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Life Cycle Energy Analysis of Eight Residential Houses in Brisbane, Australia

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Abstract

Life cycle energy analysis (LCEA) of eight residential buildings in and around Brisbane, Queensland, Australia, is undertaken in this study. Energy used in all three phases of construction, operation and demolition are considered. It is found that the main contribution to the operational energy in residential buildings is from use of general appliance. The choice of building materials is shown to have significant effects on the embodied energy for the production, construction, maintenance and demolition phases. From this study, it is shown that the embodied energy may vary from 10% to 30%, while the operational energy may vary from 65% to 90%. The demolition energy generally accounts for less than 4% of life cycle energy.

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Keywords: life cycle energy analysis; residential buildings; building embodied energy; building operational energy; building demolition energy

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Nomenclature

$EE_{assembly}$ embodied energy for an individual assembly
$EE_{material}$ embodied energy for an individual building material
EE_{total} total embodied energy for an individual house
$EE_{average}$ average embodied energy for a house

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OE_{annual} average annual energy use
$OE_{average}$ average annual energy use per square meter

1. Introduction

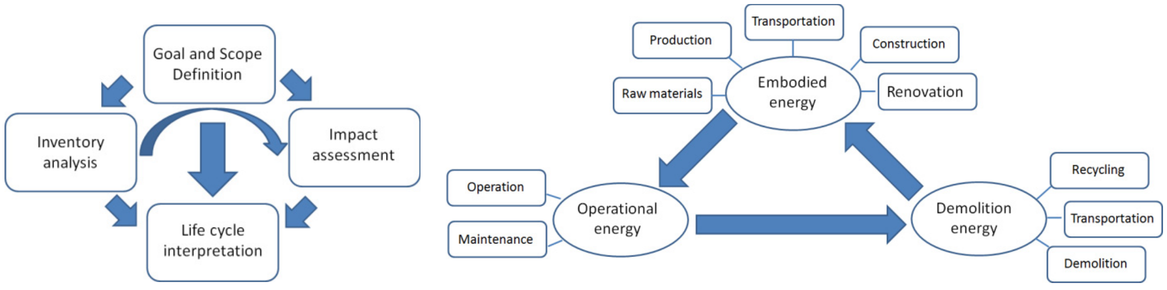
Buildings, as one of the most significant infrastructure in modern society, use energy throughout their life, from its construction to its demolition (e.g. from cradle to grave). Worldwide, buildings are responsible for 40% of the world's total energy use, having a significant influence on the total natural resource consumption and the emissions released. It was found that for the greenhouse emissions related to buildings, 40–95% of these emissions are caused by operational energy use, with the remainder being caused by construction and demolition [1].

In order to design environmentally-conscious buildings, various methods and tools have been developed to measure and compare the environmental impacts of buildings over their whole life cycle. Generally, materials and energy flows of a building system may include three phases of upstream of construction (e.g. extraction, production, transportation and construction), operation or use and downstream of deconstruction (deconstruction and disposal) [2].

In this paper, a life cycle energy analysis of eight residential buildings in and around Brisbane, Queensland, Australia, was conducted. After brief introduction, the methodology used for this study is introduced, including the overall study approach, the information of the study houses and the study assumptions adopted. This is followed with results and analysis of energy used during all three phases of construction, operation and demolition.

2. Methods

2.1. Overview of the methodology



(a) Stages (b) System boundaries

Fig. 1. Overview of the methodology for life cycle energy analysis.

Life cycle energy analysis (LCEA) is an approach that accounts for all energy inputs to a building in its life cycle [2], consisting of four stage processes as shown in Figure 1(a). First, the purposes and system boundaries of the study are defined. Then the appropriate data and information will need to be collected and analyzed to quantify the material and energy flows in various stages of a system lifecycle. The contributions of various constituents on the environmental indicators can be finally evaluated and interpreted to show the significant issues and potential environmental impacts.

Figure 1(b) further illustrates the energy involved in the life cycle of buildings. Embodied energy is the energy consumed by all of the processes associated with the production of a building, from the mining and processing of natural resources to manufacturing, product transport and delivery, and building construction and installation. It is the 'upstream' or 'front-end' component of the life cycle impact of a building [3]. Operational energy is the energy required for maintaining comfort conditions and day-to-day maintenance of the buildings [2]. It is the energy used for heating, ventilation and air conditioning (HVAC), domestic hot water, lighting, and for running appliances. The demolition energy is the energy occurring during the last destruction phase, which includes the energy used to demolish the building and transportation of dismantled materials to landfill sites and/or recycling plants.

Potential energy savings from recycling or reusing the demolished building materials is not considered in this study. This is because there is currently no agreement over the method of attributing this saved energy to the demolished building, although it would be more appropriate if this energy can be incorporated in the life cycle energy estimation in overall sense [2].

2.2. Information of study houses

Total eight residential houses in and around Brisbane, Queensland, Australia, were studied. The general information, details of construction materials and electrical appliance and equipment for these eight residential houses is gathered from site visits to these houses and is tabulated in Table 1, Table 2 and Table 3 respectively. The energy use for the studied houses was collected varying from one year to four years, depending on their availability. Information presented in these tables will be used later to estimate embodied energy and operational energy for these studied houses.

Table 1. General information of eight residential houses.

House	**Location**	**Storey**	**No. Of People**	**Living area (m^2)**	**Start Date**	**End Date**	**Billing days**	**Total energy use (kWh)**
A	Birkdale	one	1	195	10/11/2008	7/11/2011	1093	15861
B	Tingalpa	one	2	160	21/05/2008	14/02/2012	1365	28528
C	Wynnum	two	2	230	19/06/2009	14/09/2012	1183	15449
D	Wynnum	two	6	510	12/01/2011	10/04/2012	454	25453
E	Manly	two	4	350	19/09/2008	18/09/2012	1461	4630
F	Norman Park	two	3	217	4/10/2007	28/12/2011	1546	41836
G	Manly	one	3	110	15/12/2008	13/12/2011	1094	22693
H	Tingalpa	two	2	260	13/05/2009	8/02/2012	1001	15487

It can be seen in Table 2 that most of these houses are constructed with brick walls, concrete floor and metal roofs. Because the use of insulation in roofs and walls and floors are sealed, the potential difference of insulation between these houses was ignored in this study. Moreover, the possible difference in internal finishing and decoration between different houses has also not been considered in this study. For internal walls, 20% of timber framework was assumed.

Table 2. Construction materials for eight residential houses.

House	A	B	C	D	E	F	G	H
Lower level floor	Reinforced Concrete	Reinforced Concrete	Reinforced Concrete	Reinforced Concrete	Reinforced Concrete	Reinforced Concrete	Timber	Reinforced Concrete
Lower level roof	Concrete tile +Plasterboard	Detromatic-tin roof+ Plasterboard				Plasterboard	tin-iron+ Timber	
Lower level internal walls	Plasterboard	Plasterboard				Plasterboard	Timber	
Lower level external walls	Brick	Brick	Brick	Brick	Concrete Blocks	Brick	Timber	Brick
Upper level floor			Timber	Timber	Timber	Timber		Timber
Upper level roof			Super six fibro+Plasterboard	tin-iron+ Timber	tin-iron+ Timber	tin-iron+ Plasterboard		Concrete tile + Fibre
Upper level			Timber	Timber	Timber	Brick		Cement

external walls								
Upper level internal walls			Fibre Cement	Timber	Timber	Plasterboard		Brick
New extension floor					Timber			Fibre Cement
New extension roof					tin-iron+ Plasterboard			
New extension external walls					Timber			
New extension internal walls					Plasterboard			

Table 3. Main electrical appliance and equipment in eight residential houses.

House	A	B	C	D	E	F	G	H
Washing machine	√	√	√	√	√	√	√	√
Dryer	√	√	√	√		√	√	√
Iron			√		√	√	√	√
TV	√	√	√	√	√	√	√	√
DVD/CD player			√		√		√	√
Cordless phone (or iPhone)	√		√		√	√	√	√
Clock radio					√		√	√
Computer (e.g. desk top, laptop, notepad)	√	√	√	√	√	√	√	√
Printer	√		√		√	√		
Dishwasher		√		√				
Oven	√	√	√	√	√	√	√	√
Stove top & electric fryer	√	√	√	√	√	√	√	√
Fridge & freezer	√	√	√	√	√	√	√	√
Microwave	√	√	√		√	√	√	√
Kettle	√	√	√	√	√	√	√	√
Toaster	√	√	√	√	√	√	√	√
Electric toothbrush					√			
Hair dryer		√			√	√	√	√
Straightener							√	√
Lighting								
Normal lights	√		√	√		√		
Spot light	√				√			
Halogen lights	√		√		√		√	√
Energy saving lights		√						
Down lights		√	√		√	√	√	√
Swimming pool pumps		√				√		
Electric hot water system		√	√				√	√
Ceiling or Pedestal fans				√		√	√	√
Heater	√						√	√
Air conditioning	√			√	√			
Solar PV		√						√

2.3. Study assumptions

Following assumptions were also adopted in this study:

- The lifespan of the houses for this study was assumed to be 50 years.
- The possible influence of methods (e.g. by truck, train, ship or plane) and distance to transport building materials from one location to another was ignored in the calculation of embodied energy and demolition energy.
- The potential influence of the type of "raw" materials (e.g. natural or recycled sources) for the manufacturing of building materials was also ignored in the calculation of embodied energy.

- The possible contribution of embodied energy due to renovation and maintenance over a building's life was ignored.
- The potential influence of various construction methods and different brands of a building product (e.g. different efficiency of the individual manufacturing process and the fuels used in the manufacture of the materials) on embodied energy was also ignored.
- For operational energy, this study was focused on the buildings only. Therefore the possible contribution from urban scale (e.g. the transport energy of building occupants and urban infrastructure) was not considered.

3. Results and analysis

3.1. Embodied energy

Every building uses a complex combination of many processed materials, which all contribute to the building's total embodied energy [3]. Therefore, the choices of building materials will influence the amount of energy embodied in the structure of a building. Various approaches may be used to determine the embodied energy, including

- Process energy analysis, which considers the energy directly related to the manufacturing processes of the product [3]. The accuracy of this method is depended on the system boundary drawn, while all processes outside the boundary will be neglected [4].
- The input–output analysis, where the embodied energy of a product is calculated using its average price and the energy intensity of its sector. That is, all products within a sector will be assigned the same energy intensity. Moreover, the price of the product can sometimes distort the calculation results [4].
- Gross energy analysis, which is a true measure of embodied energy of a produce. In practice, however, the energy use is usually very difficult to measure [3]. Therefore, various alternative options are proposed. These include the hybrid analysis, which uses available process energy data and filling the gaps with input–output data [4].

Currently, most figures quoted for embodied energy are based on the process energy analysis [3]. In general, process energy requirement (PER) accounts for 50-80% of gross energy requirement (GER). However, by using different calculation methods, the estimation of embodied energy can vary by a factor of up to ten. Therefore, for a comparison of embodied energy, it is often desirable to use figures produced from a single source, so that the adoptions of methodology and base data are consistent.

For this study, embodied energy of common house assemblies and materials, as suggested by the "Your home – Australia's guide to environmentally sustainable homes", were adopted and is presented in Table 4 and Table 5. The values with symbol of "*" in Table 5 are extracted from the article "Choosing building materials" [5]. The embodied energy for an individual assembly ($EE_{assembly}$) is calculated as follows:

$$EE_{assembly}\ (MJ) = \text{Embodied energy}\ (MJ/m^2) \times \text{Area}\ (m^2) \quad (1)$$

For any building elements that are not listed in Table 4, the data from Table 5 would then be used instead for the calculation of embodied energy. The embodied energy for an individual building material ($EE_{material}$) was calculated as follows:

$$EE_{material}\ (MJ) = \text{Embodied energy}\ (MJ/kg) \times \text{Density}\ (kg/m^3) \times \text{Area}\ (m^2) \times \text{Thickness}\ (m) \quad (2)$$

Table 4. Embodied energy for assembled floors, roofs and walls [3].

Assembly	Embodied energy MJ/m²
Elevated timber floor	293

110mm concrete slab-on-ground	645
200mm precast concrete, T beam/infill	644
Timber frame, concrete tile, plasterboard ceiling	251
Timber frame, terracotta tile, plasterboard ceiling	271
Timber frame, steel sheet, plasterboard ceiling	330
Single skin autoclaved aerated concrete (AAC) block wall	440
Single skin AAC block wall gyprock lining	448
Single skin stabilised (rammed) earth wall (5% cement)	405
Steel frame, compressed fibre cement clad wall	385
Timber frame, reconstituted timber weatherboard wall	377
Timber frame, fibre cement weatherboard wall	169
Cavity clay brick wall	860
Cavity clay brick wall with plasterboard internal lining and acrylic paint finish	906
Cavity concrete block wall	465

Table 5. Embodied energy (PER) for common building materials [3].

Material	Embodied energy (MJ/kg)	Material	Embodied energy (MJ/kg)
Kiln dried sawn softwood	3.4	In situ concrete	1.9
Gypsum plaster	2.9	Clay bricks	2.5
Plasterboard	4.4	Concrete blocks	1.5
Plywood	10.4	Glass	12.7
Fibre cement	4.8	Fibreglass	30.3*
Cement	5.6	Cellulose insulation	3.3*
Aluminium	170	Wool insulation	2.5*
Galvanised steel	38	Polyester insulation	53.7*

The total embodied energy for an individual house (EE_{total}) would be equal to the sum of all building elements (e.g. all assemblies and materials):

$$EE_{total}\ (MJ) = \sum EE_{assembly} + \sum EE_{material} \tag{3}$$

The average embodied energy for a house ($EE_{average}$) was defined as the ratio between the total embodied energy and the liveable area as follows:

$$EE_{average}\ (MJ/m^2) = EE_{total}\ (MJ)\ /\ \text{Living area}\ (m^2) \tag{4}$$

The estimated PER embodied energy for the studied houses are shown in Figure 2. It can be seen that the difference in PER embodied energy can be up to 100%, with House F having the highest embodied energy, while House G having the lowest embodied energy. The results also show that the more use of timber, the lower embodied energy (e.g. comparing Houses A and B with Houses C and D in Figure 2). After removing the contribution of embodied energy from internal walls, the difference between different types of house construction becomes slightly larger.

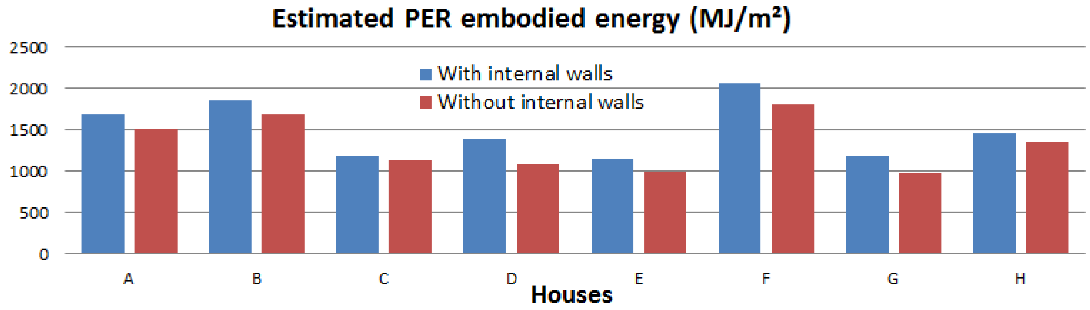


Fig. 2. Estimated PER embodied energy for the studied houses.

With the improvement of energy efficiency of manufacturing process to produce building material, it would be expected that the level of embodied energy required in building materials would become small [3]. However, with increasing energy efficiency of houses and appliances, the operational energy will decrease and the embodied energy may become increasingly important.

3.2. Operational energy

Different from embodied energy of building, the amount of building operational energy will be dependent on the occupant behaves and schedules, as well as the level of required comfort and climatic conditions. Generally, operational energy includes the energy requirements for heating ventilation and air conditioning (HVAC), lighting, demotic hot water (DHW) system and general appliance used in kitchen, living area, laundry and bathroom etc. It accumulates energy over the life time of the buildings.

The average annual energy use (OE_{annual}) was calculated as follows, where both the billed total energy use and billing days were listed in Table 1:

$$OE_{annual}\ (\text{kWh/year}) = 365 \text{ x Total energy use (kWh) / Billing days} \tag{5}$$

The average annual energy use per square meter ($OE_{average}$) is equal to the ratio between the average annual energy use (kWh/year) and the liveable area (m²):

$$OE_{average}\ (\text{kWh/m}^2) = OE_{annual}\ (\text{kWh/year}) \text{ / Living area (m}^2) \tag{6}$$

As shown in Table 3, electrical appliance and equipment varied considerably between these studied houses. Particularly, it is noted that two houses (B and F) had swimming pool, two houses (B and H) have installed solar panel and four houses (B, C, G to H) used electric hot water system. To be consistent in the comparison, the possible energy inputs from solar panels have been removed from this study. Based on the information provided in Table 3 and the possible use of them, the breakdown end energy use for these houses was also conducted. It was found that energy used by general appliance varying from 45% to 75%, by lighting energy varying from 5% to 15%, by pool pumps varying from 20% to 35%, by air conditioner varying from 15% to 45% and by electric hot water system varying from 15% to 30%.

Table 6. Average annual energy use for the studied houses.

House	A	B	C	D	E	F	G	H
Average annual energy use (kWh/year)	5297	7628	4767	20463	1157	9877	7571	5647
Average annual energy use without DHW (kWh/year)	5297	6127	3651	20463	1157	9877	4720	3891
Average annual energy use (kWh/m^2)	27	48	21	40	3	46	69	22
Average annual energy use without DHW (kWh/m^2)	27	38	16	40	3	46	43	15

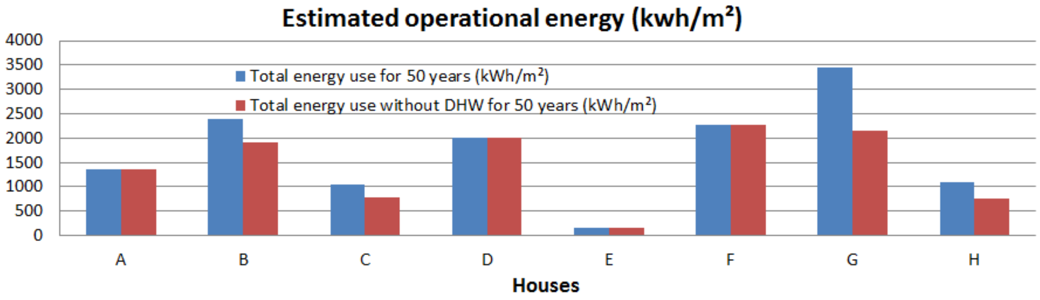


Fig. 3. Estimated 50 years operational energy for the studied houses.

Average annual energy use for households is also tabulated in Table 6. It was noted that House E had much lower total energy use than the other houses. A further investigation of the electrical appliance within the household and the energy usage of house revealed that the electricity meter for the particular house might have malfunctioned for a long time (e.g. four years). The analysis of electricity energy bills showed that there are four houses use electric domestic hot water system, while other may use gas or solar energy for hot water. To be consistent in the comparison, the results of removing the large energy use by electric hot water systems are also presented in the Table 6. The estimated 50 years operational energy for the studied houses is shown in Figure 3.

3.3. Demolition energy

The demolition phase takes into consideration of the energy used by machinery to deconstruct the existing building, as well as energy required to raze, store and transport these materials from the building site to the landfill sites and/or final treatment plants. This phase is usually quite small in comparison to that of the production and operational phases. This may be typically around 1-4% of the energy usage during the life cycle of a building.

Table 7. Demolition energy of construction materials for existing small buildings.

Construction Type	Demolition Energy (MJ/m^2)	Studied houses
Light (e.g. wood frame)	35	House G
Medium (e.g. steel frame)	106	House E
Heavy (e.g. masonry, concrete)	176	Houses A to D, F, H

Based on the demolition energy calculator suggested by Matt [6] for “the greenest building is the one already built”, the demolition energy for small buildings (e.g. 465-1395 m^2) is tabulated in Table 7. It is suggested that the demolition energy per unit area will decrease with the increase of building size. The proposed demolition energy for the studied houses is shown in the third column in Table 7.

It is noted that the potential reuse and recycling building materials have not been considered in this study. It was suggested that the energy savings from recycling of materials for reprocessing can vary considerably, from 20% for glass to up to 95% for aluminium. However, some materials such as bricks and roof tiles may be damaged [3].

3.4. Impact Assessment

Based on the above analysis, the life cycle energy analysis of these houses is shown in Figure 4. It can be seen that due to possible malfunction of the electricity meter, House E has an un-believably low operational energy, which should be excluded from the study. Although House G has relative low embodied energy and demolition energy, it has the highest life cycle energy if the energy used for DHW is included. After excluding DHW in operational energy and internal walls in embodied energy, it still has the third highest life cycle energy.

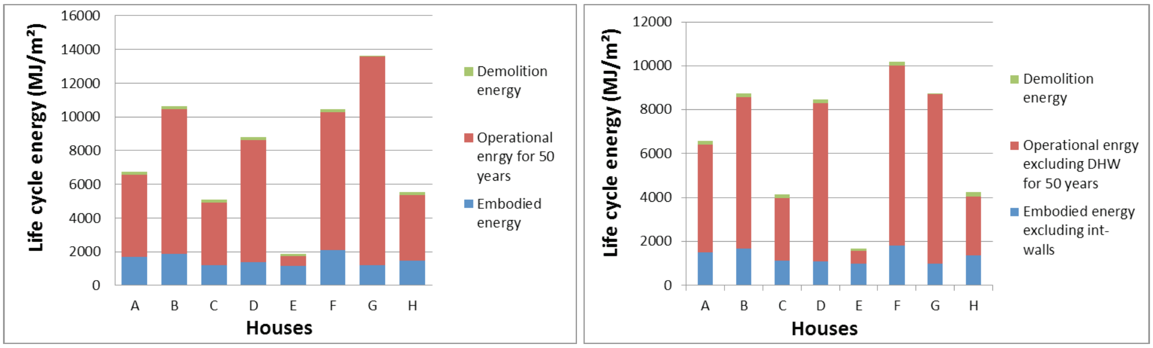


Fig. 4. Life cycle energy analysis of the studied houses.

Overall, it was found from this study that the demolition energy generally takes less than 4% of life cycle energy. This was in comparison with the embodied energy which may vary from 10% to 30%, and the operational energy which may vary from 65% to 90%.

4. Conclusions

Life cycle energy analysis (LCEA) of eight residential buildings in and around Brisbane, Australia, has been undertaken in this study. Energy used in all three phases of construction, operation and demolition has been considered. It has also been shown that the embodied energy may vary from 10% to 30%, while the operational energy may vary from 65% to 90%. The demolition energy generally accounts for less than 4% of life cycle. The main contribution to the operational energy in residential building is from use of general appliance. Future research should study the trade-off between the embodied energy and operational energy, as well as the adoption of renewable energy.

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