

Life Cycle Energy Analysis

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Figure 1: House under construction, Sydney (Image: iStock)

ABSTRACT

Energy consumption is a widely used measure of the environmental impact of buildings. Numerous studies have highlighted the importance of both the operational and embodied energy attributable to buildings over their lifetime. The method of assessing lifetime building energy is known as Life Cycle Energy Analysis (LCEA). LCEA is an easily-conducted form of Life Cycle Assessment (LCA) and one which is particularly relevant to the building industry.

This note briefly explains some of the theoretical issues associated with LCEA and then uses a case study to demonstrate its use in evaluating alternative design strategies for a residential building.

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Introduction

The aim of this note is to demonstrate and discuss how Life Cycle Energy Analysis (LCEA) can be used in the context of energy efficient buildings.

The significance of greenhouse gases attributable to building operation is well understood. However, the environment is also degraded in the mining of raw materials, the manufacturing of building materials and products, and finally their transportation and assembly into buildings. Over their lifetimes, buildings are maintained, refurbished, extended and finally demolished. In addition, resources, particularly energy, are consumed in their day-to-day operation. The assessment of the environmental impacts of buildings or other products throughout their lifetimes is known as Life Cycle Assessment (LCA). LCA attempts to provide a measure of the overall environmental impact of a product. Variables assessed include fossil fuel-based energy and other non-renewable resource requirements, as well as various emissions to soil, water and air.

LCEA can be used to estimate the net savings over a building's life and, perhaps more importantly, the 'energy payback period' (the time taken for the initial embodied energy cost to be paid back by operational energy savings accrued)

LCEA, on the other hand, uses energy as the *only* measure of environmental impact. The purpose of an LCEA is not to replace a broader environmental assessment method, such as an LCA, but rather to facilitate decision-making concerning energy efficiency. Comparing the embodied energy of a building to its operational energy can indicate potential life cycle energy efficiency and conservation strategies. Similarly, LCEA concepts can be used to demonstrate the life cycle benefits of strategies designed to optimise the operational energy or embodied energy of a building.

The main benefit of LCEA is that the embodied energy costs of products, design modifications and strategies used to optimise operational energy can be evaluated. For example, thermal insulation has an embodied energy cost – the energy to make the insulation – but savings in operational energy accrue over time. LCEA can be used to estimate the net savings over the building's life and, perhaps more importantly, the 'energy payback period' (the time taken for the initial embodied energy cost to be paid back by the ongoing operational energy savings accrued). The life cycle energy implications of an energy-saving strategy need to be considered in net terms. For example,

the installation of additional insulation would have a further embodied energy cost at the start of the life of the building. Assuming no replacements are required over time (i.e. that the insulation lasts well), the annual additional benefits in thermal performance that accrue can be modelled as further savings in energy consumption of the heating and cooling system. (In reality, some of the benefits may also be taken as improvements in comfort.)

Life cycle energy comprises the operational energy of the building and its initial and recurrent embodied energy (see below) over its expected lifetime. Life cycle energy is calculated using the equation:

$$LCE = E_i + E_{rec} + (OE \times \text{Building lifetime})$$

where:

LCE = the life cycle energy;

EE_i = the initial embodied energy of the building;

EE_{rec} = the recurrent embodied energy (for future maintenance and refurbishment); and

OE = the total annual operational energy (including thermal and non-thermal).

In LCEA, the energy embodied in a building and the energy used in the operation of the building are calculated for the anticipated lifetime of the building. Simulation methods for embodied and operational energy have been developed, however like all methods such simulations have in-built assumptions and limitations which reduce the accuracy of the results. These methods used to calculate embodied energy, operational energy and life cycle energy, together with their limitations, are discussed below, and then a LCEA of a case study building is presented.

Embodied Energy

The energy embodied in a product comprises the energy to extract, transport and refine the raw materials, and then to manufacture components and assemble the product. The energy consumed directly at each phase is clearly definable and measurable. However, the energy required indirectly to support the main processes is less obvious and more difficult to measure. This includes the energy embodied in other inputs of goods and services and the machinery used to support these processes (for example, the forklift trucks that load materials in a factory). The total embodied energy comprises the direct energy purchased to support the process under consideration plus the indirect energy embodied in inputs to the process.

In the initial construction of buildings, the direct energy is the energy purchased by contractors on-site and off-site to facilitate any construction, prefabrication, administration and transport activities under their control (i.e. including sub-contractors). The indirect energy of construction is mainly comprised of the energy embodied in building materials. Together, these amounts of energy constitute the initial embodied energy of the building. However, during a building's life, embodied energy is added through goods and services used in maintenance and refurbishment. These are usually modelled by assuming typical replacement rates for items in the building (for example, paint) and are known as the recurrent embodied energy.

EMBODIED ENERGY CALCULATION METHODS

Three main methods have been developed to calculate embodied energy as accurately and as completely as possible: process analysis, input-output analysis and hybrid analysis.

Process Analysis

In theory, although not necessarily in practice, the simplest embodied energy analysis method is known as process analysis. It is also the most commonly-used method.

Process analysis focuses on the energy required for particular industrial processes. In brick-making, for example, the energy metered at the factory boundary can be measured (i.e. the direct energy requirement). However, such a measurement is incomplete because it excludes, for example, the energy used to extract clay from the ground and then to transport it to the brickworks (i.e. the indirect energy). Process analysis can be used to measure the energy used, per brick say, for many of these processes. However, at each stage there may be many large or small inputs of goods and services which cannot all be covered in detail using the process analysis method (Boustead and Hancock 1979).

Input-Output Analysis

A method that can provide an estimate of all direct and indirect energy embodied in a product is known as input-output analysis. This method makes use of national statistical information compiled by governments for the purpose of analysing national economic flows between sectors. These economic flows can be translated into energy flows using average energy tariffs. While theoretically complete, this method has several methodological problems. Consequently, it is not considered reliable for embodied energy analysis of an individual product (Crawford 2008, 2011).

Hybrid Analysis

A third method, known as hybrid analysis, combines the strengths of process analysis (reliable energy consumption figures for particular processes) with those of input-output analysis (theoretically complete system framework) while eliminating, as much as possible, their weaknesses (incompleteness and inherent errors, respectively) (Bullard et al. 1978). The most important deficiency with the hybrid analysis method, however, is the lack of a comprehensive and reliable database of energy use data from industry. More often than not, unreliable input-output data has to be relied upon for many significant processes, which may include the main process in the case of construction, or processes which may be several transactions upstream from the main process.

Operational Energy

Operational energy comprises the energy used for space heating and cooling, hot water heating, lighting, refrigeration, cooking and appliance and equipment operation. Heating and cooling energy is often simulated using computer programs such as EnergyPlus, TRNSYS, IES-VE or DOE2.2. Many of these programs are difficult to use, due to their complexity. For further information refer to Crawley et al. (2008). Other programs, such as AccuRate, work more as design tools to help designers understand and improve the heating and cooling energy efficiency of building designs. AccuRate uses the CHENATH calculation engine but provides a more user-friendly interface than some of the more complex energy simulation programs. AccuRate allows numerous variations to a building to be modelled rapidly and because it interfaces directly with the simulation engine it is more reliable for modelling non-standard conditions, such as highly efficient buildings. The simulation engines within the various simulation programs, such as the CHENATH simulation engine within AccuRate, have a history of development, validation and modification. Their output remains, nevertheless, a prediction of the thermal performance of the building and is subject to numerous limitations, errors and potentially faulty assumptions. Furthermore, simulation programs are incapable of modelling complex human behaviour. Despite the limitations, computer simulations allow large numbers of variables to be modelled and their impact evaluated for buildings not yet constructed.

Primary Versus Delivered Energy

Since energy is the basic unit of measurement in an LCEA, the form of energy must be clarified. Energy is metered at the point of entry to the property or building. The energy used by the consumer is known as delivered energy. However, a considerable amount of energy is used to produce the delivered energy and it varies according to fuel type (for example, electricity or gas) and the means of production (for example, coal-fired power station or hydropower). Consequently, energy should be measured in terms of primary energy – the energy required from nature embodied in the energy consumed by the purchaser. For every unit of electricity used in Australia, on average, approximately 3.4 units of primary energy, such as coal, are required (Treloar 1997). This ratio of 3.4 to 1 for electricity production, or simply 3.4, is termed the primary energy factor for electricity. Primary energy is proportional to energy-related CO₂ emissions. Therefore primary energy is a more appropriate measure of the environmental implications of energy use than delivered energy.

Primary energy factors should be applied to both the operational energy and embodied energy quantities, so that valid comparisons can be made. For example, electric hot water and gas-fired hot water systems are not comparable in delivered energy terms, especially if coal is required to make the electricity (assuming otherwise equal performance). Similarly, if competing building materials or systems are manufactured using different fuel sources, then a comparison in delivered energy terms may be invalid.

LCEA Case Study

For simplicity and clarity, LCEA is demonstrated here for a residential project. The building analysed is a single-storey detached brick veneer house designed and built by Metricon Homes in Melbourne (see Figure 1). The house was designed to meet minimum regulatory requirements for energy efficiency. The habitable floor area of 270m² is only slightly larger than the average new home currently being built across Australia's suburbs.



Figure 2: Case study building, Melbourne
(Source: Metricon Homes)

Embodied Energy Analysis Method

A hybrid method was used (see boxed text, above), with product quantities calculated using process analysis (i.e. analysing the building materials required for the initial construction of the building) and embodied energy coefficients calculated using input-output analysis. National average input-output analysis suggests that the direct energy of residential construction is approximately 3% of the total embodied energy of the building (Treloar 2007). This ratio was factored into the calculations for the case study building. The recurrent embodied energy was simulated using replacement factors for many of the items in the building. They included – among others – paint (10 years), windows (50 years), plumbing and electrical systems (25 to 75 years), appliances (13 to 25 years) and roofing materials (25 to 50 years).

The analysis included all major appliances that may be fitted to a building prior to hand-over (for example, stove, dishwasher, air-conditioner and heater). Minor appliances, such as microwaves and toasters, as well as furniture were not included.

Operational Energy Analysis Method

While some LCEA studies include only the heating and cooling energy, all household operational energy is included in this study (including 'non-thermal' energy requirements such as the energy used for lighting, cooking, hot water, appliances and other power). The purpose of including non-thermal operational energy was to give a context to the relative importance of energy efficiency strategies such as adding more insulation. Heating and cooling energy requirements were simulated using the computer program TRNSYS. Non-thermal energy requirements were derived by deducting typical figures for thermal energy requirements from figures giving total household operational energy requirements (see 'Operational Energy' below).

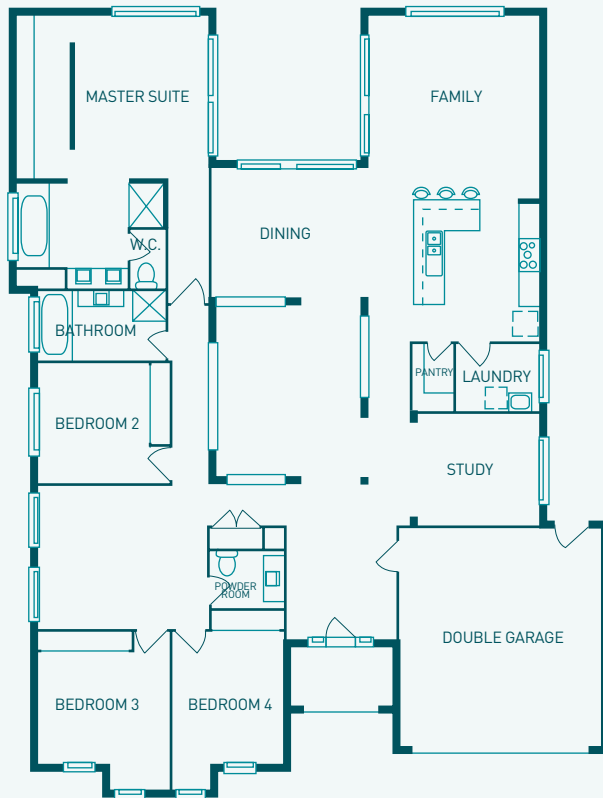


Figure 3: Case study building plan (Source: Metricon Homes)

The base case scenario for the house required a number of assumptions including thermostat settings (heating to 18° and cooling to 24°) and hours of operation (13 hours per day). Others are default settings in the TRNSYS program, such as air infiltration and ventilation rates. Other assumptions and characteristics of the base case simulation, although not necessarily of the house as built, included:

- the long axis runs north-south and the living areas are north-facing
- construction comprises brick veneer external walls with stud framed internal walls, concrete slab floor and tiled roof
- walls have R2.0 bulk insulation, ceilings have R3.0 bulk insulation and the roof has foil insulation
- windows are a mixture of single- and double-glazed as well as aluminium- and timber-framed

Heating was assumed to be delivered by a ducted gas-fired warm air system, having an efficiency of 70% while the air-conditioning system was assumed to have an efficiency of 250%.

A single variation to the base case, a higher level of insulation, was then modelled. Insulation was increased from the base case to R2.5 bulk insulation in the walls and R5.0 bulk insulation in the ceiling.

Life Cycle Energy Analysis Method

Life cycle energy analyses over lifetimes of 0, 25, 50, 75 and 100 years were carried out for the building with insulation to National Building Code requirements (i.e. the base case) and then for the same building with a higher level of insulation. Annual operational energy consumption was assumed to remain constant throughout the life cycle of the house. However, future trends are difficult to predict due to a combination of efficiency improvements (reductions in energy use), increased user comfort expectations (increases in energy use) and changes in energy pricing, legislation, behaviour, personal affluence and community attitudes to the environment (net increases or reductions in energy use). Various models were produced using a range of lifetimes, to demonstrate their implications for the case study building.

Case Study Results

The results for the embodied energy, operational energy and life cycle energy are expressed as a square metre rate based on the habitable area of 270 m², allowing comparison with other dwellings differing in size. The operational energy and embodied energy of the house were simulated using a number of assumptions regarding construction and operational use patterns.

For this reason, the results of this study may not agree with either the design predictions or the actual performance. Only one energy efficiency measure, i.e. of additional insulation, was analysed in life cycle terms. However, this demonstration shows how other energy efficiency and conservation strategies can be considered in life cycle terms, both in terms of the net benefits and the proportional improvement to the total life cycle energy.

Embodied Energy

Embodied energy was calculated for the base case and then for a higher level of insulation (see Operational Energy Analysis Method above). Initial embodied energy for the house was calculated to be 3971 GJ (14.7 GJ/m² of floor area). This value is considerably higher than many other embodied energy studies for houses (for example, see Pullen (1995), where values of approximately 5 GJ/m² were reported). This is because the results reported here were derived in primary energy terms, with a wider system boundary than most previous studies, including such features as major appliances and other small items often neglected.

Due to recurrent embodied energy requirements, the total embodied energy for the house increased over time (Figure 4). For example, for the base case, the effects of replacing items in the building over 50 years amounted to 6.8 GJ/m² of floor area. Included in the figures in Figure 4 is the increasing life cycle embodied energy for the building, due to the addition of a higher level of insulation (see 'Operational Energy Analysis Method'). The additional insulation increased the embodied energy of the house initially from the base case by 0.2 GJ/m² of floor area (i.e. this was not a recurring item). At this stage, the operational energy of the house is not included.

Age of house (years)	Base case	With additional insulation
0	14.7	14.9
25	15.9	16.1
50	21.5	21.7
75	28.1	28.3
100	34.8	35.0

Figure 4: Life cycle embodied energy for the house (GJ/m²)

Operational Energy

The thermal energy result for the base case, in primary energy terms, was calculated to be 46.2 GJ/annum (i.e. 0.17 GJ/annum per m² of building area). This house is relatively energy efficient, compared to an estimated average of approximately 54.4 GJ/annum (i.e. 0.2 GJ/m²) – based on an assumed 34 GJ of delivered energy (DEWHA 2008, p.46), a weighted primary energy factor of 1.6 used to account for a 10% cooling load and gas space heating and cooling appliance efficiencies of 70% and 250%, respectively (AGO 1999, p.103). The thermal energy result for the variation to the base case with a higher level of insulation was 0.14 GJ/m², representing an 18% reduction over the base case.

Non-thermal energy requirements, i.e. the energy used for lighting, cooking, hot water, appliances and other power, were based on estimates for household energy use. It was assumed that the average home in Victoria consumes 76 GJ/annum of delivered energy (DEWHA 2008, p. 31 and 72) and that non-thermal energy comprises 55% of total energy use. This 42 GJ of non-thermal delivered energy represents approximately 101 GJ (i.e. 0.37 GJ/m²) of primary energy, assuming an average primary energy factor of 2.4 for an even mix of electrical and gas use.

The initial embodied energy required for the additional insulation is paid back by net savings in heating and cooling energy in 6.3 years. In 25 years, the net benefit represents 297% of the initial embodied energy cost

Life Cycle Energy

Figure 5 demonstrates that the total life cycle energy reduced only marginally due to the addition of insulation to the base case. Over 25 years, the improvement was only 2%, increasing to 3.2% over 100 years. However, other factors are contributing to this comparison, such as increases in embodied energy due to replaced items. It is important to know the context for the relatively small improvement, because this might suggest that other strategies may reap more benefits, perhaps with lower initial embodied energy and financial costs.

Age of house (years)	Base case	With additional insulation
0	14.7	14.9
25	29.4	28.9
50	48.7	47.3
75	68.8	66.7
100	89.1	86.2

Figure 5: Life cycle energy for the house as constructed (GJ/m²)

A breakdown of the different contributors to the total life cycle energy of the case study house shows the significance of the initial embodied energy as well as the non-thermal operational energy. Figure 6 shows this comparison for the base case house over a lifetime of 50 years.

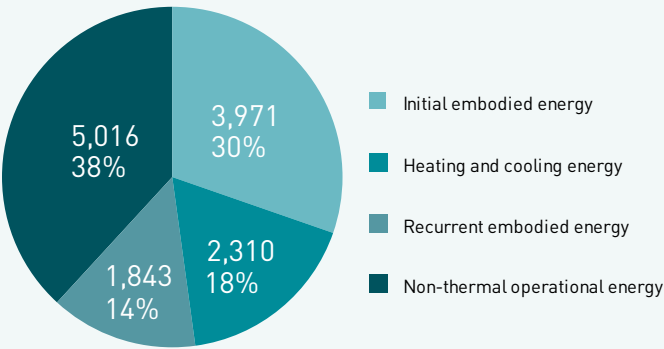


Figure 6: Life cycle energy of base case house over 50 year life cycle

To aid decision-making in terms of the long-term benefits of additional insulation, it is more helpful to perform a life cycle energy cost/benefit analysis (Figure 7). In this chart, the initial embodied energy required for the additional insulation (i.e. 0.2 GJ/m²) is paid back by net savings in heating and cooling energy (i.e. 0.03 GJ/m²/annum) in 6.3 years. In 25 years, the net benefit represents 297% of the initial embodied energy cost of the additional insulation. However, over 100 years (the likely physical life of the house if well maintained), the net benefit represents 1490% of the initial embodied energy cost of the additional insulation.

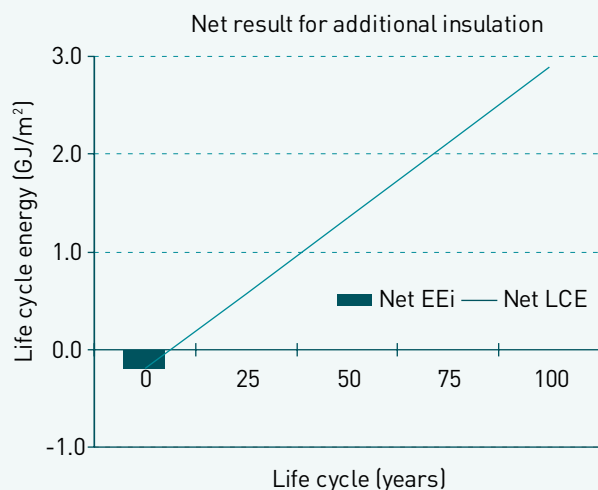


Figure 7: Life cycle energy cost/benefit for additional insulation

Discussion

Even considering that the overall net life cycle saving due to the additional insulation was less than 4% of the total calculated for the case study building, the life cycle energy cost/benefit analysis suggests that, if saving energy (and the associated environmental impacts) in the long term is a priority, then additional levels of insulation may well be justified. However, other issues come into play in this decision, including:

- the assumption that the insulation will last a long time at peak performance
- whether renewable energy generation devices will be installed (i.e. changing the type of benefits of energy efficiency measures from energy savings to possible reductions in the size of renewable energy devices)
- the additional financial cost of the insulation, and whether that is paid back over time
- and other implications for construction and environmental impacts associated with using additional insulation.

The broad life cycle energy results given in Figure 5 suggest that other energy efficiency and conservation strategies may be more effective than increased insulation, for example:

- high performance windows (for example, double glazing)
- high mass (for example, low embodied energy but massive materials)
- reduced infiltration losses (for example, an air-to-air heat exchanger in conjunction with tighter, less leaky construction)
- wider thermostat settings and shorter heating times

- renewable energy generation facilities (for example, solar power systems)
- correctly sized windows oriented appropriately
- more efficient systems and appliances
- reduced building floor area.

Conclusions

In summary, while the additional insulation improved the life cycle energy of the case study building by only a small amount, the decision was found to be worthwhile in net terms.

The LCEA method demonstrated here provides a framework for decision-making relating to energy efficiency strategies. It can provide information on:

- achieving a balance between embodied energy and operational energy over the anticipated lifetime of buildings (for example, how much insulation)
- the energy-related environmental impacts of demolishing, replacing or refurbishing a building at various stages in its life
- other design strategies to reduce energy-related environmental impacts

Other conclusions derived from LCEA research as described in this note are that:

- embodied energy is significant, relative to operational energy
- as operational energy is reduced (through efficiency improvements/life style changes), embodied energy becomes more significant
- while a zero operational energy building is now achievable, a zero life cycle energy building will be much more difficult

Energy is part of the broader sustainability problem, which also includes resource depletion, pollution from manufacturing and transportation, together with social and economic inequities. However, energy is currently an important parameter to optimise because of its national and global significance in gross terms. By widening the system boundary of the problem, counter-intuitive opportunities for the development of energy conservation and environmental impact strategies can be identified.

Furthermore, in environmental terms, the relatively high importance of the initial embodied energy of a building may suggest that new construction is not always the best solution. Renovation of an existing building may offer considerable embodied energy and financial savings, with the opportunity to provide equal

amenity and perhaps improved efficiency. For new buildings, design flaws such as redundant structure, inefficient planning and circulation, and ineffective shading devices and similar features present opportunities for developing optimisation strategies.

Other opportunities include substituting materials with low embodied energy for energy intensive ones, reducing construction waste, reusing products, using products with a high recycled content and designing for adaptability, durability, recyclability and deconstruction.

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