INFLUENCING PARAMETERS OF THE LIFE CYCLE COST-ENERGY RELATIONSHIP OF BUILDINGS

Jie Wang[1*] and Wei Pan, Ph.D.[2]

ABSTRACT
Buildings contribute around 45% of the world's energy consumption. Reducing energy demand in buildings therefore plays a vital role in addressing the depletion of energy resources and associated environmental issues. Previous research explored the optimisations of the costs and energy consumption of buildings, but often overlooked the connections, tradeoffs and synergies between them. The aim of this paper is thus to develop a theoretical model of the influencing parameters of the life cycle cost-energy relationship (LCCER) of buildings using the Political, Economic, Socio-cultural, Technological, Environmental and Legal (PESTEL) analytical framework. This study was carried out through a critical literature review, model development and validation through case studies with four zero or nearly zero energy building projects carefully selected from the European Union and Australia. The developed model addresses the buildings' LCCER by identifying the key influencing parameters and explicating the mechanisms (namely, the simultaneous and unilateral effects) by which the identified parameters affect such relationship. The important influencing parameters were found to reside in two aspects: (1) internal project designs covering building characteristics, building structure and function, and construction process, and (2) external environments covering climate, economic condition, occupant behaviour, policy and regulation, and buildings' lifespan focused in the studies. Various statistical correlations were found to exist between the costs and energy consumption of the studied cases. It is summarised that these correlations may be attributable to the synergy between the simultaneous and unilateral effects of the identified parameters. The developed model contributes a systemic approach to examining the building's life cycle economics and energy in a comparative manner.

KEYWORDS
cost, energy, life cycle approach, zero energy building

1. INTRODUCTION
The world's energy consumption has raised public concern over the shortage of the energy supply and related environmental issues, such as air pollution, global warming and climate

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change (Pérez-Lombard et al., 2008). According to the International Energy Agency (IEA, 2014), the world's electricity consumption has tripled during the last four decades, with an average annual increase rate of 3.6%. Buildings are responsible for around 45% of the world's energy consumption (Butler, 2008; Pan and Garmston, 2012). In addition, it is predicted that buildings' energy consumption will experience continuous growth given population growth, building services enhancement, comfort level increases and the increase in time spent inside buildings (Pérez-Lombard et al., 2008). Considering the significant contribution of buildings to the world's energy consumption, it is therefore essential to alleviate building energy use.

Hundreds of low or zero energy buildings (Pan and Li, 2016) have demonstrated the achievability of low or even zero energy building demand. A variety of energy-efficient approaches and materials used together on-site or off-site with a renewable energy supply can help decrease building energy consumption through a comprehensive and innovative building design (Li, 2013; Wang and Pan, 2015). Previous research on improving building energy efficiency was mainly technically-oriented. Some studies explored the optimisations of the costs and energy consumption of buildings, but they often overlooked the connections, tradeoffs and synergies between them.

There is a statistical correlation between the costs and energy consumption of buildings. Langston and Langston (2008) examined 30 recently completed residential and commercial buildings and observed a positive correlation between the capital cost investment and predicted life cycle energy. Jiao et al. (2012) compared three commercial buildings in China and New Zealand and found correlations between the embodied energy and costs of individual building components as well as of the entire buildings. However, limited research has investigated such relationships. The examination of the relationship between the costs and energy consumption of buildings through their life cycles is significant as it will pave the way for the achievement of both economic-effective and environmental-friendly design scenarios.

In addressing this gap in knowledge, the aim of this paper is to develop a theoretical model of the influencing parameters of the life cycle cost-energy relationship (LCCER) of buildings. The research was carried out through a critical literature review and case studies with four zero or nearly zero energy building projects selected from the European Union and Australia. Following the introduction, the paper investigates the influencing parameters of the costs and energy consumption of buildings over their life cycles. Based on the identified parameters, the paper then explicates the mechanisms by which the identified parameters affect the LCCER. After examining a theoretical model drawing on four case studies, the paper draws its conclusions.

2. METHODOLOGY

The research was carried out through the combination of a critical literature review and case studies with four carefully selected zero or nearly zero energy building projects. The extensive literature review was conducted to identify the influencing parameters of the life cycle cost (LCC) and life cycle energy (LCE) of buildings drawing on the Political, Economic, Socio-cultural, Technological, Environmental and Legal (PESTEL) analytical framework. A theoretical model of the influencing parameters of the LCCER was thereby developed to elaborate how these parameters influence such a relationship. The proposed model was validated and refined through case studies of four zero or zero energy building projects.

2.1 Method for Literature Review

In order to acquire a better understanding of the parameters that affect the costs and energy consumption of buildings throughout their lifespans, an extensive literature review on the LCC and LCE of buildings was carried out. The PESTEL analytical framework was used to identify the influencing parameters.

PESTEL is a useful strategic analysis tool for conducting market research. It enables a company to qualitatively evaluate the influence of the macro environment on a company. The macro environment of a company consists of political, economic, socio-cultural, technological, environmental and legal factors, which directly or indirectly affect the operation of a company. Apart from a technique for strategic business planning, the PESTEL analytical framework has been applied in the decision-making process of the building industry. Lv and Wu (2009) examined the macro environment obstacles faced by energy efficiency retrofits for existing residential buildings in China. However, Yüksel (2012) pointed out this framework could only address the macro analysis of the external environment, while it might overlook the influence of the internal environment. Previous research (e.g. Zhao et al., 2016; Pan et al., 2017) also analysed the challenges for the delivery of zero energy buildings and conducted a comprehensive examination of the macro business environment and micro company contexts by using the PESTEL analytical framework. This framework however shows a potential in microenvironment examination. Thus, this paper takes a holistic perspective in identifying the influencing parameters of the LCC and LCE of buildings, which contains both external environment analysis and internal project examination.

Although the PESTEL analytical framework provides important foundational knowledge in the precondition analysis, researchers argue that it has some limitations in terms of the relations and interactions between PESTEL factors. Thompson and Strickland (2001) pointed out that a political situation might give rise to economic and socio-cultural implications, and it was not possible to consider legal arrangements or economic conditions in isolation from political conditions. Yüksel (2012) indicated that independent measurement and evaluation of each PESTEL factor might not reflect the real macro environmental situation. These PESTEL parameters somehow interacted with each other, which would directly or indirectly influence company operation. While it should be acknowledged that, despite the cross-impacts existing between different factors, the indirect influence of any single factor will finally be realised through the direct influence of other factors, in this case, such indirect influence has already been taken into account by this framework. Therefore, this paper adopts the PESTEL analytical technique based on the interdependence of factors.

2.2 Method for Case Study

Four considerations were used for the selection of zero or nearly zero energy building projects for inclusion in this study. Firstly, the keywords of "zero or net (nearly) zero energy building" were used to describe and report the case buildings. Secondly, the selected zero or nearly zero energy building projects represent the pioneering practices of zero or nearly zero energy buildings worldwide. Thirdly, the selected case buildings cover both residential and commercial sectors to enable the provision of a comprehensive overview of the LCCER of buildings rather than of any particular building type. Finally, information on the life cycle cost performance and energy consumption of the case building projects was obtainable from accessible sources or channels.

Purposive sampling was used to enable the satisfaction of these criteria to cover as many parameters as possible. Both quantitative and qualitative information of the selected building projects was collected from relevant publications, websites and reports in order to obtain multiple perspectives on the elaboration of the projects. Meanwhile, an email questionnaire survey was administered with the providers of the information to ensure accuracy and also to facilitate gathering more details concerning the selected case projects for the case studies. The collected costs and energy data were tested and analysed through statistical analysis. Meanwhile, the collected text information was coded and interpreted in a way to verify the identified parameters. Through the case studies, the developed theoretical model was refined.

3. LITERATURE REVIEW

3.1 Life Cycle Costs of Buildings

LCC analysis of a building summarises the total discounted costs of owning, operating, maintaining, and disposing of a building or a building system over a period of time (Fuller and Petersen, 1996). It remains heavily contested concerning the scope, form and level of analysis together with an anticipated level of uncertainties and risks relating to the LCC analysis (ISO, 2008). Besides, the results of LCC analysis largely rely on the assumptions of key parameters, like study lifespan, discount rate, and inflation rate (Moore and Morrissey, 2014).

It is acknowledged that the study lifespan significantly influences the economic effectiveness of zero or nearly zero energy buildings (Aktas and Bilec, 2012; Mequignon, et al. 2013). Kneifel (2010) pointed out that a longer lifespan is more effective to capture all relevant costs of owning and operating a building. However, longer lifespans will inevitably bring about higher ongoing risks and uncertainties of future economic conditions, like energy price, discount rate and inflation rate. Moore and Morrissey (2014) summarised that, with a high energy price, a low LCC would be achieved compared to a low energy price. Discount rate and inflation rate are other important influencing parameters of the LCC of buildings by which future expenditures and incomes are adjusted to current values.

The adoption of off-site construction has been identified to have positive effects on building costs and energy performance to a certain extent. Lovell (2003) reported that the use of prefabricated housing in Britain led to increased construction costs by 7–10%, although this was qualified by reducing on-site labour costs of 50%, and yet, resulted in energy savings during building operation due to the increase of insulation levels and the decrease of air leakage. Nevertheless, from the building's life cycle perspective, off-site construction offers financial benefits to projects through minimising non-construction costs (e.g., management, design, tendering costs) and construction costs, and thereby the life cycle costs of the building (e.g., more efficient maintenance) (Blismas et al., 2006).

Policy instruments also play a vital role in the economic effectiveness of zero or nearly zero energy buildings. A mix of incentives for the installation of roof-mounted photovoltaic (PV) panels in the UK, such as the Feed-In Tariff (FiT) and other support schemes, has been reported to overcome the economic barriers of these renewable technologies (GBC, 2014). Whereas, fees and taxes are other important policy instruments, a number of countries and regions levy taxes on natural resources to promote recovery and reuse of demolition materials (European Commission, 2001; Swedish Government, 2003; Thormark, 2001). Therefore, a building's economic effectiveness will be greatly influenced by these policy instruments.

3.2 Life Cycle Energy of Buildings

LCE analysis of a building counts all energy inputs to a building across its life cycle. A building's life cycle may be in the form of cradle to gate, to site, to operation, to grave or to cradle, depending on how it covers these stages (Pan, 2014; Wang and Pan, 2015). The life cycle energy of a building comprises the embodied energy, operational energy and end-of-life energy use. Generally, the embodied energy sums up the initial embodied energy and recurring embodied energy (Teng et al. 2018); the former is the energy required to extract the raw materials, manufacture components, transport materials to site and construction of the building, while the latter is the energy required for building maintenance and refurbishment.

Embodied energy includes energy use for material manufacturing, transport to site and on-site building construction. First, energy embodied in building material manufacturing is dramatically influenced by a wide range of factors, including different proportions of materials used in building construction, and materials with different exploitation methods, production processes and recycle rates. Gustavsson and Sathre (2006) estimated that energy embodied in material manufacturing constitutes around 10–20% of the building's total energy use. Cole and Kernan (1996) summarised that the initial embodied energy of a steel structure is 1.61 times greater than that of a concrete structure and is 1.27 times greater than that of a wood structure.

Second, energy use for transport of materials to site also adds significantly to the total embodied energy. It includes the energy use for producing semi-products from natural materials (e.g. making steel from iron ore, extraction and refinement of various types of fuels and electricity generation), to transport materials to the site from domestic and overseas sources (by railroad, trucks, and deep-sea vessel), and to the final demolishment, recycle and reuse of the deconstructed materials, and various waste treatment processes (e.g. incineration and landfill). Average energy intensity in different modes of transportation, such as deep-sea transportation and class railroads, and types of fuel play a significant role in addition to the distance of travel in transporting energy use (Sundarakani et al., 2010).

Finally, the energy need for on-site construction activities is an important constituent of the embodied energy, which includes energy used for power tools, heavy equipment and lighting, and associated transportation to the construction site. According to Cole (1998), on-site energy used included the energy use for the following categories, i.e. transporting the crews, materials and equipment, the on-site equipment, and supporting processes, such as formwork and temporary heating. Also, Jiao et al. (2012) stressed the necessity of counting the energy embodied in labour into the whole embodied energy of a building and defined energy embodied in labour during the construction period into two parts, i.e. personal or somatic energy and the energy expenditure to support the worker's lifestyle.

Building energy consumption during the operating stage contributes 80–90% of the overall energy demand of buildings (Ramesh et al., 2010). Pan and Li (2016) found that the vast majority of zero energy buildings they studied were found in mild or cold climatic regions. The local climate context will greatly affect the building operational energy use and thereby the building's energy efficiency improvements. Building energy system design, especially for building heating and ventilating air conditioning (HVAC) system, is of great importance to the building operational energy consumption as well as the life cycle energy use. It is observed that HVAC accounts for 70–80% of total energy in fully-air-conditioned commercial buildings in Hong Kong (Lam and Chan, 1994). Moreover, the achievement of low energy demand in buildings relies heavily on the management of occupant behaviour and activities. Studies on occupant behaviour indicated a large potential for reducing life cycle energy use and thereby improving the building economy by motivating energy efficient behaviour (Masoso and Grobler, 2010). Many sensitive parameters of the building energy use are related to occupant behaviour, e.g., by the time and type of window opening, the use of air-conditioning (AC) units or the choice of indoor temperature set point (Fabi et al., 2012).

Researchers (Chen et al., 2001; Langston and Langston, 2008; Gustavsson and Sathre, 2006; Monahan and Powell, 2011) argued that significant energy savings from recycling and reuse of the demolished materials should also be included in the building's life cycle energy analysis. Thormark (2000) reported that the embodied energy decreased about 45% in a one-family building when the demolished materials were used. For new buildings, the recycling potential was as high as about 55% of the embodied energy (Thormark, 2000). On a national scale, the potential energy saving through recycling building waste is about 50% of the embodied energy (Thormark, 2001).

Through the extensive literature review, the influencing parameters of LCC and LCE of buildings are identified and listed in Table 1.

4. A THEORETICAL MODEL OF INFLUENCING PARAMETERS OF BUILDING'S LCCER

A theoretical model of the influencing parameters of building's LCCER is developed in this paper, which is shown in Figure 1. This model integrates the fifteen important parameters (listed in Table 1) that were identified through the literature review in the PESTEL aspects.

The connections between the identified parameters cannot be overlooked. For example, energy price will partly determine the occupant attitude toward energy consumption, and so occupants will embody such an impact on their behaviour and daily activities, thereby influencing the LCCER of buildings. However, the cross-impact of the identified parameters on the LCCER of buildings is already contained within the effects of occupant behaviour.

A further examination of these parameters was conducted to investigate the mechanisms by which the identified parameters affect such relationships. The influences of these parameters on the LCCER are different, which can be divided into two types i.e., simultaneous effect and unilateral effect. Simultaneous effect denotes the parameter effects on both the costs and energy performance of buildings, and so, it somehow has a direct influence on the LCCER of buildings, while, the unilateral effect expresses the parameter effects either on the costs or energy consumption of buildings, and finally has an influence on such relationships. Figures 2 and 3 provide the sketches of these two effects.

The identified influencing parameters are further sorted into two types according to the definitions of simultaneous and unilateral effects. Figure 4 shows the divisions of the identified influencing parameters. Some parameters simultaneously affect the building's costs and energy performance, for example, construction method. The selection of the off-site prefabrication over the traditional on-site construction has a positive influence on a building's costs and energy performance over the construction and operation stages (Lovell, 2003; Blismas et al., 2006). While other parameters only affect the costs or energy performance of buildings. For example, local climate is of great importance to the building's operational energy consumption and thereby the life cycle energy demand, but barely has a direct impact on a building's LCC, whereas the LCC of buildings is greatly variable with the economic condition, especially the

TABLE 1. Influencing parameters of LCC and LCE of buildings.

Influencing parameters	LCC of buildings	LCE of buildings
Political		
Building energy regulation	—	GBC (2014); HMT (2010)
Policy instrument	European Commission (2001); Swedish Government (2003)	Thormark (2001); Scheuer et al. (2003)
Economic		
Discount Rate	Moore & Morrissey (2014); Moore (2014); Cuellar-Franca & Azapagic (2014)	—
Inflation Rate	Moore & Morrissey (2014); Cuellar-Franca & Azapagic (2014); Moore (2014)	—
Energy Price	Moore (2014); Morrissey & Horne (2011); Cuellar-Franca &. Azapagic (2014)	—
Study lifespan	Moore (2014); Moore & Morrissey (2014); Morrissey & Horne (2011)	Moore (2014); Moore & Morrissey (2014); Morrissey & Horne (2011)
Socio-cultural		
Occupant behaviour	—	Yu et al. (2011); Al-Mumin et al. (2003); Blight & Coley (2013); Pan (2014)
Labour behaviour	Langston & Langston (2008); Jiao et al. (2012)	Langston & Langston (2008); Jiao et al. (2012)
Technological		
Building type	Cuéllar-Franca & Azapagic (2014); Somerville (1999)	Kneifel (2010); Sartori & Hestnes (2007); Yu et al. (2011); Wang et al. (2018)
Building structural frame	Moore (2014); Jiao et al. (2012); Keoleian et al. (2000)	Boyd et al. (2007); Cole & Kernan (1996); Gustavsson & Sathre (2006); Jiao et al. (2012); Cole (1998); Keoleian et al. (2000); Wang et al. (2018)
Building energy system	Pikas et al.(2014); Marszal & Heiselberg (2011); Moore (2014); Morrissey and Horne (2011)	Pikas et al.(2014); Marszal & Heiselberg (2011); Moore (2014); Morrissey and Horne (2011)
Transportation mode and distance	Jiao et al. (2012); Keoleian et al. (2000); Somerville (1999)	WRAP (2008); Blismas et al. (2006); Lovell (2003)
Construction method	Lovell (2003); Blismas et al. (2006); Jaillon & Poon (2009)	Gustavsson (1994); Cole & Kernan (1996); Kneifel (2010); Yu et al (2011); Gustavsson et al. (2010), Yu et al. (2011); Chappells & Shove (2005); Andersen (2009); Teng et al. (2018); Pan et al. (2017)
Environmental		
Climate	—	Kneifel (2010), Sartori & Hestnes (2007), Yu et al. (2011)
Legislative		
Waste treatment	Thormark (2001); Keoleian et al. (2000); Thormark (2000)	Keoleian et al. (2000), Thormark (2001)

FIGURE 1. A theoretical model of the influencing parameters of buildings' LCCER.

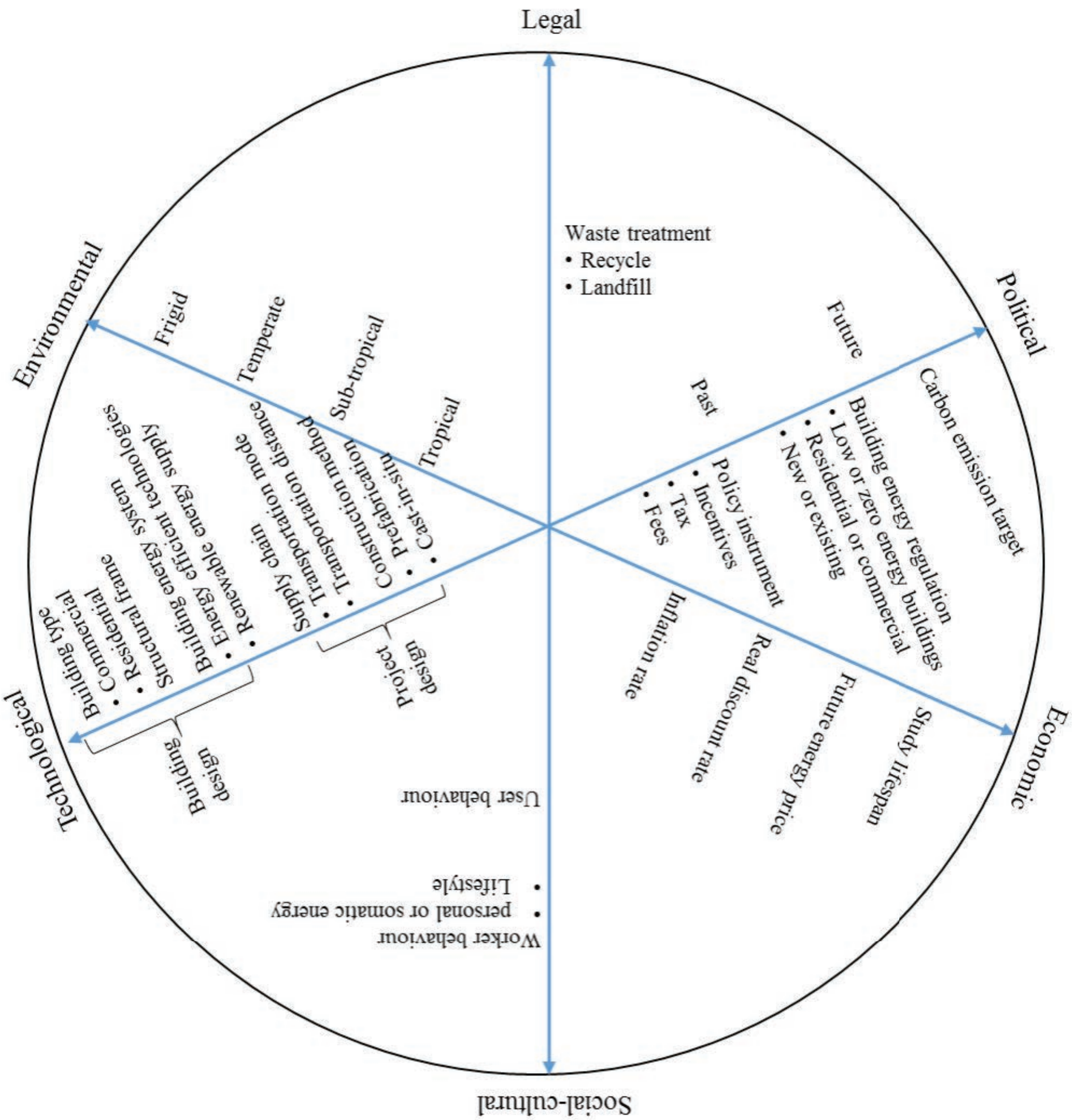
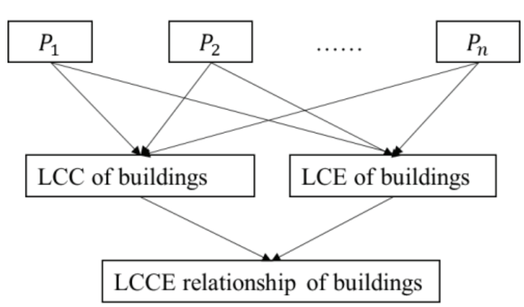
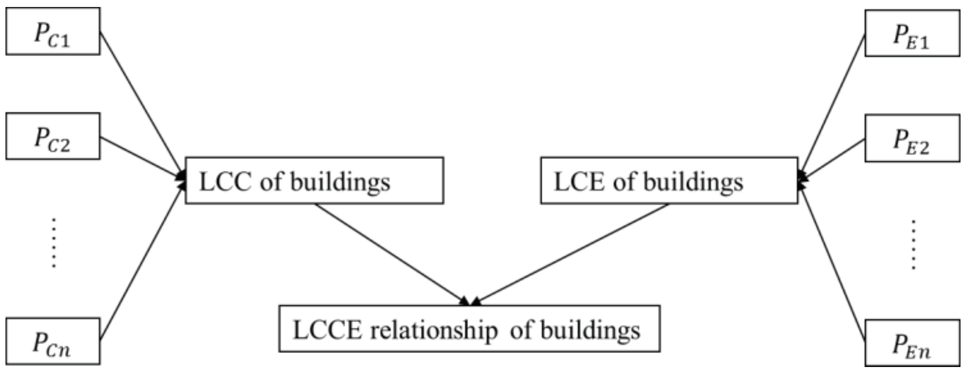


FIGURE 2. A sketch of the simultaneous effect.



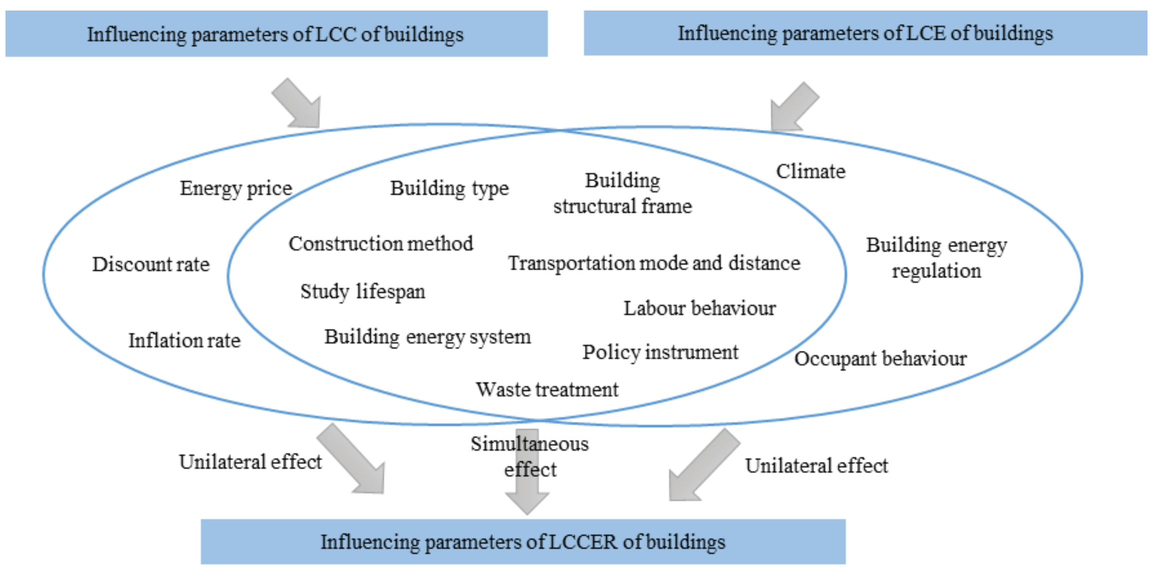
Note: P_i(i = 1,2,… …n) denotes the parameters that affect both the costs and energy consumption of buildings.

FIGURE 3. A sketch of the unilateral effect.



Note: $P_{Ci}(i = 1,2,\ldots\ \ldots n)$ denotes the parameters that only affect the costs of buildings; $P_{Ei}(i = 1,2,\ldots\ \ldots n)$ denotes the parameters that only affect energy consumption of buildings.

FIGURE 4. Division of the identified parameters.



discount rate and inflation rate. The correlations between the costs and energy consumption of buildings might be attributed to the synergy that occurs between these two types of effects.

5. CASE STUDIES

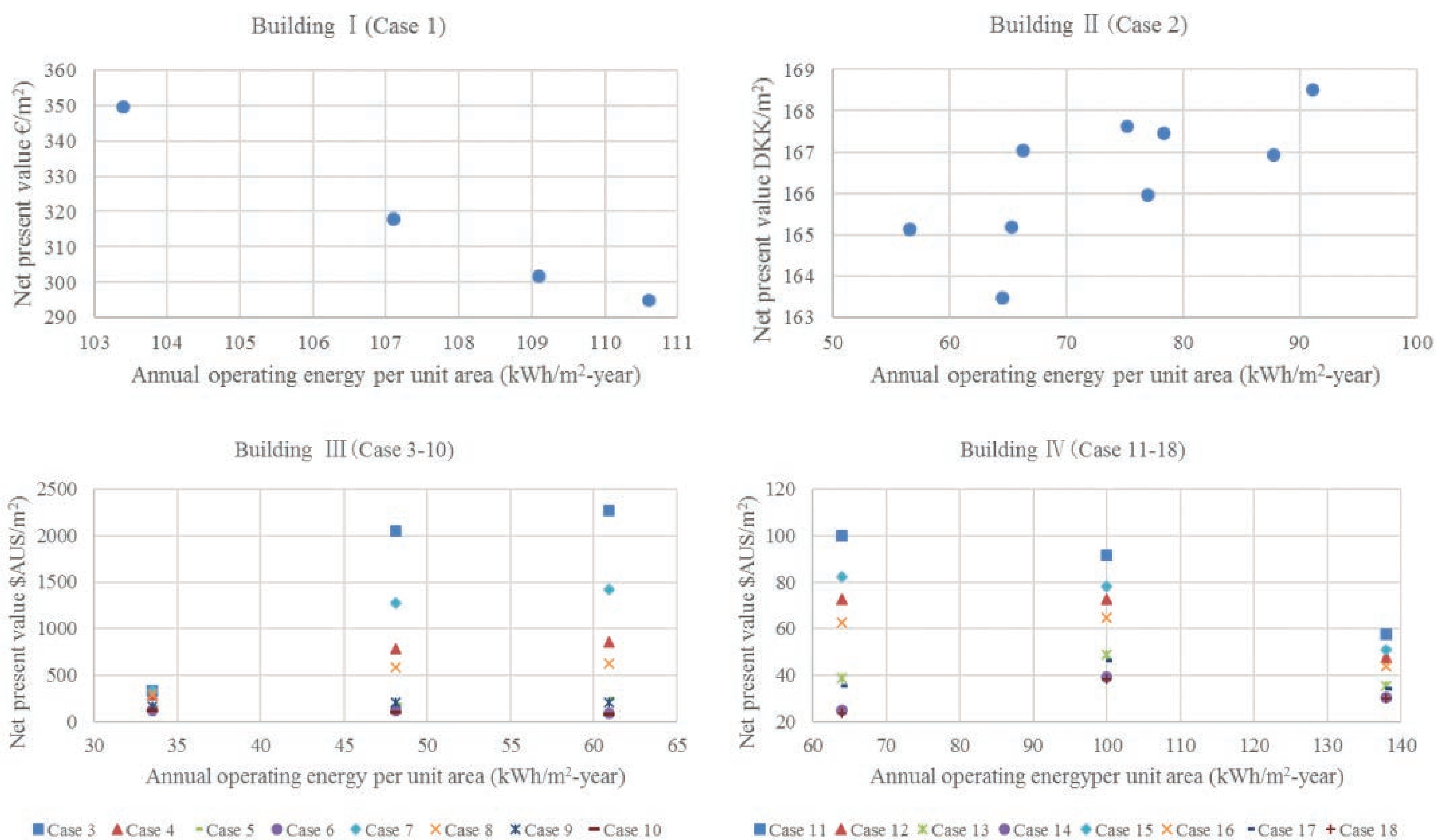
Four zero or nearly zero energy building projects with 18 cases of building designs were selected from the European Union and Australia. Where a building is reported to have more than one case, it means that different design scenarios and research designs (e.g. energy price, studied lifespan, real discount rate and inflation rate) of the same buildings were presented in the source itself. Table 2 gives a comprehensive overview of the main characteristics of the building projects presented in the literature. Cases differ by country, climate zone, type of building, building parameters, construction method, assumptions on indoor climate design and occupant

TABLE 2. Selected zero or nearly zero energy building projects for case study.

	Nearly zero energy building, Estonian (Pikas et al., 2014)	BOLIG+, Denmark (Marszal and Heiselberg, 2011)	Zero (net) energy housing, Australia (Moore, 2014)	Nearly zero energy building, Australia (Morrissey and Horne, 2011)
Building number	Building I	Building II	Building III	Building IV
Case number	• Case 1	• Case 2	• Case 3: 60 years study lifespan, high energy price • Case 4: 40 years study lifespan, high energy price • Case 5: 20 years study lifespan, high energy price • Case 6: 10 years study lifespan, high energy price • Case 7: 60 years study lifespan, low energy price; • Case 8: 40 years study lifespan, low energy price; • Case 9: 20 years study lifespan, low energy price; • Case 10: 10 years study lifespan, low energy price.	• Case 11: 40 years study lifespan, high energy price • Case 12: 25 years study lifespan, high energy price • Case 13: 10 years study lifespan, high energy price • Case 14: 5 years study lifespan, high energy price • Case 15: 40 years study lifespan, low energy price; • Case 16: 25 years study lifespan, low energy price; • Case 17: 10 years study lifespan, low energy price; • Case 18: 5 years study lifespan, low energy price.
Technological	• **Building type:** • Hypothesis model: open-plan generic single office floor • **Building energy system:** • HVAC: district heating with radiators, an air-cooled chiller and balanced heat recovery ventilation with chilled beams • Daylighting control systems • Project design: • Modular components	• **Building type** • Multi-storey residential building (one part of 6 storeys and the second part of 10 storeys) • 7,000 m^2 • **Building energy system:** • PV, heat pump • Windows and installations • Project design: • 114 modules components	• **Building type:** • Detached residential house • Floor size: 249.6 m^2 • Net conditional floor area: 126.5 m^2 • Building energy system: • Photovoltaic panel and solar hot water • Building envelope	• Building type: • Detached residential house • Net conditional floor area: 126.5 m^2 • Building energy system: • Glasswool insulation ceiling and wall; polystyrene insulation extruded shading; standard single and double windows

	Nearly zero energy building, Estonian (Pikas et al., 2014)	BOLIG+, Denmark (Marszal and Heiselberg, 2011)	Zero (net) energy housing, Australia (Moore, 2014)	Nearly zero energy building, Australia (Morrissey and Horne, 2011)
Environmental	• Temperate	• Temperate	• Tropical	• Tropical
Legal	• Forbidding landfill of post-use wood	• Forbidding landfill of post-use wood	• Recycle construction waste on-site: Australian Capital Territory (ACT 2011)	• Recycle construction waste on-site: Australian Capital Territory (ACT 2011)
Political	• EU Member States: 20% reduction in both CO_2 emissions and energy consumption by 2020 • Feed-In Tariff (FiT)	• EU Member States: 20% reduction in both CO_2 emissions and energy consumption by 2020 • Feed-In Tariff (FiT)	• The year of 1993: minimum housing energy performance requirements • The year of 2004: Nationwide House Energy Rating Scheme (NatHERS)	• The year of 1993: minimum housing energy performance requirements; • The year of 2004: Nationwide House Energy Rating Scheme (NatHERS)
Economic	• Real discount rate: 4.0% • Inflation rate: 3.5% • Electricity: 0.1245 €/kWh + VAT (20%) • District heating tariff: 0.0625 €/kWh + VAT (20%) • 20-year study lifespan	• Real discount rate: 1%, 3.36%, 6% • Distract heating tariff: 0.579, 0.444, 0.384 DKK/kWh • 20-year study lifespan	• Electricity: $0.223/kWh • Gas: $0.016/MJ • A feed-in tariff: $0.25/kWh • Real discount rate:1.65%, 1.15%, 3%, 3.5%, 6.5%, 7% • Inflation rate: 3% • Student period: 10,20,40,60 years • Energy price: high and low	Electricity: $0.1844/kWh Gas: $0.0136/MJ Real discount rate: 3%, 3.5% Inflation rate: 3.32% Student period: 5,10,25,40 years Energy price: high and low
Socio-cultural	• Consistent occupant's behaviour	• Occupants behaviour discipline	• Consistent occupant's behaviour	Consistent occupant's behaviour

FIGURE 5. Relationships between LCC and LCE of the selected building projects.



behaviour, and source of data (whether measured or calculated). For this reason, it would be inappropriate to compare the cases against each other directly. Instead, the overall variation of the LCCER of each individual case has been examined, and therefore these different variations have been compared between the different cases. Cases also differ in the anticipated assumptions on the values of key parameters that were applied in the cost (e.g. discount rate, inflation and studied lifespan) and energy calculations (e.g. floor area and studied lifespan). Cost data and energy data were normalised per unit of area (dollar/m^2) and time (kWh/m^2-year) in order to neutralise these differences.

Figure 5 shows the relationships between the costs and energy consumption of the studied 18 cases. A statistical correlation (Pearson correlation) analysis was conducted through the utilisation of IBM SPSS Statistics Version 24.

Table 3 presents the results of the statistical correlation analysis of LCC and LCE of the selected building projects The analysis demonstrates a significant negative correlation between

TABLE 3. Results of the statistical correlation analysis of LCC and LCE of the selected building projects.

	Case number	Pearson correlation (*r*)	Significance (*p*)
Building I	Case 1	–.996**	.004
Building II	Case 2	.725*	.027
Building III	Case 3	.928	.243
	Case 4	.927	.244
	Case 5	.934	.233
	Case 6	–.925	.248
	Case 7	.934	.232
	Case 8	.933	.235
	Case 9	.801	.409
	Case 10	–.996	.059
Building IV	Case 11	–.950	.202
	Case 12	–.877	.319
	Case 13	–.265	.829
	Case 14	–.927	.250
	Case 15	–.924	.250
	Case 16	–.822	.386
	Case 17	–.119	.924
	Case 18	.403	.736

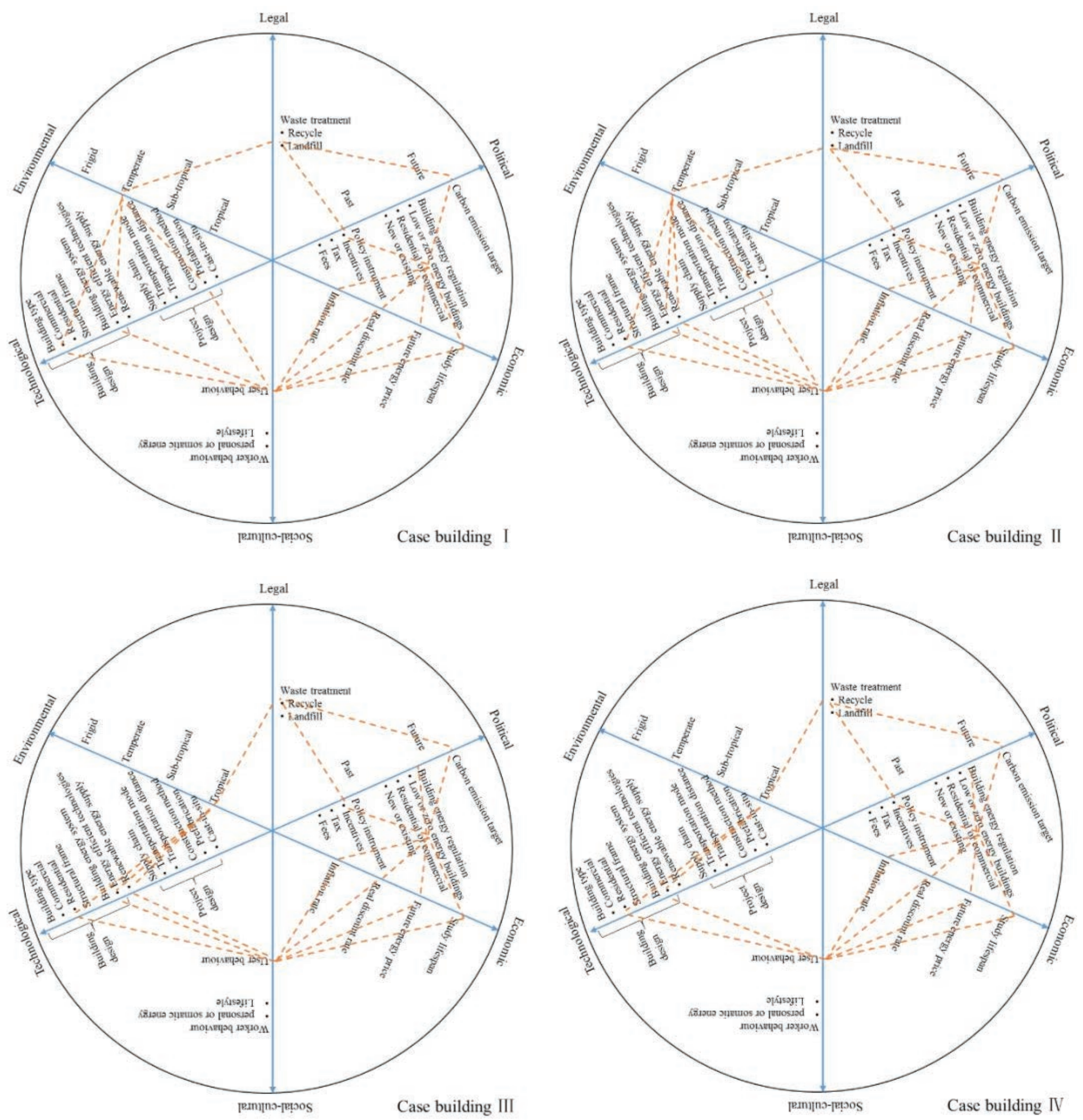
**: Correlation is significant at the 0.01 level;
*: Correlation is significant at the 0.05 level.

the annual energy consumption per unit area and net present value (NPV) for Building I (r = –996, $p < 0.01$). Also, there is a strong positive correlation between the annual energy consumption per unit area and NPV for Building II ($r = 7.25$, $p < 0.05$). Whereas, the analysis shows that a positive correlation and a negative correlation are found between the annual energy consumption per unit area and NPV for Buildings III and IV, respectively, albeit these correlations did not reach statistical significance.

The relevant values against the influencing parameters of the selected four building projects are graphically illustrated in Figure 6 for a visual comparison.

Several common features across the four building projects were identified in relation to the influence of the identified parameters.

FIGURE 6. Influencing parameters of the LCCER of the selected building projects.



First, the importance of user discipline is highlighted in all four building projects in order to achieve their net energy use targets. The occupants' behaviour for energy consuming activities such as the use of appliances currently falls outside the scope of minimum building standards. This is particularly vital in the case of investing in zero or nearly zero energy buildings, where predicted benefits may not in actuality accrue due to behavioural factors. The change of user behaviours and practices during occupying the building is therefore of great significance to achieving a low level of energy need and associated economic benefits as designed.

Second, the selected four building projects show that a low or net zero level of energy need is primarily achievable in low-rise or small-scale buildings. Among the four building projects, only BOLIG+ in Denmark is a multi-story building (one part is 6 storeys and the other 10 storeys), and the others are all low-rise. According to Pan and Li (2016), hundreds of low or zero energy buildings have emerged, but small buildings outnumber blocks of flats, and there are virtually no high-rise buildings. Fong and Lee (2012) explained that it was currently not feasible to achieve 'zero carbon' or 'zero energy' in high-rise buildings due to their high energy demand and limited renewable energy technology.

Lastly, due to the perceived higher capital costs of building towards zero carbon or energy compared to conventional buildings, zero carbon or energy building practices are faced with market barriers. Therefore, support from local government is essential to help unlock market potential. With the goal of showcasing state-of-the-art renewable technologies, the European Union has already set up policy incentives for making use of renewable energy supplies. This is the same with Australia. Government support with incentives and subsidies would contribute to a reduction of the high initial capital investment of the selected building projects.

6. DISCUSSION

The results reveal statistical correlations between the costs and energy consumption of buildings over a building's lifespan. The finding supports those reported in previous research, e.g. by Langston and Langston (2008) and Jiao et al (2012). A negative correlation was observed between the annual energy consumption per unit area and NPV for Building I and IV; whereas, these correlations were found to be positive for Building II and III. The difference might be attributed to the adoption of PV panels in Building II and III. The cost of building tends to increase as common approaches to reduce operational energy is supplanted in favour of more energy-efficient building fabrics and services that are associated with a cost premium. When renewable technologies are used to help offset operational energy, like the cases of Building II and III, the capital cost of the building increases significantly. The costs of building towards zero energy are dramatically variable among the four building projects, as such costs are influenced by a wide range of factors, including location of the building, wider economic conditions operating at local, national and global scales, and design and size of the building. Therefore, the LCCER of buildings is precisely determined by the economic effectiveness of the energy efficient and renewable technologies.

Important parameters, like study lifespan and future energy price, are identified to have a significant influence on the LCCER of buildings. As shown in Figure 5, when Case 3–6, Case 7–10, Case 11–14 or Case 15–18 are compared, a long lifespan would lead to a high NPV compared with a shorter one. Also, when Case 3–6 are compared to Case 7–10, or Case 11–14 are compared to Case 15–18, a low energy price would cause a low NPV. As stated by Langston and Lauge-Kristensen (2002), sufficient time is essential for energy efficient buildings to maximise their economic efficiency. Meanwhile, it is also shown that zero energy buildings would offer more advantages with future increases in energy prices.

7. CONCLUSIONS

This paper has developed a theoretical model of the influencing parameters of the life cycle cost-energy relationship (LCCER) of buildings using the PESTEL analytical framework. Based on this model, the paper has examined the LCCER by identifying the influencing parameters and the mechanisms, namely simultaneous and unilateral effects, by which the parameters affect such a relationship. The findings have been validated through case studies with four real-life zero or nearly zero energy building projects.

The paper first concludes that buildings' LCCER is affected by a wide range of parameters that reside in two aspects: (1) internal project designs covering building characteristics, building structure and function, and construction process, and (2) external environments covering climate, economic condition, occupant behaviour, policy and regulation, and buildings' lifespan focused in the studies. The paper secondly concludes that the LCCER of buildings may be attributable to the synergy between the simultaneous and unilateral effects deriving from the identified influencing parameters. The paper thirdly concludes that such a relationship is highly influenced by the economic effectiveness of the installed renewable technologies. A high capital cost of renewable technologies may lead to an energy-efficient but costly design scenario.

This paper contributes a systemic approach to examining a building's life cycle economics and life cycle energy in a comparative manner. The developed theoretical model guides the quest for insights into the causes of the relationship between the costs and energy consumption of buildings. The model should support future research on the optimisations of building costs and energy in a synergistic way and inform policy-makers in the promotion of low energy buildings with economic merits.

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