UTS ePRESS

Construction Economics and Building

Vol. 20, No. 4
December 2020

Citation: Ding, G., Nguyen, D. M., and Runeson, G. 2020. Energy and economic analysis of environmental upgrading of existing office buildings. *Construction Economics and Building*, 20:4, 82-102. http://dx.doi.org/10.5130/AJCEB.v20i4.7239

ISSN 2204-9029 | Published by UTS ePRESS | https://epress.lib.uts.edu.au/journals/index.php/AJCEB

RESEARCH ARTICLE

Energy and economic analysis of environmental upgrading of existing office buildings

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DOI: 10.5130/AJCEB.v20i4.7239
Article history: Received 01/06/2020; Revised 15/09/2020; Accepted 02/10/2020; Published 07/12/2020

Abstract

Over many decades, buildings have been recognised as a significant area contributing to the negative impacts on the environment over their lifecycle, accelerating climate change. In return, climate change also impacts on buildings with extreme heatwaves occurring more frequently and raising the earth's temperature. The operation phase is the most extended period over a building's lifespan. In this period, office buildings consume most energy and emit the highest amount of greenhouse gas pollution into the environment. Building upgrading to improve energy efficiency seems to be the best way to cut pollution as the existing building stock is massive. The paper presents an economic analysis of energy efficiency upgrade of buildings with a focus of office buildings. The paper identifies upgrading activities that are commonly undertaken to upgrade energy efficiency of office buildings and a case study of three office buildings in Sydney, Australia has been used to analyse the results. The upgrading activities can improve the energy performance of the case study buildings from 3 stars to 5 stars NABERS energy rating in compliance with the mandatory requirement in the Australian government's energy policy. With the potential increase in energy price, energy efficiency upgrading will become more affordable, but currently, most of them, except solar panels and motion sensors show a negative return and would not be undertaken if they did not also contribute to higher rental income and an increased life span of the building. The upgrading

DECLARATION OF CONFLICTING INTEREST The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. **FUNDING** The author(s) received no financial support for the research, authorship, and/or publication of this article.

discussed in the paper represent a potentially attractive alternative to demolition and building anew.

Keywords:

Energy upgrading, existing office buildings, energy efficiency, upgrading activities, economic analysis.

Introduction

Over the years, the building sector has been recognised as one of the main sectors to negatively impact on the environment, creating shortages of natural resources, ozone depletion, emissions of carbon dioxide (CO_2), climate changes, and the deterioration of living and working environments. This means that the building sector must improve to meet sustainability requirements. The major challenge in the building sector today, therefore, is to construct and maintain buildings in a more sustainable manner (Chan, Wang and Raffoni, 2014).

Climate change, as debated for several decades, has captured people's attention because of the increase in the earth's average temperature (IPCC, 2014). The building sector is one of the sectors contributing to accelerated climate change. However, in return, climate change also impacts on buildings with extreme weather conditions occurring more frequently, hampering indoor comfort, and impacting productivity (Clarke, 2009; Cleugh et al., 2011). Increased temperatures make many advanced technologies applied in buildings ineffective, which then require more energy to maintain indoor comfort (Ürge-Vorsatz et al., 2007; Hinnells et al., 2008). The situation is particularly severe in office buildings as people spend most of the time indoor during working hours.

The operating phase is the most extended period over a building's lifecycle. In this period, buildings consume most of the energy and consequently emit the highest amount of greenhouse gases (GHG) into the environment (Huovila et al., 2009; Ibn-Mohammed et al., 2013). The primary substance that contributes to climate change is CO_2 (Lynas, 2007; Li and Yao, 2009). Existing buildings are one of the major sources responsible for emitting high levels of CO_2 into the environment in the process of material manufacture and consumption for maintenance in addition to the operating phase of a building (Wilson and Tagaza, 2006; Ürge-Vorsatz, Koeppel and Mirasgedis, 2007; Ürge-Vorsatz et al., 2007; Kohler and Yang, 2007; Wright, 2009; Zhou et al., 2016).

Even though new buildings are increasingly constructed more sustainably, the number of new buildings added each year is small compared to the many largely old and outdated buildings in the stock (Wilkinson and Reed, 2006; Zhou et al., 2016). Since the general conditions of the existing building stock is deteriorating, the adverse impacts on the environment will continue unless the buildings' performance is improved (Wilkinson and Reed, 2006). Hence, the approach to alleviating the environmental impact of existing buildings is to either demolish and rebuild or retain and upgrade the existing building stock.

The primary target in reducing the impact of buildings in the environment is to reduce CO_2 emissions (Lynas, 2007; Li and Yao, 2009; Burroughs, 2018). Research has shown that sustainable upgrading of the existing building stock can achieve this and so improve the value of buildings (Newell, MacFarlane and Walker, 2014; Wilkinson, 2014). However, many barriers limit stakeholders' willingness to make their buildings more environmentally friendly. The main obstacles include budgetary constraint, insufficient information, various uncertainties as well as the lack of knowledge of and confidence in new technologies for upgrading (Wilson and Tagaza, 2006; Elmualim et al., 2010; Bruce et al., 2015; Regnier et al., 2018).

The research aims at identifying upgrading activities commonly undertaken to improve energy efficiency to the base building of existing office buildings. The research design includes a comprehensive literature review to characterise upgrading activities and the associated potential savings on energy consumption. There are several research objectives, including identifying activities and technologies that cause minimal disturbance to the existing operation of buildings. Therefore, activities that require major renovation, such as building envelope, are excluded from the study. Secondly, analyse potential saving in energy consumption, CO_2 emissions and the associated upgrading costs and saving of these activities and technologies. The final objective is to validate the analysis of these upgrading activities through a case study of three buildings.

The paper began with a discussion of the impact of existing office buildings on the environment, followed by a discussion of upgrading activities that are commonly conducted to improve energy efficiency of existing office buildings. The discussion focuses on analysing upgrading cost and the potential savings in energy cost, energy consumption and CO_2 emissions after upgrading. Finally, the paper presents a case study of three office buildings in Sydney, Australia to analyse the upgrading improvement, potential savings and compliance with the energy requirements for buildings in Australia.

Environmental impact of existing office buildings and the role of energy upgrading

Recently, the rapidly increasing average temperature on earth has influenced the living environment significantly. As a direct result of climate change, and in particular, the continual and extreme heatwaves, people are responding by increasing the use of indoor climate modifiers such as Heating, Ventilation and Air Conditioning (HVAC) systems to maintain indoor comfort, which has escalated the demand for energy and hence CO_2 emissions (Kentwell, 2007; Anderson, Hawkins and Jones, 2016).

The operating phase is the most extended and complicated period in a building's lifecycle. The most significant emissions happen in the operating phase, approximately 80-90% of CO_2 emissions, which is typically about 20-60 years, compared to the construction phase of usually 2-3 years (Huovila et al., 2009).

The cost of operation and maintenance of office buildings can be as high as two times more than the cost of the initial construction for a period of 30 years and it can increase up to five times more for a longer lifespan (Ive, 2006; Snodgrass, 2008). The most significant expenses are for indoor comfort, lighting, and the operation of equipment. Office buildings are among the highest consumers of energy, and consequently, contribute high levels of GHG emissions (Ibn-Mohammed et al., 2013). The annual energy consumption of office buildings varies between 100 and 1,000 kWh per square metre depending on many variables, such as geographic location, type and use of office equipment, operational schedules, type of envelope, use of HVAC and lighting systems (Juan, Gao and Wang, 2010).

In order to keep an office building functioning, it generally requires a major refurbishment every 20–25 years (Wilkinson and Reed, 2006; Bruce et al., 2015). Furthermore, most of the existing office buildings are several decades old and therefore are becoming energy inefficient and may require upgrading to alleviate their impact in the environment (Wilkinson and Reed, 2006; Taylor, 2009). A deteriorating building decreases in value and the quality of the indoor environment will also deteriorate to the extent that it may harm the occupants, threaten production and cost more to operate (Pitt, Goyal and Sapri, 2006; Huovila et al., 2009). Therefore, old buildings need refurbishment to meet green standards and regulations and improve energy performance (Bullen, 2007; Connelly and Adam, 2009). Improving the energy efficiency of existing buildings attracts much attention as an important strategy to reduce energy consumption and CO_2 emissions (Huovila et al., 2009; Ibn-Mohammed et al., 2013).

Energy efficiency upgrading of existing office buildings is a key target for public policy addressing climate change (Kentwell, 2007; Wild, 2008; Burroughs, 2018; Regnier et al., 2018). However, budget constraint is a major barrier to restrict building upgrading activities. Additional costs, increased risks, and unknown performance of technologies to meet green building standards may lead stakeholders to become reluctant to considering upgrading their buildings (Regnier et al., 2018).

However, even though there are barriers that may prevent owners from upgrading an existing building, there are many drivers that may lead stakeholders to consider upgrading their buildings. The financial return is one of the major drivers as sustainable upgrading has the potential to improve an existing building to satisfy the economic needs of long-term wealth and the requirements of environmental protection (Pitt et al., 2009; Häkkinen and Belloni, 2011). Tenant demand is another significant driver for energy efficiency upgrading as these buildings will benefit from the green branding, meet standards for the building leases and occupations, and provide an indoor environment quality that improves user's health and productivity (Henderson, 2006; Wilson and Tagaza, 2006; Clarke, 2009; Cleugh et al., 2011; Burroughs, 2018). The building sector is moving towards becoming greener with more injections of green buildings, and when a building is deemed outdated, building owners could consider upgrading the building, so that it can re-entering the building market (Chan, Qian and Lam, 2009).

Identifying criteria for improving sustainability in existing office buildings

IMPROVING ENERGY EFFICIENCY IN EXISTING OFFICE BUILDINGS

The rapid growth of the property industry has accelerated change in the environment, including technologies, standards, policies, and regulations. Existing office buildings, particularly older ones, may not have kept up with the changes. However, under the current environmental protection policies and regulations, older buildings are required to satisfy environmental protection standards.

For the existing building stock, the target is to improve buildings to be more environmentally friendly (Abdallah and El-Rayes, 2015). The primary demand for improving buildings for sustainability is to ensure energy consumption and CO_2 emissions reductions in buildings (Henderson, 2006; Wright, 2009). This can be achieved by upgrading buildings to improve their energy efficiency, indoor comfort for occupants, lighting and air conditioning systems, and waste reusing and recycling (Jentsch, James and Bahaj, 2010; Abdallah and El-Rayes, 2015).

While almost every new office building is now constructed encompassing green technologies and innovative design, existing office buildings can also be improved or upgraded to meet sustainability standards (Abdallah and El-Rayes, 2015). The most significant advantage that existing office buildings gain by being sustainable is that they will stay competitive, increase energy efficiency, reduce vacancy rates, increase rental levels, improve assets and counteract obsolescence (Wilkinson and Reed, 2006; Chan, Qian and Lam, 2009). Sustainable buildings increase in value, gain positive influence in keeping tenants, who will be provided with considerable savings on energy and water in running their businesses.

The challenge is improving the performance of existing buildings to lessen their negative environmental impact. The challenge is not only to limit CO_2 emissions but to reduce CO_2 emissions with a target level that is high but achievable. Reducing energy consumption will result in reduced CO_2 emissions. As reported by the Fourth Assessment Report of the IPCC (2007), the commercial sectors can save approximately 1.4 billion tonnes (approximately 29%) of CO_2 by 2020 when buildings are improved for energy efficiency. These GHG emissions can be reduced by approximately 29% or even to zero-net with a further commitment (Ürge-Vorsatz, Koeppel and Mirasgedis, 2007).

During the operating stage of a building, energy consumption to provide heating, cooling, lighting and to operate equipment and appliances is recognised as the most important (Juan, Gao and Wang, 2010; Lecamwasam, Wilson and Chokolich, 2012; Abdallah and El-Rayes, 2015; Regnier et al., 2018). In the US, the building sector is responsible for approximately 39% of the total primary energy requirements, of which 35% was used for HVAC as about 80% of buildings in the US are equipped with air-conditioning systems (Nicol, 2009; Wan et al., 2012). In Canada, building space heating and cooling account for 54% and 6% of energy use respectively; while equipment, lighting, and hot water systems account for 20%, 13% and 7% respectively (Ürge-Vorsatz et al., 2007).

In China, energy use in the building stock has been steadily increased since the 1980s. Buildings consumed around 24% of the total national energy use in 1996, rose to around 28% in 2001 and the growth was projected to rise to about 35% in 2020 (Wan et al., 2012). In Australia, office buildings account for 25% of the total energy which is projected to increase to 29% in 2020 (Department of Climate Change and Energy Efficiency, 2012; Higgins et al., 2014). The CO_2 emissions will increase from 23% in 2005 to 110% by 2050 if no action is taken (CIE 2008; Höhne et al., 2017). Therefore, energy efficiency upgrading of the existing building stock plays a crucial role in reducing energy demand and the associated CO_2 emissions.

Energy efficiency upgrading activities

A way to minimise adverse environmental impacts is the upgrading of building systems or components (Abdallah and El-Rayes, 2015). As stated previously, the HVAC system consumes a significant amount of energy and it is a crucial element that provides the required indoor comfort (Lecamwasam, Wilson and Chokolich, 2012). The quality of indoor air has negative and positive effects on the productivity of users, in particular occupant health and safety. According to Barlow and Fiala (2007), by 2050, buildings which installed conventional HVAC systems will increase energy use by more than 20% to provide the required indoor comfort due to climate change on working days. Consequently, CO_2 emissions and pollution will also increase. Lecamwasam (2014) also suggests that HVAC systems in older buildings can waste approximately 20 to 40% of total energy consumption. Therefore, in achieving the efficient use of energy and reducing CO_2 emissions relating to indoor thermal comfort, conventional air-conditioned offices have to be upgraded to improve productivity and maintain a comfortable work environment (Barlow and Fiala, 2007; Kwon, Chun and Kwak, 2011; Au-Yong, Ali and Ahmad, 2014).

Artificial lighting is another important area to improve energy efficiency in buildings. In the life of a building, the combined HVAC and lighting accounts for about 80% of total energy use during the operating stage (Juan, Gao and Wang, 2010; Abdallah and El-Rayes, 2015; DIS, 2015). In existing office buildings, the lighting systems that include inefficient lamps and fixtures can be upgraded with more energy effective ones or by eliminating the use of unnecessary lamps. Daylighting in office buildings is broadly considered an important design strategy of energy preservation that demanded cautious architectural design to satisfy that optimum benefits are achieved (Ko, Elnimeiri and Clarke, 2008; Raimondia et al., 2016).

Improving the lighting load will not only reduce annual energy consumption but also reduce heat gains in buildings. The reduction of electricity consumption in office buildings can be achieved with proper design, which integrates daylight and artificial lighting systems. Thus, building energy expenses can be affected by two key climatic factors, solar radiation and outdoor illuminance, which can cool the buildings without the use of electricity where there is a proper strategic plan (Li, Lam and Wong, 2006; Li et al., 2009).

Another factor affecting the effectiveness of the lighting system in office buildings is that the lighting system continuously interacts with the HVAC system. To improve energy efficiency for heating in the winter and reducing energy use for cooling in summer, the upgrading of the lighting systems must be coordinated with HVAC systems (Juan, Gao and Wang, 2010; Abdallah and El-Rayes, 2015; Regnier et al., 2018). Due to daylight constantly being associated with solar heat gain, when design levels exceed the space luminance required, solar heat gains will increase, and consequently, the electrical cooling load will also increase (Li, Lam and Wong, 2006; Li et al., 2009). When a large office building is upgraded with an automation system, such as building management and control systems (BMCS), a savings of 30% can be achieved from energy consumption (Colmenar-Santos et al., 2013). It can be expected that the initial capital outlay for becoming green can be recovered by decreasing long-term energy costs.

The literature review has identified areas that are commonly upgraded to improve energy efficiency of existing office buildings and are summarised in Table 1. The table presents the upgrading activities that have contributed to reducing energy consumption and CO_2 emissions. The potential savings in the table may vary according to various variables such as climatic situation, geographical location of buildings, size, shape, operating and physical conditions of individual buildings, and should be considered as a guide only. From the table installing dimming control to the lighting system is found to have the most potential savings, followed by upgrading to the HVAC, BMCS, lifts and escalators, and replacing conventional hot water supply with a solar-boosted hot water system.

Table 1 Summary of energy efficiency of common upgrading activities in office buildings

Upgrading activities	Details	Potential savings	References
HVAC-Minor	Replace part of the system	5-9%	Jenkins, Liu & Peacock, 2008; Steinfeld, Bruce & Watt, 2011; Lecamwasam, Wilson & Chokolich, 2012; Lecamwasam, 2014
HVAC-Major	Replace the entire system	20-40%	
Solar-boosted hot water	Replace conventional hot water system	30%	Cabeza et al., 2014
BMCS	Install the system to control, monitor and alert facility malfunction to automatically turn on or off services	20-30%	Steinfeld, Bruce & Watt, 2011; Colmenar-Santos et al., 2013
Solar panel	Install onsite electricity generation to replace consumption from the main grid	26%	Steinfeld, Bruce & Watt, 2011; Bondanza, 2011
Lifts & escalators	Upgrade service to reduce waiting and transporting time	30%	Australian Building Code Board, 2004; De Almeida et al., 2012
Electrical switchgear	Replace main and sub-main switchgear to reduce electricity consumption at peak time	26%	Jenkins, Liu & Peacock, 2008; Steinfeld, Bruce & Watt, 2011; Lecamwasam, Wilson & Chokolich, 2012
Motion sensor	Install the system to automatically turn on or off lights	14%	Atif & Galasiu, 2003; Bourgeois, Reinhart & MacDonald, 2006; Galasiu & Veitch, 2006; Li, Lam & Wong, 2006; Jenkins, Liu & Peacock, 2008; Steinfeld, Bruce & Watt, 2011; Lecamwasam, Wilson & Chokolich, 2012; Zografakis, Karyotakis & Tsagarakis, 2012
Lighting systems-minor	Replace existing lighting with T5 or LED	5-6%	Roisin et al., 2008; Zografakis, Karyotakis & Tsagarakis, 2012
Lighting systems-major	Replace the entire system	20%	Atif & Galasiu, 2003; Bourgeois, Reinhart & MacDonald, 2006; Galasiu & Veitch, 2006; Jenkins, Liu & Peacock, 2008; Ihm, Nemri & Krarti, 2009; Li et al., 2009; Steinfeld, Bruce & Watt, 2011; Lecamwasam, Wilson & Chokolich, 2012
Dimming control	Install system to automatically dim artificial light when daylight is sufficient	46%	Atif & Galasiu, 2003; Li et al., 2009
Double glazing	Install system to reduce heat gain or loss	9%	Jenkins, Liu & Peacock, 2008; Steinfeld, Bruce & Watt, 2011; Lecamwasam, Wilson & Chokolich, 2012; Lecamwasam, 2014

Research method

The research aims at undertaking an economic analysis of energy efficiency upgrade of existing office buildings. The literature review identified ten activities that are commonly upgraded, and details are summarised in Table 1. Economic analysis of energy efficiency upgrade is important as a budgetary constraint is one of the major barriers to the upgrading of existing office buildings. Three case studies are used to analyse the economic impact of different upgrading activities. The case studies involve three existing office buildings in Sydney, Australia, selected to illustrate the potential economic impact of energy efficiency upgrades.

Case study buildings

The case study buildings, located in the Sydney Central Business District (CBD), are referred to as Building 1, 2 and 3. The characteristics of the three buildings are summarised in Table 2. The three case study buildings are A-Grade buildings according to the Property Council of

Australia commercial building grading that represent high quality office buildings in the CBD (PCA, 2019).

These three buildings were considered the best suited for the study due to the following reasons:

- These buildings range from 24 to 33 years old represents a suitable range of ages for the investigation as literature review reveals that buildings within this range are due for refurbishment or upgrade (Burroughs, 2018).
- They are medium and high-rise office buildings having gross floor area (GFA) from 17,000m^2 to 45,000m^2.
- The three case study buildings have annual energy consumption per GFA of 128, 103 and 135 kWh/m^2/annum which is considered high (Hestnes and Kofoed, 2002; Steinfeld, Bruce and Watt, 2011). Therefore, these buildings have opportunities for improvement in the annual usage and savings on energy and CO_2 emissions

The maintenance and upgrade records and three years of utility bills (2015-2018) from the facility management department were collected from each building. Additional data were also collected from meetings with facility managers and site visits to each building to examine building conditions and investigation into the maintenance and renovation records.

Table 2 Characteristics of the three case study buildings

Building details	Building 1	Building 2	Building 3
Year of completion	1990	1986	1995
Age (years)	29	33	24
GFA* (m^2)	17,682	40,089	45,356
Hours of occupancy (hours/week)	52.1	52.5	52.9
Building characteristics	· G/F retail and entrance foyer · 18 upper floors of office space · 2 levels of basement car parking	· G/F café and entrance foyer · 32 upper floors of office space · 3 levels of basement car parking	· G/F retail and entrance foyer · lower G/F retail and loading dock · 31 upper floors of office space · 5 levels of basement car parking
**Average annual energy consumption (average 3 of years)	2,256,933	4,125,003	6,134,401
Average annual energy consumption per GFA (kWh/m^2)	128	103	135
**Average annual CO_2 emission (average of 3 years) (kg CO_2)	2,528,224	4,501,961	6,649,808
Average annual CO_2 emission per GFA (kg CO_2/m^2)	143	112	147

Note:
* GFA is gross floor area which is a measure of total floor areas from the inside face of exterior walls.
** Figures for average annual energy consumption and CO_2 emissions derived from three years of energy bills provided by the facility

The GFA of Building 2 is about 127% more than that of Building 1 but about 13% smaller than Building 3. Even though Building 3 has the biggest GFA its average annual energy consumption and CO_2 emissions are not much higher than Building 1 per m^2. Building 2 has the best performance of 103 kWh/m^2/year and 112 kg CO_2/m^2/year respectively for the average annual energy consumption and CO_2 emissions.

Potential energy savings and economic analysis of upgrading activities

The principal concern in upgrading an office building is financial; however, the other factor that should be considered in decision-making is the environmental impacts. Key stakeholders may be reluctant to invest money to improve their existing buildings. They face uncertainty about the long-term benefits of their investment. Financial concerns can prevent or delay stakeholders in improving buildings due to the required capital outlays (Ellison and Sayce, 2007; Sev, 2009). Therefore, for energy efficiency upgrade to be implemented in an existing office building, affordability and long-term financial return must be included in the decision making

In the assessment of economic impact and potential energy savings in the case study, the analysis concentrates on estimating the costs and savings of upgrading in the areas identified from the literature review to improve energy efficiency of buildings. The estimated costs and savings of upgrading are based on the data from research studies and published data. The annual costs of upgrading are calculated in cost per square metre ($/m^2), and savings are by percentage (%) on energy consumption and CO_2 emissions. The end-use shares of energy consumed in office buildings are computed for electricity use only as gas consumption is very little in this type of building (DIS, 2015).

Estimating potential energy savings of upgrading activities

The energy savings are based on savings on building services running on normal and peak loads. The energy savings calculated are the end-use of energy consumption per annum. The upgrading activities for energy efficiency and potential savings in the table were derived from the literature review and published data on a typical office building in Australia for the base building load only. Tenancy spaces[1] were excluded from the study.

Table 3 is developed based on the information in Table 1. Table 3 presents the calculation of the percentage savings on various upgrading activities. According to the Department of Industry and Science (DIS, 2015), the peak electricity demand in office buildings (base building load) is HVAC accounting for 67%, lighting for 16%, equipment for 11%, domestic hot water for 2% and others for 4%.

Table 3 Summary of energy efficiency upgrading in office buildings (Base building load)

Upgrading activities	Potential savings[1] (%)	Energy consumption distribution[2] (%)	Estimated annual saving[3] (%)
HVAC-Minor	5-9 (average 7)	67	4.7
HVAC-Major	20-40 (average 30)	67	20.1
Solar-boosted hot water	30	2	0.6
BMCS	20-30 (average 25)	11	2.8
Solar panel	26	16	4.1
Lifts & escalators	30	4	1.2
Electrical switchgear	26	4	1.1
Motion sensor	14	16	2.2
Lighting systems-minor	5-6 (average 5.5)	16	0.9
Lighting systems-major	20	16	3.2
Dimming control	46	16	7.4
Double glazing	9	67	6

Note:
[1] Percentage savings developed from the literature review in Table 1 (Column 3)
[2] Industry average energy consumption distribution developed by the Department of Industry and Science, Australia (DIS, 2015)
[3] Calculated by multiplying the percentage of potential savings in Column 2 with the energy consumption distribution in Column 3

In the table, Column 3 represents the energy consumption distribution of a typical office building and it indicates that HVAC consumes the most electricity, followed by lighting. The fourth column shows the estimated savings in percentage should the systems be upgraded.

1 Tenancy space is defined as an office space occupied by individual tenants for their intended business.

Therefore, in considering the various energy demand per upgrade activity, the estimated annual savings (Column 4) is calculated by multiplying the potential savings (Column 2) with the energy consumption distribution (Column 3) in Table 3. From the table, a major upgrade of the HVAC generates the highest potential saving of 20%, followed by lighting dimming control of 7% in energy consumption.

Estimating annualised upgrading costs

The estimation of upgrading costs that include both capital and maintenance during the lifecycle of the building has been summarised and presented in Table 4. The capital costs in upgrading are priced as at 2019 in terms of $\$/m^2$ of GFA (excluding GST[2] or VAT). The maintenance costs were developed from journal articles and building maintenance websites (Menzies and Wherrett, 2005; Kubba, 2010; Steinfeld, Bruce and Watt, 2011; CostWeb, 2019; Rawlinsons, 2019; WePowr, 2019; Synergy, 2019). However, according to Nalewaik and Venters (2009) and Wu (2010), there are no fixed costs in the maintenance of building service system. Annual maintenance costs may vary depending on the frequency in schedules, the size and operation of systems. Therefore, the maintenance cost for each upgrade activity is estimated from information from facility managers of each case study buildings with appropriate adjustment to suit.

The lifespan of each system or equipment is also included in Table 4. It is expected that each system or equipment may need to be upgraded one or more times over the building's lifecycle. To simplify the calculation, the upgrading cost is annualised on a 30-year study period at a discount rate of 5%.

Table 4 Economic analysis of energy efficiency upgrading in office buildings (base building load)

Upgrading activities	Lifespan[1] (Years)	Upgrading capital cost[2] ($\$/m^2$)	Annual maintenance cost[3] ($\$/m^2$)	NPV of upgrading capital and annual maintenance cost for 30 years[4] ($\$/m^2$)	Annualised upgrading cost at 30 years[5] ($\$/m^2$)
HVAC-Minor	30	Various	Various	Various	Various
HVAC-Major	30	320	1	335.37	21.8
Solar-boosted hot water	30	10	0.2	13.07	0.9
BMCS	15	0.95	0.02	1.68	0.1
Solar panel	30	2.5	0.05	3.27	0.2
Lifts & escalators	30	58	0.02	58.31	3.8
Electrical switchgear	15	147	3.1	288.07	18.7
Motion sensor	15	5.5	0.05	8.77	0.6
Lighting systems-minor	20	Various	Various	Various	Various
Lighting systems-major	20	130	4.93	252.92	16.5
Dimming control	30	128	1.28	147.68	9.6
Double glazing	15	393	1.96	602.27	39.2

Note:

[1] Adapted from Menzies & Wherrett, 2005; Kubba, 2010 (lifespan of 15 and 20 years will require a new replacement within the 30 year study period)

[2] Developed from CostWeb, 2019 and Rawlinsons, 2019

[3] Developed from Steinfeld, Bruce & Watt, 2011

[4] Calculated by $NPV = \sum_{n=1}^{n} \frac{R_n}{(1+r)^n}$ (NPV is net present value, R is net cash flow, n is number of time period, r is discount rate)

[5] Calculated by $\frac{NPV \times r}{1-(1+r)^{-n}}$

2 GST is Goods and Services Tax in Australia levied on market transaction of goods and services, similar to VAT in UK.

In the table, the minor upgrade to HVAC and lighting have been left open due to significant variations in the type and size of upgrading activities. From the table, the highest annualised upgrading cost is the installation of double glazing to windows to reduce heat gain and loss in the building of approximately \$39/m^2 with an approximate potential saving of 6% on annual energy consumption and CO_2 emission. While upgrading the entire HVAC system has an annualised cost of approximately \$22/m^2 but will give a saving on annual energy consumption and CO_2 emissions of 20%. The lowest upgrading cost is the installation of BMCS with an annualised cost of \$0.1/m^2 for a potential savings of 3%.

Analysing potential energy savings and upgrading costs for the case study buildings

The maintenance and renovation records for the three buildings were collected and analysed. The analysis found that the following upgrading activities have been undertaken in the past three years:

- Both Building 1 and 2 have upgraded BMCS
- Building 2 and 3 have upgraded electrical/power switchgear
- All three buildings have replaced all lightings to T5

Therefore, the analysis has focused on the rest of the upgrading activities as included in Tables 3 and 4. Table 5 summarises the estimated potential savings in energy consumption (kWh/m^2), CO_2 emissions (kg CO_2/m^2) and energy cost (\$/m^2) for the three buildings. The potential annual savings on energy cost is calculated from the energy price of approximately \$0.35/kWh adapted from WePowr (2019) and Synergy (2019) and multiplied with annual savings on energy consumption for each building.

The annualised upgrading cost in the table includes both the capital and maintenance costs. The three case studies, with current ages from 24 to 33 years old, are all due for a major refurbishment within the next few years. This means that all items with lifespans of 15 and 30 years will have to be replaced in this process. Therefore, it provides a significant opportunity to improve the energy performance of these buildings. In the table, the highest savings on annual energy cost is the HVAC with a saving in the range of \$7.2–\$9.5/m^2, followed by an automatic dimming of lighting (\$2.7–\$3.5/m^2) and double glazing to windows (\$2.2–\$2.8/m^2). Similar outcomes can be found for the potential savings of energy consumption and CO_2 emissions. When comparing annualised upgrading cost and the potential savings of energy cost after upgrading, only for BMCS, solar panels and motion sensors do savings outweigh the upgrading cost. All other activities have higher annualised upgrading cost than the potential saving in energy cost which may have tendered the upgrading unprofitable. However, the gap between upgrading cost and energy cost saving can be narrowed or reversed with the likely increases in the price of energy.

The annualised upgrading cost and potential savings are also presented graphically in Figure 1. The annualised upgrading cost is presented from the lowest to highest (\$/m^2). The horizontal axis represents upgrading activities. The vertical axis on the left is the annualised upgrading cost (\$/m^2), ranging approximately from \$0.1–39/m^2. The vertical axis on the right shows the percentage of potential savings on energy consumption and CO_2 emissions, which range from approximately 0.6–20%.

Table 5 Summary of potential savings for the three buildings

Upgrading activities	Building 1				Building 2				Building 3			
	Annualised upgrading cost[1]	Potential savings after upgrade			Annualised upgrading cost[1]	Potential savings after upgrade			Annualised upgrading cost[1]	Potential savings after upgrade		
		Energy cost[2]	Energy consumption[3]	CO_2 emissions[4]		Energy cost	Energy consumption	CO_2 emissions		Energy cost	Energy consumption	CO_2 emissions
	$/m^2	$/m^2	kWh/m^2	kg CO_2/m^2	$/m^2	$/m^2	kWh/m^2	kg CO_2/m^2	$/m^2	$/m^2	kWh/m^2	kg CO_2/m^2
HVAC system	21.8	9.0	25.7	28.7	21.8	7.2	20.7	22.6	21.8	9.5	27.2	29.5
Solar-boosted hot water system	0.9	0.3	0.8	0.9	0.9	0.2	0.6	0.7	0.9	0.3	0.8	0.9
BMCS	-	-	-	-	-	-	-	-	-	1.3	3.8	4.1
Solar panel	0.2	1.8	5.2	5.9	0.2	1.5	4.2	4.6	0.2	1.9	5.5	6.0
Lifts and escalators	3.8	0.5	1.5	1.7	3.8	0.4	1.2	1.3	3.8	0.6	1.6	1.8
Electrical/power switchgears	18.7	0.5	1.4	1.6	-	-	-	-	-	-	-	-
Motion sensors	0.6	1.0	2.8	3.1	0.6	0.8	2.3	2.5	0.6	1.0	3.0	3.2
Lighting	-	-	-	-	-	-	-	-	-	-	-	-
Automatic dimming	9.6	3.3	9.4	10.6	9.6	2.7	7.6	8.3	9.6	3.5	10.0	10.8
Double glazing	39.2	2.7	7.7	8.6	39.2	2.2	6.2	6.7	39.2	2.8	8.1	8.8
Total upgrading costs/savings	**94.8**	**19.1**	**54.5**	**61.1**	**76.1**	**15.0**	**42.8**	**46.7**	**76.1**	**21.0**	**60.1**	**65.1**

Note:

[1] Derived from the annualised upgrading cost from Table 4 Column 6

[2] Energy cost is calculated from the energy consumption after upgrading in Columns 4, 8 & 12 and multiplied it by Sydney electricity cost (i.e. $0.35/kWh) (WePowr, 2019 & Synergy, 2019)

[3] Derived from the annual energy consumption per GFA in Table 2 Rows 8 and multiplied by potential energy savings in Table 3 Column 4

[4] Derived from the annual CO_2 emissions per GFA in Table 2 Row 10 and multiplied by potential energy savings in Table 3 Column 4

The budgetary constraint may dictate the upgrading activities to be undertaken or may even have forbidden energy efficiency upgrade of existing office buildings to take place. The figure presents the annualised upgrading costs from the least to the most expensive activities to suit the appropriate work for the budget allowed in improving a building.

Each building can be independently assessed and upgrading criteria selected depending on its geographic location, type, use of equipment, operational and maintenance schedules. Improvements can start from basic and consider activities with lesser intervention through to more major upgrading to one or more parts of a system rather than upgrading or replacing the entire system unless it is necessary.

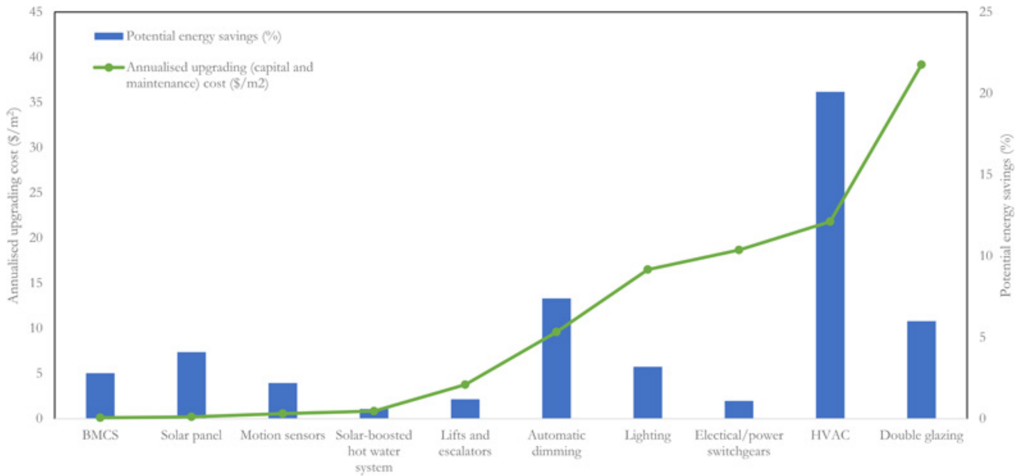

Figure 1 Compare upgrading activities between annualised upgrading costs and potential energy savings over a 30-year period

The upgrading can start with basic activities such as upgrading BMCS to monitor building services, install solar panels to offset energy demand from the main grid, motion sensors to turn off lightings of unoccupied space and replace hot water supply with solar-boosted hot water systems. Upgrading these basic activities can contribute approximately 10% reduction of energy consumption and the associated CO_2 emission with an annualised upgrading cost of $1.8/m^2.

With a more generous budget, more expensive upgrading activities can take place to achieve more reduction. A major upgrade to the HVAC system and installation of automatic dimming control can lead to a potential reduction of energy consumption and CO_2 emissions by approximately 28% with an annualised upgrading cost of $31.4/m^2. However, for more expensive upgrading activities such as double glazing to windows, upgrading can be undertaken to part of the system only. In most cases, HVAC systems can be upgraded partially by replacing components such as cooling towers, chillers, or air handling units with more efficient alternatives.

The results of the analysis are also presented in Table 6 to compare the outcomes of the three buildings. Building 1 has the highest annualised upgrading costs of $95/m^2 with potential annual savings on the energy cost of $19/m^2. Buildings 2 and 3 have similar annualised upgrading costs of approximately $76/m^2. However, Building 3 generates more potential annual energy cost savings of $21/m^2, approximately 29% more than Building 2 with the same amount of investment.

Table 6 Comparing annual potential savings of energy cost, energy consumption and CO_2 emissions for the three buildings

Case study building	Annualised upgrading cost ($/m²)	Potential savings after upgrading		
		Energy cost* ($/m²)	Energy consumption (kWh/m²)	CO_2 emissions (kg CO_2/m^2)
1	94.8	19.1	54.5	61.1
2	76.1	15	42.8	46.7
3	76.2	21	60.1	65.1

Note:
* Energy cost refers to the savings on the cost of electricity consumption per annum on undertaking the upgrading activities as detailed in Table 2

With regards to energy consumption and CO_2 emissions, Building 2 outperforms the other two buildings. Building 2 is lower in energy consumption by approximately 22% and 29%, CO_2 emission by approximately 24% and 28% respectively for Buildings 1 and 3. With the upgrading activities in the table, Building 1 can be improved to achieve total potential annual savings of approximately 55 kWh/m² of energy consumption and 61 kg CO_2/m^2 of CO_2 emissions, which results in an annual saving of approximately $19/m² of operating energy costs. The calculation can reduce the energy consumption of Building 1 from the annual average of 128 to approximately 73 kWh/m² and CO_2 emissions from 143 to approximately 82 kg CO_2/m^2 annually.

In a similar context, Building 2 can be improved to achieve total potential annual savings of approximately 43 kWh/m² of energy consumption and 47 kg CO_2/m^2 of CO_2 emissions. The upgrading may result in an annual savings of approximately $15/m² on energy costs. The upgrading activities can reduce the energy consumption of Building 2 from the original annual consumption of 103 to approximately 60 kWh/m² and CO_2 emissions from 112 to approximately 65 kg CO_2/m^2 per annum. Building 3 can also be improved to achieve total potential annual savings of approximately 60 kWh/m² of energy consumption and 65 kg CO_2/m^2 CO_2 emissions which results in an annual savings of approximately $21/m² on energy costs. The upgrading activities can reduce the energy consumption of Building 3 from the average annual consumption of 135 to approximately 75 kWh/m² and CO_2 emissions from 147 to approximately 82 kg CO_2/m^2 per year.

Compliance with the Australian government energy efficiency policy

The sustainability agenda in green office buildings in Australia have significant developments in recent years. This has been driven at all levels. Nationally, the government has implemented an energy efficiency policy and has introduced the Green Lease policy which requires tenant occupied buildings to have a low impact on the environment, such as a 4.5 star or higher in the National Australian Built Environment Rating Scheme (NABERS) energy rating (Bannister, 2012; Burroughs, 2018). Under the national energy program for Commercial Building Disclosure, from 1 November 2010, when selling or leasing an office space greater than 2,000 m² sellers or lessors are required to obtain or disclose up-to-date NABERS energy ratings with the Building Energy Efficiency Certificates for all existing buildings (Newell, MacFarlane and Walker, 2014; DIS, 2015).

According to the guidelines from the NABERS rating, a 2 stars NABERS is equivalent to the energy consumption of 150-190 kWh/m2/year whilst 5 stars rating accounts for 40-80 kWh/m^2/year (Steinfeld, Bruce and Watt, 2011; Bannister, 2012; DIS, 2015). The three case study buildings undertaking the upgrading activities in Table 6 can improve the energy performance from 3 stars to a 5 stars NABERS energy rating which could make a significant impact to improve performance of the existing building stock. The increased star rating of these buildings is likely to have better tenant retention with higher rents as potential tenants of office buildings would recognise the energy efficiency of NABERS rating which would help to pay for the costs of upgrading.

The Australian building stock comprises many older buildings which consume great quantities of energy and produce a high rate of CO_2 emission (Burroughs, 2018). Traditionally, to maintain its intended function a building must be well maintained and, particularly, have a major refurbishment every 20–25 years (Wilkinson and Reed, 2006). However, according to Wilkinson and Reed (2006), and Mulholland, Hartman and Plumb (2005), the average age of the office building stock in major CBDs throughout Australia varies from 25 to 31 years since construction or from 13 to 19 years since the last refurbishment; and the average age of office buildings in Sydney is 28 years and 19 years respectively. Existing building stock continues to contribute negatively to the environment and the well-being of users. Therefore, the current existing office buildings in Australia must be improved to meet environmental standards (Remøy and Wilkinson, 2012; Strachan and Banfill, 2012; Xu, Chan and Qian, 2012). With CBD office buildings being the primary focus for economic and financial activity in Australia, the existing office space accounts for approximately 25 million square metres (Newell, MacFarlane and Walker, 2014). For undertaking the upgrading activities as identified in the study, a potential saving of 4,7222,300 GJ and 1,440,750 t CO_2 of energy consumption and CO_2 emissions could be achieved each year.

Conclusion

The paper examined and analysed the cost implication of energy efficiency upgrading of existing office buildings and a case study of three Sydney office buildings has been conducted to present research results. The objectives set for the study have been researched and addressed in the paper. Firstly, the paper identified and discussed ten upgrading activities that are commonly undertaken to improve energy efficiency of existing office buildings. These include upgrades to HVAC, BMCS, hot water systems, lightning, lifts, and escalators Secondly. The upgradings were applied to a case study of three buildings located in the Sydney CBD and varying in age from 24 to 33 years old. to demonstrate the potentials for significant improvement in reducing energy consumption and the associated CO_2 emissions.

As discussed in the paper, existing office building stock is largely dated and energy inefficient. The literature review indicates that an existing office building can be improved to meet environmental protection standards by upgrading that may be a better alternative than knocking down and rebuilding. When undertaking energy efficiency upgradings, the annual energy consumption (kWh/m^2) and emissions (kg CO_2/m^2) can be significantly decreased. Most existing office buildings in Australia, especially in Sydney, are outdated. It was demonstrated in the case studies that by undertaking upgrading activities, energy consumption could be reduced by 55, 42 and 60 kWh/m^2/year and CO_2 emissions by 61, 47 and 65 kg CO_2/

m^2/year respectively for Building 1, 2 and 3. The energy efficiency of the three buildings could be improved from 3 stars to 5 stars NABERS Energy rating. The improved 5 stars NABERS Energy rating of the three case study buildings can achieve the requirement set by the Commercial Building Disclosure stipulated by the government in 2011. From the study, the annualised upgrading costs still outweighed annual saving in energy cost in most activities. The likely increase in future energy prices is likely to improve the attractiveness of energy efficiency upgrade. In the long-term, the improvement in the energy efficiency of the existing building stock will no doubt benefit both the natural and man-made environment.

Creating sustainable buildings from existing office buildings is an attractive and important alternative to demolition and rebuilding as a means to entice tenants. It is argued that sustainability is the expected way forward where retrofitting or upgrading of mature buildings is seen as necessary to meet the environmental protection requirements. The sustainable improvement of existing office buildings would help in harmonising the growth of the economy and environmental protection. A balance must be achieved between protecting and improving the natural environment and contributing positively to the economy over the building's lifecycle. Buildings which offer multiple uses that meet market demands will reduce vacancy rates and thus survive longer and stay competitive, yet, improving the sustainable performance of existing office buildings in a long-tern approach has been largely untapped. However, the paper has limitations similar to other case studies in the literature. The generalisation of research result is often difficult with case studies that are subjected to variances such as geographical location and climate conditions. The research focuses on economic and environmental aspects only while the social aspect is an equally important consideration for future research.

References

Abdallah, M. and El-Rayes, K., 2015. Optimizing the selection of building upgrade measures to minimize the operational negative environmental impacts of existing buildings. *Building and Environment*, 84(0), pp.32-43. https://doi.org/10.1016/j.buildenv.2014.10.010

Anderson, T.R., Hawkins, E. and Jones, P.D., 2016. CO_2, the greenhouse effect and global warming: from the pioneering work of Arrhenius and callendar to today's earth system models. *Endeavour*, 40(3), pp.178-87. https://doi.org/10.1016/j.endeavour.2016.07.002

Atif, M.R. and Galasiu, D., 2003. Energy performance of daylight-linked automatic lighting control systems in large atrium spaces: report on two field-monitored case studies. *Energy and Buildings*, 35(5), pp.441-61. https://doi.org/10.1016/s0378-7788(02)00142-1

Australian Building Code Board, 2004. *Energy efficiency of building transport equipment*. Canberra, Australia: The Australian Building Code Board.

Au-Yong, C.P., Ali, A.S. and Ahmad, F., 2014. Improving occupants' satisfaction with effective maintenance management of HVAC system in office buildings. *Automation in Construction*, 43(0), pp.31-37. https://doi.org/10.1016/j.autcon.2014.03.013

Bannister, P., 2012. NABERS: Lessons from 12 years of performance-based ratings in Australia. *Energy Systems Laboratory, Proceedings of the 12th International Conference for Enhanced Building Operations*. Manchester, UK. October.

Barlow, S. and Fiala, D., 2007. Occupant comfort in UK offices-how adaptive comfort theories might influence future low energy office refurbishment strategies. *Energy and Buildings*, 39(7), pp.837-46. https://doi.org/10.1016/j.enbuild.2007.02.002

Bondanza, J., 2011. *How to design and build a green office building: a complete guide to making your new of existing building environmentally healthy.* Florida, USA: Atlantic Publishing Group.

Bourgeois, D., Reinhart, C. and MacDonald, I., 2006. Adding advanced behavioural models in whole building energy simulation: a study on the total energy impact of manual and automated lighting control. *Energy and Buildings*, 38(7), pp.814-23. https://doi.org/10.1016/j.enbuild.2006.03.002

Bruce, B., Zuo, J., Rameezdeen, R. and Pullen, S., 2015. Factors influencing the retrofitting of existing office buildings using Adelaide, South Australia as a case study. *Structural Survey*, 33(2), pp.150-66. https://doi.org/10.1108/ss-05-2014-0019

Bullen, P.A., 2007. Adaptive reuse and sustainability of commercial buildings. *Facilities*, 25(1/2), pp.20-31. https://doi.org/10.1108/02632770710716911

Burroughs, S., 2018. Improving office building energy-efficiency ratings using a smart-engineering–computer-simulation approach: an Australian case study. *Advances in Building Energy Research*, 12(2), pp.217-34. https://doi.org/10.1080/17512549.2017.1287127

Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G. and Castell, A. 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review. *Renewable and Sustainable Energy Reviews*, 29(0), pp.394-416. https://doi.org/10.1016/j.rser.2013.08.037

Chan, E.H.W., Qian, Q.K. and Lam, P.T.I., 2009. The market for green building in developed Asian cities–The perspectives of building design. *Energy Policy*, 37(8), pp.3061-70. https://doi.org/10.1016/j.enpol.2009.03.057

Chan, H.K,. Wang, X. and Raffoni, A., 2014. An integrated approach for green design: life-cycle, fuzzy AHP and environmental management accounting. *The British Accounting Review*, 46(4), pp.344-60. https://doi.org/10.1016/j.bar.2014.10.004

CIE, 2009. The buildings sector and greenhouse: key facts. *Canberra: The Centre for International Economics*..

Clarke, R., 2009. Global warming and Australia's big dry. *Green Left Weekly*, 809, pp.12-15.

Cleugh, H., Smith, M.S., Battaglia, M. and Graham, P., 2011. *Climate change: science and solutions for Australia.* Collingwood, Victoria, Australia: CSIRO.

Colmenar-Santos, A., Terán de Lober, L.N., Borge-Diez, D. and Castro-Gil, M., 2013. Solutions to reduce energy consumption in the management of large buildings. *Energy and Buildings*, 56(0), pp.66-77. https://doi.org/10.1016/j.enbuild.2012.10.004

Connelly, P. and Adam, N., 2009. Retrofitting for sustainablility. *Architecture Australia*, 98(1), pp.105-07.

CostWeb, 2019. Making predictions of construction costs. Sydney, Australia.

De Almeida, A., Hirzel, S., Patrão, C., Fong, J. and Dütschke, E., 2012. Energy-efficient elevators and escalators in Europe: an analysis of energy efficiency potentials and policy measures. *Energy and Buildings*, 47(0), pp.151-58. https://doi.org/10.1016/j.enbuild.2011.11.053

Department of Climate Change and Energy Efficiency, 2012. *Baseline energy consumption and greenhouse gas emissions in commercial buildings in Australia, Part 1.* COAG [online] Available at: https://www.energy.gov.au/sites/default/files/baseline-energy-consumption-part_1-report-2012.pdf.

DIS, 2015. Commercial building disclosure program review. Canberra, Australia: *Department of Industry and Science.*

Ellison, L. and Sayce, S., 2007. Assessing sustainability in the existing commercial property stock. *Property Management*, 25(3), pp.287-304. https://doi.org/10.1108/02637470710753648

Elmualim, A., Shockley, D., Valle, R., Ludlow, G. and Shah, S., 2010. Barriers and commitment of facilities management profession to the sustainability agenda. *Building and Environment*, 45(1), pp.58-64. https://doi.org/10.1016/j.buildenv.2009.05.002

Galasiu, A.D. and Veitch, J.A., 2006. Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review. *Energy and Buildings*, 38(7), pp.728-42. https://doi.org/10.1016/j.enbuild.2006.03.001

Häkkinen, T. and Belloni, K., 2011. Barriers and drivers for sustainable building. *Building Research and Information*, 39(3), pp.239-55. https://doi.org/10.1080/09613218.2011.561948

Henderson, H., 2006. Wanted for lease: 6 star office. *ECOS*, 131, pp.8-11.

Hestnes, A.G. and Kofoed, N.U., 2002. Effective retrofitting scenarios for energy efficiency and comfort: results of the design and evaluation activities within the OFFICE project. *Building and Environment*, 37(6), pp.569-74. https://doi.org/10.1016/s0360-1323(02)00003-3

Higgins, A., Syme, M., McGregor, J., Marquez, L. and Seo, S., 2014. Forecasting uptake of retrofit packages in office building stock under government incentives. *Energy Policy*, 65(0), pp.501-11. https://doi.org/10.1016/j.enpol.2013.10.041

Hinnells, M., Bright, S., Langley, A., Woodford, L., Schiellerup, P. and Bosteels, T., 2008. The greening of commercial leases. *Journal of Property Investment and Finance*, 26(6), pp.541-51. https://doi.org/10.1108/14635780810908389

Höhne, N., Kuramochi, T., Warnecke, C., Röser, F., Fekete, H., Hagemann, M., Day, T., Tewari, R., Kurdziel, M., Sterl, S. and Gonzales, S. 2017. The Paris Agreement: resolving the inconsistency between global goals and national contributions. *Climate Policy*, 17(1), pp.16-32. https://doi.org/10.1080/14693062.2016.1218320

Huovila, P., Ala-Juusela, M., Melchert, L., Pouffary, S., Cheng, C.C., Ürge-Vorsatz, D., Koeppel, S. and Svenningsen, N., 2009. In: Yamamoto, J. and Graham, P. eds. *Building and climate change: summary for decision-makers*. [online] UNEP SBCI. Available at: https://ledsgp.org/wp-content/uploads/2015/07/buildings-and-climate-change.pdf.

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L. and Acquaye, A., 2013. Operational vs. embodied emissions in buildings—a review of current trends. *Energy and Buildings*, 66(0), pp.232-45. https://doi.org/10.1016/j.enbuild.2013.07.026

Ihm, P., Nemri, A. and Krarti, M., 2009. Estimation of lighting energy savings from daylighting. *Building and Environment*, 44(3), pp.509-14. https://doi.org/10.1016/j.buildenv.2008.04.016

IPCC, 2007. *Climate change 2007: synthesis report, Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Pachauri, R.K. and Reisinger, A. eds. Geneva, Switzerland.

IPCC, 2014. *Climate change 2014: synthesis report, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Pachauri, R.K. and Meyer, L.A. eds. Geneva, Switzerland.

Ive, G., 2006. Re-examining the costs and value ratios of owning and occupying buildings. *Building Research and Information*, 34(3), pp.230-45. https://doi.org/10.1080/09613210600635192

Jenkins, D., Liu, Y. and Peacock, A.D., 2008. Climatic and internal factors affecting future UK office heating and cooling energy consumptions. *Energy and Buildings*, 40, (5), pp.874-81. https://doi.org/10.1016/j.enbuild.2007.06.006

Jentsch, M.F., James, P.A.B. and Bahaj, A.S., 2010. A climatic envelope extension of an office building - perception and reality of the change in environments conditions. In: *Proceedings CIBSE National Conference. Sustainable Energy Research Group*, School of Civil Engineering and the Environment, University of Southampton, UK, March 21-22.

Juan, Y.K., Gao, P. and Wang, J., 2010. A hybrid decision support system for sustainable office building renovation and energy performance improvement. *Energy and Buildings*, 42(3), pp.290-97. https://doi.org/10.1016/j.enbuild.2009.09.006

Kentwell, A., 2007. Climate change adaptation issues for planners. *Australian Planner,* 44(3), pp.20-21. https://doi.org/10.1080/07293682.2007.9982584

Ko, D.H., Elnimeiri, M. and Clarke, R.J., 2008. Assessment and prediction of daylight performance in high-rise office buildings. *The Structural Design of Tall and Specific Buildings*, 17(5), pp.953-76. https://doi.org/10.1002/tal.474

Kohler, N. and Yang, W., 2007. Long-term management of buildings stock. *Building Research & Information*, 35(4), pp.351-62. https://doi.org/10.1080/09613210701308962

Kubba, S., 2010. *Green construction project management and cost oversight.* Oxford, UK: Architectural Press.

Kwon, S.H., Chun, C. and Kwak, R.Y., 2011. Relationship between quality of building maintenance management services for indoor environmental quality and occupant satisfaction. *Building and Environment*, 46(11), pp.2179-85. https://doi.org/10.1016/j.buildenv.2011.04.028

Lecamwasam, L., 2014. Commissioning HVAC systems: quick, cost-effective energy efficiency. Available at http://esbsconsult.com.au/wp-content/uploads/2014/11/Commissioning-HVAC-Systems-FM-Magazine.pdf

Lecamwasam, L., Wilson, J. and Chokolich, D., 2012. *Guide to best practice maintenance & operation of HVAC systems for energy efficiency*. Canberra, Australia: COAG and DCCEE.

Li, B. and Yao, R., 2009. Urbanisation and its impact on building energy consumption and efficiency in China. *Renewable Energy*, 34, pp.1994-98. https://doi.org/10.1016/j.renene.2009.02.015

Li, D.H.W., Lam, T.N.T., Chan, W.W.H. and Mak, A.H.L., 2009. Energy and cost analysis of semi-transparent photovoltaic in office buildings. *Applied Energy*, 86(5), pp.722-29. https://doi.org/10.1016/j.apenergy.2008.08.009

Li, D.H.W., Lam, T.N.T. and Wong, S.L., 2006. Lighting and energy performance for an office using high frequency dimming controls. *Energy Conversion and Management*, 47(9-10), pp.1133-45. https://doi.org/10.1016/j.enconman.2005.06.016

Lynas, M., 2007. How to stop climate change: the easy way. *New Statesman*, 136(4870), pp.24-28.

Menzies, G.F. and Wherrett, J.R., 2005. Multiglazed windows: potential for savings in energy, emissions and cost. *Building Services Engineering Research and Technology*, 26(3), pp.248-59. https://doi.org/10.1191/0143624405bt132tn

Mulholland, V., Hartman, A. and Plumb, C., 2005. Building refurbishment - repositioning your asset for success. *Australian Property Journal*, 38(7), pp.506-15.

Nalewaik, A. and Venters, V., 2009. Cost benefits of building green. *Cost Engineering*, 51(1), pp.28-34.

Newell, G., MacFarlane, J. and Walker, R., 2014. Assessing energy rating premiums in the performance of green office buildings in Australia. *Journal of Property Investment and Finance*, 32(4), pp.352-70. https://doi.org/10.1108/jpif-10-2013-0061

Nicol, J.F., 2009. Cooling in a low carbon world. *Building Research & Information*, 37(4), pp.345-47. https://doi.org/10.1080/09613210902920714

PCA, 2019. *A guide to office building quality. 3rd Edition*. Sydney, NSW: Property Council Australia.

Pitt, M., Tucker, M., Riley, M. and Longden, J., 2009. Towards sustainable construction: promotion and best practices. *Construction Innovation*, 9(2), pp.201-24. https://doi.org/10.1108/14714170910950830

Pitt, M., Goyal, S. and Sapri, M., 2006. Innovation in facilities maintenance management. *Building Services Engineering Research & Technology*, 27(2), pp.153-64. https://doi.org/10.1191/0143624406bt153oa

Raimondia, A., Santuccib, D., Bevilacquaa, S. and Corsoa, A., 2016. Daylight autonomy as a driver for office building retrofitting. *Energy Procedia*, 96, pp.180-89. https://doi.org/10.1016/j.egypro.2016.09.119

Rawlinsons, 2019. *Australian Construction Handbook.* Perth, Western Australia: Rawlinsons Publishing.

Regnier, C., Sun, K., Hong, T. and Piette, M.A., 2018. Quantifying the benefits of a building retrofit using an integrated system approach: a case study. *Energy and Building*, 159, pp.332-45. https://doi.org/10.1016/j.enbuild.2017.10.090

Remøy, H.T. and Wilkinson, S.J., 2012. Office building conversion and sustainable adaptation: a comparative study. *Property Management*, 30(3), pp.218-31. https://doi.org/10.1108/02637471211233738

Roisin, B., Bodart, M., Deneyer, A. and D'Herdt, P., 2008. Lighting energy savings in offices using different control systems and their real consumption. *Energy and Buildings*, 40(4), pp.514-23. https://doi.org/10.1016/j.enbuild.2007.04.006

Sev, A., 2009. How can the construction industry contribute to sustainable development? A conceptual framework. *Sustainable Development*, 17(3), pp.161-73. https://doi.org/10.1002/sd.373

Snodgrass, K., 2008. *Life-cycle cost analysis for buildings is easier than you thought.* Missoula, MT: U.S. Department of Agriculture Forest Service Technology and Development Center.

Steinfeld, J., Bruce, A. and Watt, M., 2011. Peak load characteristics of Sydney office buildings and policy recommendations for peak load reduction. *Energy and Buildings*, 43(9), pp.2179-87. https://doi.org/10.1016/j.enbuild.2011.04.022

Strachan, M. and Banfill, P., 2012. Decision support tools in energy-led, non-domestic building refurbishment-towards a generic model for property professionals. *Facilities*, 30(9-10), pp.374-95. https://doi.org/10.1108/02632771211235215

Synergy, 2019. *Standard electricity prices and charges*. [online] Available at https://www.synergy.net.au/Your-business/Energy-products/Electricity-plans/Synergy-Business-Saver?tid=Energy-products:side_nav:Business Saver.

Taylor, R., 2009. Old buildings take the green lead. *ECOS*, 148, pp. 24-7.

Ürge-Vorsatz, D., Harvey, L.D., Mirasgedis, S. and Levine, M.D., 2007. Mitigating CO_2 emissions from energy use in the world's buildings. *Building Research and Information*, 35(4), pp.379-98. https://doi.org/10.1080/09613210701325883

Ürge-Vorsatz, D., Koeppel, S. and Mirasgedis, S., 2007. Appraisal of policy instrument for reducing buildings' CO_2 emmissions. *Building Research and Information*, 35(4), pp.458-77. https://doi.org/10.1080/09613210701327384

Wan, K.K.W., Li, D.H.W., Pan, W. and Lam, J,C., 2012. Impact of climate change on building energy use in different climate zones and mitigation and adaptation implications. *Applied Energy*, 97(0), pp.274-82. https://doi.org/10.1016/j.apenergy.2011.11.048

WePowr, 2019. How much maintenance to solar hot water systems require? [online] Available at http://wepowr.com/technology/shw/maintenance.

Wild, A., 2008. Green collar workforce the key to a triple bottom line. *ECOS*, 146, pp.17.

Wilkinson, S., 2014. The preliminary assessment of adaptation potential in existing office buildings. *International Journal of Strategic Property Management*, 18(1), pp.77-87. https://doi.org/10.3846/1648715x.2013.853705

Wilkinson, S.J. and Reed, R.G., 2006. Office building characteristics and the links with carbon emissions. *Structural Survey*, 24(3), pp.240-50. https://doi.org/10.1108/02630800610678887

Wilson, J.L. and Tagaza, E., 2006. Green buildings in Australia: drivers and barriers. *Australian Journal of Structural Engineering*, 7(1), pp.57-63. https://doi.org/10.1080/13287982.2006.11464964

Wright, R., 2009. Old buildings take the green lead. *ECOS*, 148, pp.24-27.

Wu, S., 2010. Research opportunities in maintenance of office building services systems. *Journal of Quality in Maintenance Engineering*, 16(1), pp.23-33. https://doi.org/10.1108/13552511011030309

Xu, P.P. ,Chan, E.H.W. and Qian, Q.K., 2012. Key performance indicators (KPI) for the sustainability of building energy efficiency retrofit (BEER) in hotel buildings in China. *Facilities*, 30(9-10), pp.432-48. https://doi.org/10.1108/02632771211235242

Zhou, Z., Zhang, S., Wang, C., Zuo, J. and He, Q. and Rameezdeen, R., 2016. Achieving energy efficient buildings via retrofitting of existing buildings: a case study. *Journal of Cleaner Production*, 112, pp.3605-15. https://doi.org/10.1016/j.jclepro.2015.09.046

Zografakis, N., Karyotakis, K. and Tsagarakis, K.P., 2012. Implementation conditions for energy saving technologies and practices in office buildings: Part 1 lighting. *Renewable and Sustainable Energy Reviews*, 16(6), pp.4165-74. https://doi.org/10.1016/j.rser.2012.03.005