The Life Cycle Cost - Energy Relationship of Buildings

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ABSTRACT

Buildings account for nearly 45% of the worldwide energy consumption and carbon emissions, and play a vital role in formulating sustainable strategies. Many regions and countries have set targets to achieve low or zero energy in their building energy policies. However, despite the policy drive, the uptake of low energy building (LEB) has been low in practice. Previous research on LEB was largely technical solutions oriented. Some examined the impacts of low energy design solutions on the economic effectiveness and energy efficiency of the building over the building's lifespan, but there is still a lack of exploration of the embedded relationship between the cost and energy performance of buildings.

The aim of this paper is to explore the relationship between the costs and energy consumption of buildings from the life cycle perspective. A combination of a critical literature review and case studies of 5 residential buildings selected from UK and Australia was employed for the research. The results of the review suggest that there is second order polynomial regression relationship between the costs and energy consumption of buildings over their lifespans. The optimizations of the cost and energy efficiency of buildings are found to be not mutually exclusive goals, which need to be considered in a synergistic way in order to allow low energy designs and construction practices to be achieved cost-effectively. The findings should inform designers in their decision-making on building design and material selection to make LEB more cost attractive. The identified life cycle cost-energy relationship contributes a novel life cycle perspective to future systemic research into building energy and economics.

Keywords: *low energy building, cost-energy relationship, life cycle assessment*

1. INTRODUCTION

Buildings take up nearly 45% of the worldwide energy consumption and carbon emissions (Butler, 2008). With the population growth, building services enhancement, comfort level increase and the rise in time spent inside buildings, building energy consumption will experience a predictable growth in the coming future (Pérez-Lombard et al., 2008). It is therefore very important to improve the energy efficiency of buildings in order to alleviate the building energy demand but provide the same or even higher level of the indoor comfort for inhabitants. Low energy building (LEB) has been drawing more and more attention as a result of its superiority on addressing the shortage of energy supply from the building sector through a comprehensive energy systems design.

A number of religions and countries have set regulatory targets to achieve low or zero energy in new buildings within the next decades as part of their building energy policy, like EU and US (Recast, 2010; Sissine, 2011). Despite the policy drive of LEB, the diffusion of LEB in the building market is however slow (Pan, 2014; Pan and Ning, 2015). The prohibitively high costs of low energy design solutions added to buildings are identified as the main barrier (Pellegrini-Masini et al., 2010). A challenging task for architects and other building professionals today is to design and promote LEB in a cost effective and environmentally responsive way (Hui, 2001). Previous research on LEB was largely technical solutions oriented. Some examined the impacts of low energy design solutions on the economic efficiency and energy use of the general building over the building's lifespan, but scant research provided an insight into the embedded relationship between the cost and energy consumption of buildings. In addressing this gap in knowledge, the aim of this paper is to explore the relationship between the cost and energy consumption of buildings from the building's cradle-to-grave life cycle. Following this introduction, the paper investigates the cost effectiveness and energy efficiency LEBs in a systems manner in order to give a more comprehensive view on different technologies applied to the building. Based on the critical review, case studies of 5 residential buildings selected from UK and Australia is employed to examine the life cycle cost-energy relationship of buildings. The paper then compares and reflects on the results in relation to the findings of previous research, and finally draws conclusions.

2. COST EFFECTIVENESS AND ENERGY EFFICIENCY OF LEBS

In general, energy efficient measures are more indispensable compared with renewable energy and other technologies considering the restrictions come from the cost effectiveness and energy efficiency of the potential technologies as well as building surface area in real ZEB cases (Fong and Lee, 2012). In addition to these common considerations, many regions and countries have their own building energy standards and design guidelines based on the region's typical building designs, local climates, and construction practices (e.g. Zero Carbon Homes and Nearly Zero Energy Buildings in the UK (Regulations, U. B., & Directives, E. U. (2014), ASHRAE Energy-Related standards and guidelines in the US (Holness, 2008) and the Design Standard for Energy Efficiency of Public Buildings in China (Bureau, 2005)).

Author	Country	Building Type	Technologies	Energy Efficiency	Cost Effectiveness
Kneifel (2010)	US	Commercial building	Thermal insulation, low-emissivity windows, window overhangs, and daylighting controls	Conventional energy efficiency technologies can decrease energy use by 20–30% on average and up to over 40% for some building types and locations.	58% buildings have an adjusted internal rate of return above 3.0% with one year study period. Over 56% for all study periods have an AIRR greater than 10%.
Zhu et al. (2009)	US	Residential house	High performance windows, compact fluorescent lights, highly-insulated roofs, air conditioners with water-cooled condensers. PV tiles, thermal mass walls, integrated collector storage	A radiant barrier and a water-cooled air conditioner are major contributors to energy savings; insulated floor slab and thermal mass walls are ineffective. Photovoltaic roof tiles produce enough green power to cover the use, and solar water heater can reach peak efficiency of 80%.	PV tiles show a good financial return when rebates are considered. The Integrated Collector Storage (ICS) unit has a high efficiency but with a little higher thermal price. Thermal mass walls are too costly to have wide market appeal.
Marszal and Heiselberg (2011)	Denmark	Multi-storey residential building	PV and air/solar source heat pump; PV and ground-source heat pump; PV and district heating grid.	The most energy efficient solution is the one in which the PV installation is combined with PV/T and a solar heat pump.	The investment in energy efficiency is more cost-effective than investment in renewable technologies.
Moorea (2014)	Australia	Residential house	6 star building envelope, 8 star building envelop, photovoltaics (PV), a solar hot water (SHW) system).	A single detached 6 star BAU house was calculated to generate 8.3 t/yr of CO2-e for the operational phase of the house.	The ZEH scenario achieves pay-back in around 12 years for a high energy price or 14 years for a low energy price.
Morrissey and Horne (2011)	Australia	Residential building	Glasswool insulation ceiling, glasswool insulation wall, polystyrene insulation extruded, shading, windows and weatherstrip	'Six stars' scenario brings 24% energy efficiency improvement; 45% for 'Seven stars' scenario; 65%' for Eight stars' scenario.	For low energy price modeling, the 'seven stars' scenario produces optimal NPVs over 5 and 10 years time horizons,39.23$AUS/SqM CFA at 5 years and 48.95$AUS/SqM CFA at 10 Years; for high energy price scenario, 'eight stars' is the optimal across both 25 years and 40 years time-horizons (72.76$AUS/SqM CFA at 25 years and 99.96$AUS/SqM CFA at 40 years).

Table 1: A summary of cost effectiveness and energy efficiency of some recent studies of LEB

3. THE COST-ENERGY RELATIONSHIP OF BUILDINGS

Previous research has realized the importance of identifying the relationship between the cost and energy consumption of buildings. Gustavsson et al. (2010) penetratingly pointed out those connections, trade-offs and synergies between the cost and energy consumption of a building in different phases of the life cycle must be identified in order to ensure that any further energy efficiency improvement of the buildings could be achieved in a cost effective way. Langston and Langston (2008) investigated the relationship between the life cycle energy and capital investment of 30 recently completed residential and commercial buildings, and observed a positive correlation between the predicted life cycle energy and capital cost investment. The same correlation is also found between the embodied energy and cost investment of individual building components as well as of the entire buildings by Jiao et al (2012). Three commercial buildings in China and New Zealand were compared and the results show a stronger correlation of the individual building components compared with that of the entire buildings.

The research was carried out through the examination of the empirical studies of life cycle assessment of buildings. In total 5 buildings with 51 cases from UK and Australia were collected from previous relevant research. Table 2 gives a comprehensive overview of the main characteristics of the cases presented in literature. Where a source is reported to have more than one case, it means that either different design scenarios or research designs, i.e., energy price and studied lifespan, of the same buildings were presented in the source itself. Cases differ for country, climate, type of building, building parameters, type of construction method, assumptions on indoor climate design and occupant behaviour, and source of data (whether measured or calculated). For this reason, it would be inappropriate to directly compare the cases against each other. Rather, the overall variation of the life cycle cost-energy relationship within each individual case has been examined, and then these different variations have been compared amongst the various cases. Cases also differ in the anticipated assumptions for the values of key parameters that are applied in the cost and energy calculations, like discount rate, inflation and studied lifespan, and also floor area. Cost data (life cycle cost and NPV) and energy data were normalized per unit of area (dollar/ m^2) and per unit of area and time (kWh/m^2 year) in order to neutralize these differences.

Source	Country	Case numbers	Type of buildings	Area (m^2)	Lifespan (years)	Energy price	Data	Building designs
Cuellar-Franca and Azapagic (2014)	UK	1	Detached house	130	50	NA	T+G	Strip footing, foundations, brick external walls and pitched roofs with, concrete tiles
		2	Semi-detached house	90				
		3	Terraced house	60				
Moorea (2014)	Australia	4-6	Detached house	249.6	60	High	T	Photovoltaic panel, building envelope
		7-9			40			
		10-12			20			
		13-15			10			
		16-18			60	Low		
		19-21			40			
		22-24			20			
		25-27:			10			
Morrissey and Horne (2011)	Australia	28-30,	Detached house	126.52	40	High	T	Glasswool insulation ceiling, Glasswool insulation wall, Polystyrene insulation extruded, Shading, Windows, Weatherstrip glazing and internal wall insulation
		31-33,			25			
		34-36,			10			
		37-39,			5			
		40-42			40	Low		
		43-45			25			
		46-48			10			
		49-51			5			

Note: NA, not applied; G, graph; T, table and/ or text.

Table 2: General information of the selected cases

The relationship between the costs and energy consumption of the studied 51 cases are statistically very significant (Figure 1, 2 and 3). Although linear regression describes the data reasonably well, second order polynomial regressions accounted for more of the variance. In all cases, curvilinear patterns provide the best fit with the data. The r^2 values for the second order polynomial regressions are all equal to 1, which indicates the second order polynomial regressions perfectly fit the data. The limited data size should be taken into consideration for the high r^2 values.

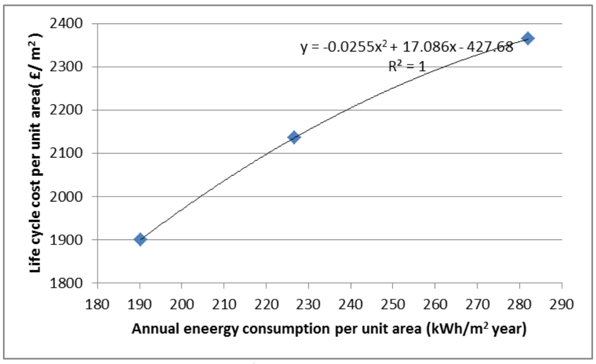

Figure 1: The relationship between the life cycle cost and energy consumption of Cases 1-3

The buildings in Case 1 to 3 are detached house, semi-detached house, and terraced house respectively with the difference in the floor area. The total life cycle cost per square meter increases gradually as the annual energy consumption per square meter grows (Figure 1). In a world, the most energy saving house may have the lowest life cycle cost. This result conforms to the general costs and energy consumption patterns of buildings. The assumptions made in this examined research are also quite reasonable. Owing to relative small proportion that construction cost takes in the overall life cycle cost of buildings, the construction and end-of-life costs are assumed to be similar for the detached house, semi-detached house and terraced house, albeit they are varies in building area. In addition, another assumption is that the household size for all three types of houses is the same, and thereby the energy used for water heating, cooking and appliances is the same. Therefore, it is not surprising that the larger floor area (e.g. detached house), which has a lower energy use per unit area, will have a lower life cycle cost per unit area than a smaller one (e.g. terraced).

In Cases 4-27, three different design scenarios with three different levels of annual energy consumption, i.e., 33.49, 48.08 and 60.9 kWh/m² in respective are applied in a detached house (Figure 2). Each group of data represents three different levels of annual energy consumption and associated NPV under different examined lifespans and energy prices. The figure shows that the NPV per unit area rapidly rise with the energy consumption per unit area goes up.

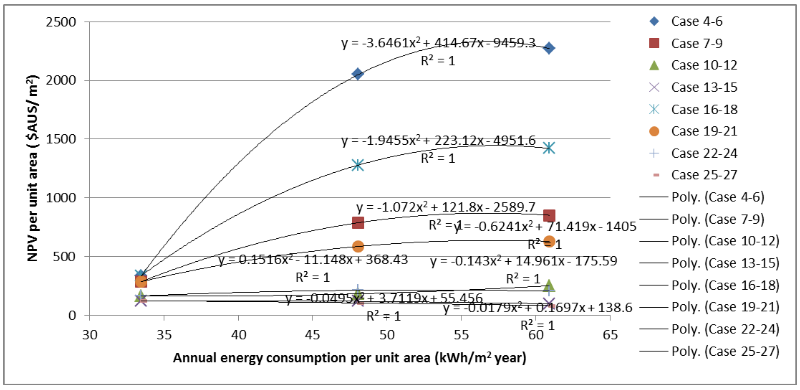

Figure 2: The relationship between NPV and energy consumption of Cases 4-27

In Cases 28-51, three different design scenarios with three different levels of annual energy consumption, i.e., 64,100 and 138kWh/m² in respective are applied in a detached house (Figure 3). Each group of data represents three different levels of annual energy consumption and associated NPV under different examined lifespans and energy prices. The figure shows that the NPV per unit area decreases slowly as the energy consumption per unit area increases.

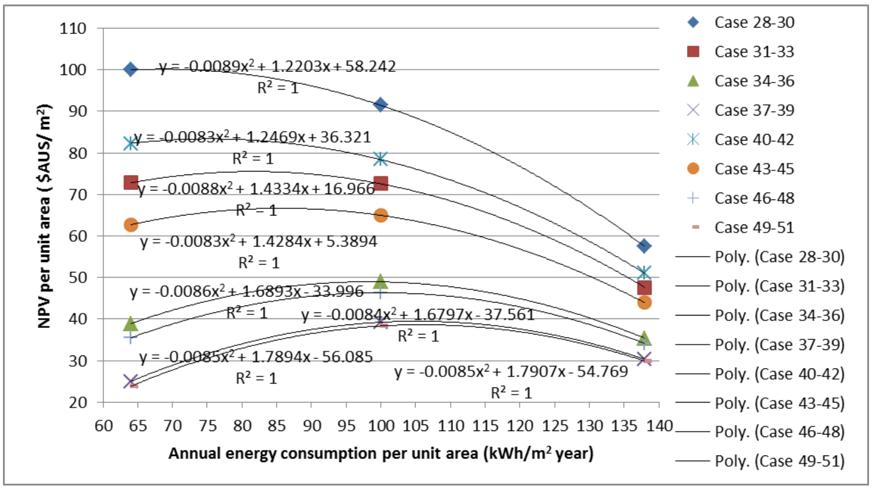

Figure 3: The relationship between NPV and energy consumption of Cases 28-51

Compared Cases 4-27 with Cases 28-51, the key similarity concluded from Figure 2 and 3 is that both energy-efficient and renewable technologies are found to have positive influences on the building's energy consumption and overall cost performance over the study periods. Furthermore, longer study lifespan and high energy price would bring a higher NPV compared with shorter study lifespan and low energy price. However, the major difference comes from the variation direction of the two groups of lines. In Cases 4-27, a positive relationship is found between NPV and annual energy consumption, while a negative relationship is found in Cases 28-51. Such difference may be attributed to the economic efficiency of examined low energy designs applied on buildings. Cases 4-27, both energy-efficient measures and renewable technologies (e.g. photovoltaic panel) are studied in the life cycle cost and energy performance evaluation of zero (net) energy house, while Cases 28 to 51 examined the impacts of energy-efficient measures only on the cost performance and energy consumption of the building. The economic efficiency of photovoltaic panel is relatively lower over economic-efficient technologies. The cost of installing photovoltaic panel is quite high in order to achieve a low level of energy consumption and therefore leads to a low NPV value. However, the high NPV will be abstained to achieve the same energy consumption level through the application of mere energy-efficient technologies.

4. DISCUSSION

The results of this study support the finding of previous research that a correlation is embedded between the costs and energy consumption of buildings over the building's lifespan. Also, this paper contributes to elaborating such relationship by deriving three improvements. Firstly, the results identify the second order polynomial regression relationship exists between the costs and energy consumption of buildings over their lifespans. Secondly, the results suggest the economic efficiencies of the applied low energy design solutions crucially determine such relationship is positive or negative. Finally, the results highlight the importance of the longer study lifespan in improving the significance of such relationship. Langston and Lauge-Kristensen (2013) emphasized that cost should also be accounted over a longer time span when conducting the life cycle costing of an asset since any shorter lifespan that is applied cannot ensure sufficient time for the energy efficient building to maximize its economic efficiency.

5. CONCLUSIONS

This paper has examined the embedded life cycle cost-energy relationship of buildings. The research was carried out through a combination of a critical literature review and case studies of 5 building selected from UK and Australia. The paper concludes that there is second order polynomial regression relationship exists between the costs and energy consumption of buildings over their lifespans. This paper suggests that the optimizations of the costs and energy efficiency of buildings are not mutually exclusive goals, which need to be considered in a synergistic way in order to allow low energy designs and construction practices to be achieved in a cost-effective way. The identified relationship between the costs and energy consumption of buildings can be exploited to enable better design solutions to be identified. The low and zero energy designs usually apply to exist the low-rise buildings from a variety of demonstration projects (Fong and Lee, 2012), especially in residential buildings. Nevertheless, it has been proven that a certain amount of potential for energy saving can be achieved on office buildings in Hong Kong (Lee and Yik, 2002). The embedded life cycle cost-energy relationship of high-rise buildings in Hong Kong should be investigated in future research to identify the most economical and environmental-friendly design solutions.

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