equates to 33% the total EE figure, which compares closely to the 32% figure as reported in [10], however it is much lesser than the 60% figure suggested in [13], this could be due to the reason that the study in [13] used input–output-based hybrid embodied energy assessment approach. The study EE_r figure of 33% is also lower to the reported EE_r figure in [15] and [16]. On the other hand, it is higher to the reported EE_r in the Indian study [9].

On the material basis, the extruded aluminum represent the highest proportion of EE_r of the houses (56.45%) followed by the concrete roof tiles (18.7%). Despite, being replaced only once within the 50 years lifetime, the EE_r of both this materials are high due to the high EC_m of aluminum and the large quantity of concrete roof tiles. This evidently shows that poor selection materials with lower quality and high-energy intensity influence the recurring energy tremendously. Next, paint contributes 11.47% to the total EE_r figure. This is mostly due to the frequent replacement wall paint (every 5 years). This proportion of EE_r can be reduced significantly if the frequency of repainting the walls are reduced. The other materials for instance wall plaster, door panels (plywood and timber), and glass for door and window represents 13.3% of EE_r. Figure 2 below shows the average EE_r of building materials of case study houses. Findings from the study shows that the EE_r component is significant to the total EE profile of the houses. The results generated from this study reveals that EE_r of common building materials used in the construction of typical terraced houses is significant (33%) of total EE. The EE_r component is higher in this study than in previous studies [9]. The reason for this can be due to high replacement and maintenance rate of building materials of lower quality and durability. Another factor that could have contributed to this is the specification of materials with high embodied energy intensity (EC_m) by designers due to cost factor. This suggests that the EE_r component is significant in the life cycle embodied energy demand and attention must be given by designers in reducing the EE_r of buildings by exploring alternatives particularly in selecting the building materials during the design stages.

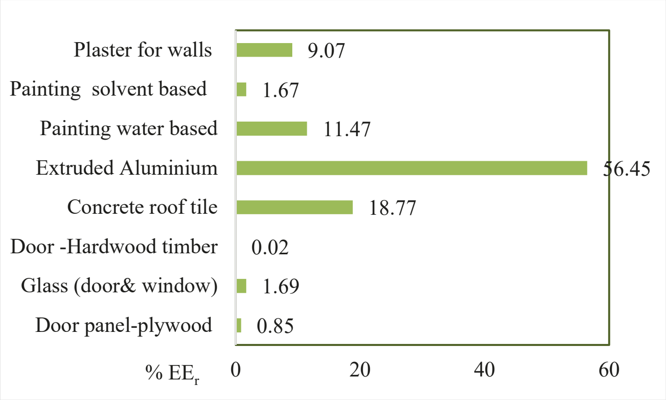

Figure 2: Average recurrent embodied energy (EE_r) of building materials of case study houses

C. *Total Embodied Energy*

The total embodied energy (EE) demand associated with the case study houses are 1,103.06GJ ($8.05GJ/m^2$) and 1,427.89MJ ($9.85GJ/m^2$). The calculated average EE for the study is 1,265.47MJ ($8.95GJ/m^2$). Figure 3 below shows the EE_{mi} of building materials that represents the largest proportion (65.40%) of total average EE, This is followed by the average EE_r of the houses (32.44%) while the E_c represents only 2.16% of the total EE. This findings though is considerably higher but is comparable with previous studies [18], [15], [16], yet it is lesser compared to EE reported by [10]. Based on building materials extruded aluminum contributes the highest to the EE. (37.87%) due to the high EC_m and inferior quality of the material. The concrete roofing tiles follows next with a figure of 12.59%. The finishing materials for instance paint contributes significantly to EE. The EE_r of these materials are high due to the frequent replacement, larger quantity and higher EC_m (97MJ/kg), whilst materials like plaster with low EC_m (1.3MJ/kg) also demands a significant amount of energy (6.08%) due to large quantity of material and replacement rate. Contrasting to previous finding in [6] this study finding shows that the combined embodied energy component (EE) is much more significant than reported and the of EE_r (32.94%) significantly influences the total EE of the case study houses.

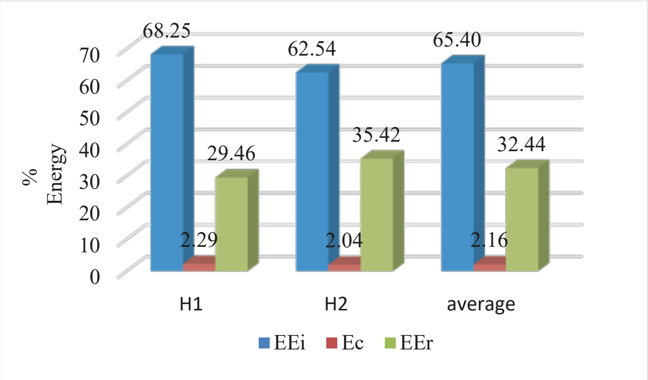

Figure 3: The proportion of building materials initial embodied recurrent embodied and construction energy for the case study houses.

V. CONCLUSION

The study provided life cycle embodied energy demand analysis for the typical linked double story terraced houses located in Malaysia. The embodied energy demand was calculated considering the initial embodied energy of materials, construction and installation associated energy and recurring embodied energy over 50 years of service life of building. The initial and recurrent embodied energy of the case study houses were calculated using a process base assessment approach, with material service life values based on average figures obtained from various literatures. The aim of this study was to determine the significance of recurrent embodied energy (EE_r) in contributing towards the total embodied energy demand (EE), and to identify materials that contribute significantly towards the total embodied energy. Calculated total embodied energy (EE) of the houses are 8.05 and $9.85GJ/m^2$, thus $8.95GJ/m^2$ was the averaged embodied energy. The recurrent embodied energy (EE_r) for the case studies are 2.37 to $3.49GJ/m^2$, and the averaged EE_r was $2.93GJ/m^2$. The findings shows that the average EE_r equates to 33% of total EE and this component (EE_r) of embodied energy can significantly influence the life cycle embodied energy. Findings have shown that EE_r can be as significant as the EE_{mi} of materials or even more for building over 50 years, for instance materials such as aluminum, plaster, concrete roof tiles and water-based paint. The findings suggest there is potential in reducing the embodied energy demand of the houses, thus reducing the impact of these materials to the environment. Therefore, any attempt to reduce embodied energy (EE) demand should consider building materials with longer service life, lower embodied energy coefficient (energy intensity) and durability. Service life of building materials (durability) may be the most significant criterion when it comes to the selection of materials such as paint. On the contrary, most designers do not emphasize on materials service life and its impact to recurring embodied energy due to cost factor. Consideration of alternative materials with recycled content could also reduce the initial and recurrent embodied energy for instance aluminum, cement sand plaster, concrete and concrete roof tiles. Alternative material such as timber to substitute plywood for doors can be considered by designers due to the reason that plywood has high embodied energy coefficient despite its poor durability. The findings from this study though explicit to a building type and limited of process energy data, and service life of materials from various published literatures, provides a better understanding of life cycle embodied energy and the significance of recurrent embodied energy of building materials used commonly in local construction of housing.

REFERENCES

[1] WEO 2017: Key Findings", *Iea.org*, 2018. [Online]. Available: https://www.iea.org/weo2017/. [Accessed: 14- 8 Feb- 2018].

[2] "Malaysia - urbanization 2006-2016 | Statistic", *Statista*, 2018. [Online].Available: https://www.statista.com/statistics/455880/urbanization-in-malaysia/. [Accessed: 11- Feb-Mar- 2018].

[3] Construction Industry Development Board Malaysia (CIDB), "Country Report, Malaysia", AsiaConstruct Conference Seoul, Korea, 2017

[4] "Construction in Malaysia, Key Trends and Opportunities to 2020", *Reportlinker.com*, 2018. [Online]. Available: https://www.reportlinker.com/p03488659/Construction-in-Malaysia-Key-Trends-and-Opportunities-to.html. [Accessed: 14- Mar- 2018

[5] T. Ramesh, R. Prakash and K. Shukla, "Life cycle energy analysis of buildings: An overview", *Energy and Buildings*, vol. 42, no. 10, pp. 1592-1600, 2010.

[6] T. S. Mari, Embodied Energy of Building Materials: A Comparative Analysis of Terraced Houses in Malaysia, Proc. 41st Annual Conference of the Architectural Science Association (ANZAScA), Deakin University, Australia, 2007.

[7] T. Chen, J. Burnett and C. Chau, "Analysis of embodied energy use in the residential building of Hong Kong", *Energy*, vol. 26, no. 4, pp. 323-340, 2001.

[8] S. Bardhan Embodied energy analysis of multi storied residential buildings in urban India, ISSN 1743-3541 (on-line) WIT Transactions on Ecology and the Environment, Vol 143, © 2011 WIT Press, doi:10.2495/ESUS110351 Dept. of Architecture, Jadavpur University, India, www.witpress.com

[9] T. Ramesh, R. Prakash and K. Shukla, "Life cycle approach in evaluating energy performance of residential buildings in Indian context", *Energy and Buildings*, vol. 54, pp. 259-265, 2012.

[10] G. Treloar, R. Fay, P. Love and U. Iyer-Raniga, "Analysing the life-cycle energy of an Australian residential building and its householders", *Building Research & Information*, vol. 28, no. 3, pp. 184-195, 2000.

[11] A. Rauf and R. Crawford, "The relationship between material service life and the life cycle energy of contemporary residential buildings in Australia", *Architectural Science Review*, vol. 56, no. 3, pp. 252-261, 2013.

[12] R. Haynes, Embodied Energy Calculations within Life Cycle Analysis of Residential Buildings. Available online: www.loriweb.com/CMGT380/Dis_03/Embodied-Energy-Paper-Richard-Haynes.pdf. (accessed 22 February 2018), 2013.

[13] R. Crawford, "Post-occupancy life cycle energy assessment of a residential building in Australia", *Architectural Science Review*, vol. 57, no. 2, pp. 114-124, 2013.

[14] C. Thormark, "The effect of material choice on the total energy need and recycling potential of a building", *Building and Environment*, vol. 41, no. 8, pp. 1019-1026, 2006.

[15] J. Paulsen and R. Sposto, "A life cycle energy analysis of social housing in Brazil: Case study for the program “MY HOUSE MY LIFE”", *Energy and Buildings*, vol. 57, pp. 95-102, 2013.

[16] I.C. Ezema, Estimating Embodied Energy in Residential Buildings in a Nigerian Context, International Journal of Applied Engineering Research ISSN 0973-4562 Volume 10, Number 24 (2015) pp 44140-44149, © Research India Publications. http://www.ripublication.com

[17] A.H. Buchanan, B.G. Honey, Energy and carbon dioxide implications of building construction, Energy and Buildings 20 (1994) 205–217.

[18] A. Debnath, S. Singh and Y. Singh, "Comparative assessment of energy requirements for different types of residential buildings in India", *Energy and Buildings*, vol. 23, no. 2, pp. 141-146, 1995.

[19] J. Monahan and J. Powell, "An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework", *Energy and Buildings*, vol. 43, no. 1, pp. 179-188, 2011.

[20] B. Venkatarama Reddy and K. Jagadish, "Embodied energy of common and alternative building materials and technologies", *Energy and Buildings*, vol. 35, no. 2, pp. 129-137, 2003.

[21] G. Hammond and C. Jones, "Embodied energy and carbon in construction materials", *Proceedings of the Institution of Civil Engineers - Energy*, vol. 161, no. 2, pp. 87-98, 2008.

[22] India Construction Materials Database of Embodied Energy and Global Warming Potential, METHODOLOGY REPORT, 2017. [Online]. Available:https://www.edgebuildings.com/wp-content/uploads/2017/12/IFC-India-Construction-Materials-Database-Methodology-Report.pdf. [Accessed: 11- Feb- 2018].

[23] "Embodied Energy and Embodied Carbon", *Circular Ecology*, 2018. [Online]. Available: http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html. [Accessed: 14- Mar- 2018].

[24] R. Emmanuel, "Estimating the environmental suitability of wall materials: preliminary results from Sri Lanka", *Building and Environment*, vol. 39, no. 10, pp. 1253-1261, 2004.

[25] Cole, R. J. 1999. Energy and greenhouse gas emissions associated with the construction of alternative structural systems. *Building and Environment 34(1999): 335-348*

[26] K. Adalberth, "Energy use during the life cycle of single-unit dwellings: Examples", *Building and Environment*, vol. 32, no. 4, pp. 321-329, 1997.

[27] C. Chau, F. Yik, W. Hui, H. Liu and H. Yu, "Environmental impacts of building materials and building services components for commercial buildings in Hong Kong", *Journal of Cleaner Production*, vol. 15, no. 18, pp. 1840-1851, 2007.

[28] M. K. Dixit, C. H. Culp, S. Lavy and J. Fernandez-Solis, "Recurrent embodied energy and its relationship with service life and life cycle energy", *Facilities*, vol. 32, no. 34, pp. 160-181, 2014

[29] A. Utama and S. Gheewala, "Indonesian residential high rise buildings: A life cycle energy assessment", *Energy and Buildings*, vol. 41, no. 11, pp. 1263-1268, 2009.

[30] G. Ding, "Life cycle energy assessment of Australian secondary schools", *Building Research & Information*, vol. 35, no. 5, pp. 487-500, 2007.

[31] 2018. [Online]. Available: http://www.roofkey.com/concrete-rooftile. Html. [Accessed: 11- Feb- 2018].

[32] G. Ding, "The Development of a Multi-Criteria Approach for the Measurement of Sustainable Performance for Built Projects and Facilities.”", PhD, University of Technology, Sydney., 2004.

[33] Kotaji, A. Schuurmans and S. Edwards, *Life cycle assessment in building and construction,* 1st ed. Society of Environmental Toxicology and Chemistry, SETAC Press, 2003.

[34] Robert H. Crawford An as-occupied life cycle energy assessment of a residential building, 46th Annual Conference of the Architectural Science Association, ANZAScA 2012, Griffith University