Energy Diversification Approach to Optimise Buildings' Energy Consumption and Greenhouse Gas Emissions beyond Green Ratings

Submitted by:

Xiaofeng Li
Department of Environment and Geography
Faculty of Science
Macquarie University
Sydney, Australia

Supervisor:

Assoc. Professor Vladimir Strezov
Department of Environment and Geography
Faculty of Science
Macquarie University
Sydney, Australia

Thesis submitted for a Doctor of Philosophy

April 2014

Declaration

I certify that work in this thesis entitled "Energy Diversification Approach to Optimise Buildings' Energy Consumption and Greenhouse Gas Emissions beyond Green Ratings" has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree to any other university or institution other than Macquarie University.

I also certify that the thesis is an original piece of research and it has been written by me. Any help and assistance that I have received in my research work and the preparation of the thesis itself have been appropriately acknowledged.

In addition, I certify that all information sources and literature used are indicated in the thesis.

Signed:

Xiaofeng Li (Student ID: 42146399)

Date: 15th April, 2014

Acknowledgement

My deepest gratitude goes first and foremost to my supervisor, Associated Professor Vladimir Strezov, for his constant encouragement and guidance. During each stage of my PhD study, he spent his valuable time for critical reading of various drafts and offering valuable suggestions to improve the manuscript. Without his patient instruction, insightful criticism and expert guidance, the completion of this thesis would not have been possible.

I also would like to express my heartfelt gratitude to Doctor Marco Amati, my previous co-supervisor for welcoming me and my wife to study in Macquarie University. He offered generous help to me for establishing connections with academic and industrial communities, getting familiar with the local culture and lifestyle, which ensured me to fast track my study and research.

Moreover, my numerous thanks go to my colleagues in the Faculty of Science at Macquarie University who have provided friendship, scientific insights and constructive discussions during the whole study period. Selective mention here of Tao Kan, Sarge Bray, Suraj Opatokun, Aal-e Ali, Kazi Mohiuddin and my dear friends, John Merrick, Mingzhu Wang and Ye Wu, who offer me their help and time in listening to me and helping me work out my problems along the way.

Finally, my thanks would go to my beloved family for their generous consideration and great confidence in me all through these years. I owe eternal gratitude to my wife Yaoyao for standing beside me throughout my study. She has been my inspiration and motivation for continuing to improve my knowledge and move my research forward.

Table of Contents

List of Figures

List of Tables

Abstract

The conflict between lowering ecological footprints of the building sector and its rapidly growing energy demand due to accommodating growth in population, increasing demand for building services and comfort levels, as well as the prolonged time spent inside buildings exacerbates the concerns over sustainable development. The energy supply difficulties and depletion of energy resources, coupled with mounting evidence regarding climate change, makes it imperative for reshaping the design, construction and operation of buildings to use our resources efficiently without the compromise of reducing our living standard. Sustainable building, otherwise referred to as "green building", is believed to be one of the promising solutions to help alleviate the depletion of energy resources and the deterioration of our environment. In Australia, more than 600 green buildings were constructed since the first green building was built in 2004. A rapid growth of green buildings in universities and higher institutions was also identified. Up to the first half of 2011, the educational green projects have reached a ratio of 15% of the total green building project applications. Through a comparison study of 24 educational green buildings in Australian campuses, the motivations and expectations of the university decision makers to invest in green facilities were investigated using a qualitative analytical approach based on grounded theory. The results revealed that the green buildings provide the universities diverse benefits, such as enhancing university's reputation and meeting the specific needs for education and research, as well as ensuring environmental protection and strengthening the university's financial condition, apart from the reduction in building's energy consumption.

In addition to the energy conservation parameters, the in-depth integration of renewable energy resources and their utilisation in building are other key components of green buildings. Under this context, the exploitation of renewable energy resources and technologies applicable for integration into the green buildings were investigated in this thesis based on a case study. A 5-star green building at Macquarie University Campus was selected as a research object and the feasible alternative energy sources, which could be potentially applied to the building, were examined taking into consideration the building design and local climate conditions.

Solar energy was initially selected as a promising renewable energy source for study, due to the abundant solar radiation throughout the year and its highly coordinated activity schedule with building occupants' daily routine. The objective of this study was to ascertain the potential of the solar energy that could be used by the case building through Building Integrated Photovoltaic (BIPV) technique. A 3-D geometrical building model, as well as the surrounding objects that could potentially influence the library's solar exposure, were first constructed in computer simulation software based on the architectural drawings and field measurements. Then the function of solar radiation calculations was applied to predict the annual accumulative solar radiation that falls on the surface of the building, from which the annual electricity production was estimated. Moreover, the performance of hybrid solar assisted air conditioning system was modelled and compared to conventional air cooling systems. The simulation results indicate that under ideal conditions, the electricity generated by the photovoltaic panels will entirely cover for the annual electricity consumption for cooling of the building, which is equivalent of reducing 140 tonnes of greenhouse gas emissions each year. However, the overall performance of the hybrid solar air conditioning system did not meet the expectations.

The study then proceeded at investigating the potential for generating energy from sources inside the building. The vibration-based energy harvesting, piezoelectric energy generation was selected as another renewable energy source which possesses the potential to be integrated into buildings due to its ability to capture the surrounding ambient vibration and directly convert applied strain energy into usable electrical energy. The application of a commercial piezoelectric energy harvester in the studied building was modelled. The ideal places for the harvester deployment, regarding the total amount of collectable footsteps and the frequency of pedestrian mobility, were analysed based on a study of the mobility behaviour of the building occupants. The results revealed that the total annual energy harvesting potential was 1.1 MWh/year for the proposed tile pavement plan which covered 3.1% of the building's total floor area. The potential energy generation might be further increased to 9.9 MWh/year with a possible improvement in piezoelectric energy conversion efficiency integrated into the system, contributing 0.5% of the annual energy needs of the building.

Furthermore, the feasibility of converting biomass into bioenergy was analysed using different techniques, due to the considerable amount of coffee wastes generated in a cafeteria of the case building. Pyrolysis, as one of the most developed thermochemical conversion techniques, was employed to achieve thermal decomposition of biomass in the absence of oxygen to derive bio-char, bio-oil and biogas. These pyrolytic products were further examined to determine the energy generating potential when used as biofuels. Together with direct combustion, the bioenergy production potential of the conversion techniques of coffee grounds were evaluated and compared. With the results the most efficient technique can be applied to offset the building's overall carbon footprint from energy consumption.

Taking into account the outdoor and indoor energy source potentials, the energy generation portfolio that maximises energy diversification of the green star buildings was modelled. The renewable energy sources that mentioned above were integrated into the case building to analyse the overall energy replacement ratio regarding the total annual energy consumption of the building. The equivalent greenhouse gas mitigation obtained by the application of alternative energy sources was also discussed.

List of Publications

Li, X., Strezov, V. and Amati, M. A Qualitative Study of Motivation and Influences for Academic Green Building Developments in Australian Universities, *Journal of Green Building*, 8(3), 166-183, 2013.

Li, X. and Strezov, V. Energy, CO_2 Emission Assessment of Conventional and Solar Assisted Air Conditioning Systems, *The 8th Conference on Sustainable Development of Energy, Water and Environment Systems, Dubrovnik*, Croatia, 22-27 September, 2013.

Li, X. and Strezov, V. Modelling piezoelectric energy harvesting potential in an educational building. *Energy Conversion and Management*. 85 (2014) 435-42.

Li, X., Strezov, V. and Kan, T. Energy Recovery Potential Analysis of Spent Coffee Grounds Pyrolysis Products, *Journal of Analytical and Applied Pyrolysis*, accepted 16/08/2014.

The detail information about authorship contributions is shown in Appendix A.

Chapter 1 Introduction

1.1 Green Urban Energies

In the broader context of increasing demands for energy associated with expanding populations and urbanisation, as well as the imperative for more sustainable practices, this thesis focuses on utilisation of renewable energies within the built environment. During the processes of construction, occupation and decommissioning, the buildings and their surroundings have extensive environmental impacts in the short to long term. Operation and activities in the buildings have been confirmed as one of the principal causes of the most environmental damaging impacts. This is primarily due to the carbon footprint of the fossil fuels used to produce the electricity used for operation of the buildings, which has dominated energy consumption and has remained unchanged for decades. There are now many incentives for buildings to upgrade or transform into structures with the ability to implement innovative renewable energy technologies, to minimise negative impacts on the environment.

Green building measures are defined as a sustainable, integrated approach, balancing environmental, economic, and social considerations with large scale of implemented innovative renewable technologies. The level of sustainability a building achieves is strongly coupled with the degree that renewable energy is exploited and utilised. Historically, the evidence indicates that the discovery of a new energy source has led to the sprouting of numerous relevant green technologies. However, these new technologies have to overcome competition and critical testing before they are finally accepted. The renewable energy industry in the civil engineering sector is mainly concerned with energy conversion efficiency, energy production costs and adaptability to buildings. So, in this context, it is necessary to first consider the potential that these alternative energy source candidates might represent, along with the corresponding utilisation techniques.

Practical evaluation of whether a renewable energy source and its applications are a reliable alternative energy approach needs to take a number of factors into account. For example, it is necessary to adjust the measures to local climates, to combine with the conditions of a particular building, including its geographical location, geometric profile, operational strategy, as well as occupant density and schedule. In this work, an educational sustainable building with large volume, complex surface area, numerous occupant mobilities and multi-functionalities, is selected as a case study building to evaluate the feasibility and adaptability of the candidate renewable energy technologies that are either very close to full commercialisation or have only just recently been commercialised. Specifically, the large surface area of the case building offers opportunity for integration of these multiple outside and inside renewable energy sources.

1.2 Research Objectives and Significance

The overall intent of this thesis is to present a comprehensive study of renewable energy sources and their corresponding application techniques, which possess the potential to be integrated into buildings to achieve sustainability on a higher level. This research intends to determine the extent to which the renewable energies capable of being integrated into a sustainable building improve the building's energy consumption profile, and whether their relevant application techniques are mature for the market. The properties of these alternative energy sources and the application techniques were examined and optimised based on modelling and subsequent analytical methods, which provide a holistic prospect in order to derive a final conclusion regarding the implications for further development of green buildings. Thus, this study provides an important opportunity to advance the understanding of developing novel renewable energy sources for buildings, making a major contribution to research on energy neutral buildings by demonstrating the application of their corresponding techniques.

1.3 Thesis Structure

In Chapter 2, the literature that underpins the framework of this thesis is reviewed. This highlights the gaps between the gradually increasing concerns over environmental implications, the current socio-political attitudes and more sustainable strategies; it also explains the rapidly changing scientific context in which this work has unfolded. Aspects reviewed from the literature include: the conflicts of minimising building energy demand while increasing occupant's living comfort; the development of sustainable building in order to address the environmental deterioration problem; evaluating the widely employed green building rating systems to explore the essence of rating standards and predict their evolving direction; determining the drivers or barriers that affect the acceptance of green product applications; and finally summarising the body of energy diversification studies to which this thesis aims to make a contribution. Each of several potential renewable energy sources was examined, in relation to the energy property or output and its energy converting techniques, which can be integrated into buildings.

The introductory review led to analysis of the rapid development of the green building industry in Australia, which is a subject of Chapter 3. The Chapter compares the number of green buildings constructed with total building projects approved in the period from 2004 to 2011. The discussion then focuses on the motivations and expectations of decision makers in Australian universities to invest in green facilities, through a qualitative analytical approach based on the grounded theory. The objectives of this chapter are: to examine the drivers affecting the implementation of green buildings, investigate the benefits gained by the green educational buildings in universities from a holistic perspective; to review the factors that are important to promote the benefits from building green into drivers for investing in green university projects. More broadly, this research seeks to highlight the contribution that higher educational institutions can make to the overall implementation of green buildings within Australia. This chapter is based on a paper that has been published in the *Journal of Green Building*.

Having considered the situation relating to greening of buildings in Australian educational institutions, Chapter 4 focuses more specifically on methods of more effectively harvesting solar energy in new or existing buildings. First, the full potential of solar energy harvesting achieved by Building Integrate Photovoltaic (BIPV) technology is investigated using, as an example, a building which has a vast flat roof area and complex vertical facades. The studies illustrate the variation in available solar radiation falling on the irregular building. In addition, a comparative study between a hybrid solar assisted air-conditioning system and conventional cooling systems is undertaken. The energy consumption profiles of these cooling systems, as well as their greenhouse gas emission predictions are investigated. This work was presented at the 8th Conference on Sustainable Development of Energy, Water and Environment Systems.

The following Chapter 5 demonstrates the adaptability and electricity generating potential of a commercial piezoelectric energy harvester, when deployed in heavy pedestrian traffic areas of the case building, to recover kinetic energy generated from the footsteps. These investigations discuss the parameters which could significantly affect energy harvesting efficiency, including the orientation of deployment and the mobility density flow of the installation area. Subsequently, optimal tile deployment strategies are proposed. The chapter has been published in the *Journal of Energy Conversion and Management.*

Having investigated solar and kinetic energy harvesting, Chapter 6 considers the bioenergy potential of using spent coffee grounds collected in the case building as biomass feedstock to supply part of the building's energy demand. These studies demonstrate different biomass processing routes to recovery energy from spent coffee grounds by using thermochemical and biochemical methods. An extensive experimental campaign was undertaken to characterise the by-products derived from each pathway and to evaluate their energy value as a potential source for renewable fuel. This work has been accepted by the *Journal of Analytical and Applied Pyrolysis* and is currently under publishing process.

Based on the above outcomes, Chapter 7 attempts to integrate the key findings of on-site renewable energy generation studies, with the objective of highlighting the benefits of using selected technologies in a case study building. The renewable energy sources include solar energy, kinetic energy and bioenergy. The wind energy is excluded in this study due to the limited wind source in the Macquarie University district. The annual energy consumption profiles of the case building, before and after integrating the renewable energy sources, are presented. The greenhouse gas mitigation potential is also discussed in this chapter.

Finally, Chapter 8 presents the concluding remarks and recommendations that reflect on the outcomes of the research.

Chapter 2 Literature Review

2.1 Minimising Energy Demand and Increasing Building Living Comfort

In the early 1960s, the idea of energy efficiency was first tested in commercial buildings. Due to the lack of experience and limited reference, the principle to reduce the building energy consumption was initially focused simply on minimising the energy demand. Following this principle, buildings were constructed or refurbished for the purpose of reducing the energy consumption using a range of solutions. These solutions included adding an additional thermal insulation layer to the exterior of the building envelope and replacing single layer windows into multilayered air-tight windows [1]. By reducing the fresh air flow, the energy demand of the buildings was significantly reduced. However, a group of adverse effects emerged for the building occupants for the first time in history. It was noted that nonspecific symptoms were reported by occupants in newly constructed or remodelled offices. These consisted of symptoms, such as sensory irritation of the eyes, nose, throat; odour and taste sensations; skin irritation; nonspecific hypersensitivity reactions; and even neurotoxic or general health problems. Notably, in most cases, these symptoms were relieved soon after the occupants left the particular room or building [2].

After a series of diagnoses and examinations of the building environment, the term "Sick Building Syndrome (SBS)" was coined by the World Health Organization (WHO) in 1984. SBS was then used to describe situations in which building occupants experience acute health and comfort effects that appear to be linked to the time spent in a building, but no specific illness or alternative cause can be identified [3]. During the process of SBS investigations, poor indoor air quality (IAQ) was the main factor causing the syndrome

[4]. The IAQ was then highlighted increasingly in academic areas with many studies performed in individual buildings [5, 6]. It was generally agreed that energy saving in building design should not be achieved by compromising the occupants' living quality. With the rapid acknowledgement of building health, further connections were established between building environmental quality and occupant health. A much wider suite of indoor environment quality (IEQ) characteristics was defined which includes not only the IAQ, but also thermal comfort, illumination and ventilation [7]. Now the balance between IEQ and energy usage has become the main concern of building designers.

2.2 The Development of Sustainable Building and the Green Building Rating Standards

2.2.1 Sustainable Building Development

The development of sustainable building formally started in 1987 when the term 'sustainability' was firstly defined in the Brundtland Report as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs [8]". In essence, the concept of sustainable development is being a satisfactory balance between environmental protection, social equity and economic development [9].

In the building sector, the sustainability of buildings is recognised as the ability to provide the basic function of a building and meet the specified building performance requirements, while minimising disturbance to and improving the functioning of local, regional, and global ecosystems during the whole life span from construction to demolition [10]. Architectural design that conforms to the adaptation of environmental, economic and socio-cultural concerns holistically can be defined as sustainable building or green building. Furthermore, Bumett [11] complemented the above definitions with the interaction between building and people in his study as “a green building optimises efficiencies in resource management and operational performance; and minimises risks, which threaten the human health and environment”.

A number of studies have been conducted to reveal the relationship between sustainable building and the environment [12-14]. Medineckiene, et al. [15] describe a construction impact on the environment from environmental, financial and social aspects. They found that the life cycle of the construction should be evaluated when dealing with uncertainties in the strategic decision making period. Moreover, the study illustrated that the use of renewable materials in building construction is useful for both the environment and people, when financial and qualitative issues are considered.

The correlation between green building and economies was established by analysing the demand for green buildings in the volatile property markets [16]. The study related the economic premiums for green buildings to their relative efficiency in energy use. It was shown that the building sustainability ultimately contributes to premiums in rents and asset values. Similar benefits were also identified by Mao and Yang [17] through analysing the incremental return on incremental costs of green building projects from a real estate investor’s perspective.

2.2.2 Green Building Rating Standards

A range of building rating tools have been developed over the past few years in order to complement the knowledge about the level of sustainability and these rating systems are still in the process of improvement [18]. The most representative and widely used building rating methods are Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), and Green Star [19-21]; features of each are summarised in Table 1. BREEAM is the oldest and was developed by the U.K. Building Research Establishment (BRE) as a measure of best practice in environmental building design and management [18]. LEED was developed by the U.S. Green Building Council (USGBC) and has been the most widely accepted rating tool in the United States [19]. Green Star is the third building sustainability rating system which is equivalent to BREEAM and LEED. It was launched by the Green Building Council of Australia (GBCA) [22].

There are many similarities between these three schemes. First of all, they take a common approach as they assess a building against multiple criteria in different categories. BREEAM evaluates a building by ten criteria, such as Land Use & Ecology, Water, Energy Materials, Health & Wellbeing, Transport, Waste, Pollution, Management and Innovation [23]. LEED evaluates seven aspects, such as Sustainable Sites, Water Efficiency, Energy & Atmosphere, Materials & Resources, Indoor Environmental Quality, Innovation in Design and Regional Priority [24]. Green Star is focusing on nine categories, namely, Management, Indoor Environment Quality, Energy, Transport, Water, Materials, Land Use & Ecology, Emissions and Innovation [25]. Secondly, all these schemes are based on credit collecting systems that determine the level of sustainability and hence the building's rating classification [20]. BREEAM adopts a rating scale from Pass to Excellent; LEED uses a scale of Bronze, Silver, Gold and Platinum to indicate a ranking from low to high; while Green Star adopts a star rating from 1 to 6 accordingly. Thirdly, all three rating tools have been developed into a series aimed at rating of a wide range of building types, both newly constructed and existing buildings. Due to the functionality difference in varied building types, a comparison between the similar type of buildings with the same standard, can greatly minimise the potential bias [26, 27]. All three rating methods are compared in Table 1.

Table 1 demonstrates that the building rating methods have differences in their methodologies, evaluation scopes, weighting in credits and certification processes. Some criteria have different relative importance, and different assigned weightings, depending on the geographical locations. For instance, the Water category in the Green Star rating tool possesses more weight comparing to the BREEAM and LEED rating tools. This is due to the water economy measures being of higher importance in Australia, compared to the U.K. or U.S. For BREEAM, the rating method puts more attention on Land use and Pollution which is in accordance with U.K.'s objective conditions such as relatively smaller national territory and heavier air pollution compared to the U.S. and Australia. It is also noted that buildings designed to meet the highest LEED (Platinum) or Green Star (Six Stars) ranking, are likely to achieve a BREEAM result of Very Good or Good level [28]. This is probably because the building code or building regulation standards vary from country to country. The building code standards in the U.S. and Australia are lower than those in the U.K. [20], indicating a need for the metrics and performance standards for assessing buildings to be standardised globally.

It should be noted that these building assessing schemes put the Energy criterion as the most significant weight, accounting for nearly 25% of the total weightings. However, this may not be sufficient for buildings aiming for ultimate energy neutral or fully self-sustained. Under these circumstances, a recast of the Energy Performance of Buildings Directive (EPBD) was adopted on 19 May 2010 by the European Parliament and the Council of the European Union in order to strengthen the energy performance requirements. The EPBD states that the nearly zero or very low amount of energy required should to a very significant level be covered by energy from renewable source, including renewable energy produced on-site or nearby. [29] The new European building schemes are still under development and the EPBD will take force on 31 December 2018.

Table 1. Comparison of the building rating methods.

Feature	Rating Method Name		
	BREEAM	LEED	Green Star
Launch Date	1990	1998	2003
Ratings	Pass/Good/Very Good/Excellent/ Outstanding	Certified/Silver/Gold/ Platinum	One –Six Star
Weightings	Applied to each criterion (consensus based on scientific/open consultation)	All credits equally weighted, although the number of credits related to each criterion is a de facto weighting	Applied to each criteria category (industry survey based)
Information Gathering	Design/management team or assessor	Design/management team or Accredited Professional	Design team
Third Party Valuation	BRE	N/A	GBCA
Update Process	Annual	As required	Annual
Assessment Collation Fee	$4000-20000	$75,000	$4002-8004
Cost of credit appeals	Free	$500	$800
Building Covered			
New	+	+	+
Interiors	-	+	+
Core & shell	-	+	+
Existing	+	+	+
Renovated	+	+	+
Mixed-use	+	+	-
Category Weightings			
Management	15%	8%	12%
Energy	25%	25%	24%
Transport	N/A	N/A	12%
Health	15%	N/A	12%
Well-being	N/A	13%	N/A
Water	5%	5%	14%
Materials	10%	19%	12%
Land use	15%	N/A	9%
Ecology	N/A	5%	N/A
Pollution	15%	11%	6%
Sustainable Site	N/A	16%	N/A

2.3 Drivers and Barriers of Green Building Development

2.3.1 Barriers to the Construction of Sustainable Buildings

The lack of unified building rating standards is one, but not the only, obstacle that hinders the implementation of green building projects. With the aim to govern the development of building sustainability, many studies have been conducted to identify the obstacles that prevent decision makers from investing in green industry [30-35]. Mair and Jago [36] articulated the barriers as being the lack of resources and limited knowledge, awareness, and skills in eco-conscious behaviour. While according to the environmental behaviour model, ecological behaviour is not only the result of internal factors as Mair and Jago claimed, but is also affected by external factors [37]. Internal factors refer to personal attributes, such as attitudes, beliefs and knowledge; on the other hand, external factors include social institutions, economic forces, and physical structures.

In terms of internal factors, previous research indicates that once knowledge regarding greening practices is developed within individuals, it is likely to influence the individuals to behave in an eco-friendly manner [37]. McCoy, et al. [33] proposed and demonstrated an approach for exploring diffusion barriers specific to innovative green building products. They found that promoting attributes of green building products could reduce the barriers to diffusion and commercialisation across the residential construction industry. On the contrary, inadequate knowledge or misunderstanding of sustainability greatly hinders environmental responsible actions [38], especially when the traditional perception of how a building should be constructed still prevails. The perceived risks emerged from uncertainty about the benefits drove many developers to resist building green [39].

High cost premium is widely accepted as one of the most significant external factors to inhibit development of green buildings [40]. The capital cost of green buildings is much higher when compared with conventional buildings, as the green materials cost significantly more [41]. Meanwhile, as listed in Table 1, the certification process requires a considerable amount of additional costs. These additional costs include expenditure in the preplanning and construction stages for the use of green alternatives as well as expenses in the operational stage for using green techniques and maintaining green products. The problem of unequal distribution of benefits is another inhibiting factor [40]. Generally, it is the developers who pay the high cost premium for green buildings but the tenants of the building enjoy the benefits generated from the green building, such as better indoor environmental quality and cost savings in energy and water. In most cases, the developers' primary goal is to make benefits or to get a return on investment [42]. They evaluate the investment by three different indicators: payback time, the return on investment, and the internal rate of return. However, the payback time of investment in green building projects can be very long due to the fact that energy saving benefits occurs in the operational stage. In addition to the lack of previous experience, unfamiliar techniques can make investors relatively apprehensive, as they prefer a short-term payback time to minimise the uncertainty regarding project success and the possibility of increasing interest rates [43].

2.3.2 Motivations to Invest in Green Buildings

Although the development of green building faces the types of obstacles discussed above, the number of green projects is increasing rapidly [41]. This is probably because when developers are examining the potential risks which may occur over the long payback time, they also have to mitigate downside risks due to the development of future legislations [44]. The clear tendency towards more comprehensive and strict legislation on sustainable design has become a powerful driver to lead the developers and property investors to adopt green construction procedures and practices [45].

Energy savings in the operating stage are the most substantial benefits of green buildings. A detailed review of 60 LEED rated buildings demonstrates that green buildings are on an average 25-30% more energy efficient compared to conventional buildings [46]. Energy savings in green building are achieved primarily by reducing electricity purchases from the power grid and secondly by reducing the peak energy demand. The reduced energy demand from power grids contributes to simultaneous decreases in greenhouse gas emissions [47]. Castleton, et al. [48] confirmed the energy saving potential by studying one of the most common green technologies, the green roof. They summarised an energy saving potential coming from the application of a green roof for heating as 45% in non-insulated buildings and 13% in moderately insulated buildings. Li, et al. [49] tested the energy efficiency of semi-transparent photovoltaics in office buildings. They found that when semi-transparent PV panels are used together with dimming controls, a peak cooling load reduction of 450 kW was achieved. This was equivalent to annual building electricity saving of 1203 MWh, which contributed a reduction of 12% of the annual building electricity expenditure.

The building tenants' indoor comfort is an additional reason for investing in green buildings. Many studies have demonstrated the strong connection between building indoor environmental quality and the productivity of people who work in this environment [46, 50-52]. Similar conclusions are drawn that an improved indoor environmental quality in a green building might result in higher employee productivity

[47]. Ries, et al. [53] compared working performances of the same group of people who had just moved from a conventional working place to a new green facility. The new facility offered more natural daylight, better air quality and thermal comfort than the old building. The results indicated that the employees experienced an enhanced productivity because of the size of the work area, the temperature, and the relative humidity in the green indoor environment. This result has other implications. First, employers may be willing to pay higher rents for green buildings. Second, tenants' preferences for green facilities feed back to the developer as a positive signal that a property with green features would improve the lease pattern [45]. The property can be leased more easily and the vacant period is significantly reduced. Thus the sustainable building could have longer economic life-span than conventional buildings [16].

Apart from the direct benefits, green buildings offer indirect benefits through an increase in reputation [54]. As an improved working environment is provided, firms that lease space in a green building may gain a favourable reputation, which enables the employers to charge premium prices [55], to attract a better work force [56], and to attract investors [57].

2.4 Outdoor Energy Sources for Buildings

Renewable energy resources and their utilisation in buildings are key components of sustainable development [58]. This statement is further confirmed through the comparison of various building rating tools shown in Table 1. The Energy criterion is the most significant in the rating tools, accounting for nearly 25% of total weightings. Ferreira, et al. [59] and Schwartz, et al. [60] compared the sustainable construction assessment tools using case studies, including a comparative analysis focusing on the

Energy criterion. The results showed that renewable energy production is assigned a very important weight in all the rating tools. In this context, the exploitation of renewable energy resources and technologies applicable for integration into the green buildings, are divided here into those that can generate energy from outdoor sources and indoor energy sources. One of the most important outdoor energy sources is solar radiation.

Solar energy is the most abundant and inexhaustible of all the renewable energy resources [61, 62]. The amount of solar energy incident on the overall land area far exceeds the total world energy demand. The world's overall solar energy resource potential is nearly 5.6 gigajoules (GJ) (1.6 megawatt-hours (MWh)) per square metre per year [63]. Compared to other places, Australia has the highest solar radiation per square metre of any continent in the world. In Australia, the annual solar radiation is approximately 58 million petajoules (PJ), which is approximately 10,000 times Australia's annual energy consumption [64]. In recent years, the use of solar energy has increased significantly, however, there is still vast room for further expansion.

Aside from the access and abundance of the solar resource, there are other positive features that make solar energy the ideal source of alternative energy. First, due to the correlation between solar radiation and daytime peak electricity demand, solar energy has the potential to provide electricity during peak demand times [64]. Second, solar energy technologies have high compatibility and can be easily operated within other hybrid systems [65, 66]. Third, solar technologies can offer distribution utilities ancillary services, such as grid support. Fourth, solar generation can also provide electricity to remote townships or facilities where the cost of alternative electricity sources is high [67].

Utilisation of solar energy has been an indispensable element in the long pursuit of building sustainability. To date, there are mainly two types of solar technologies: solar photovoltaic (PV) and solar thermal (STE) as shown in Figure 1.

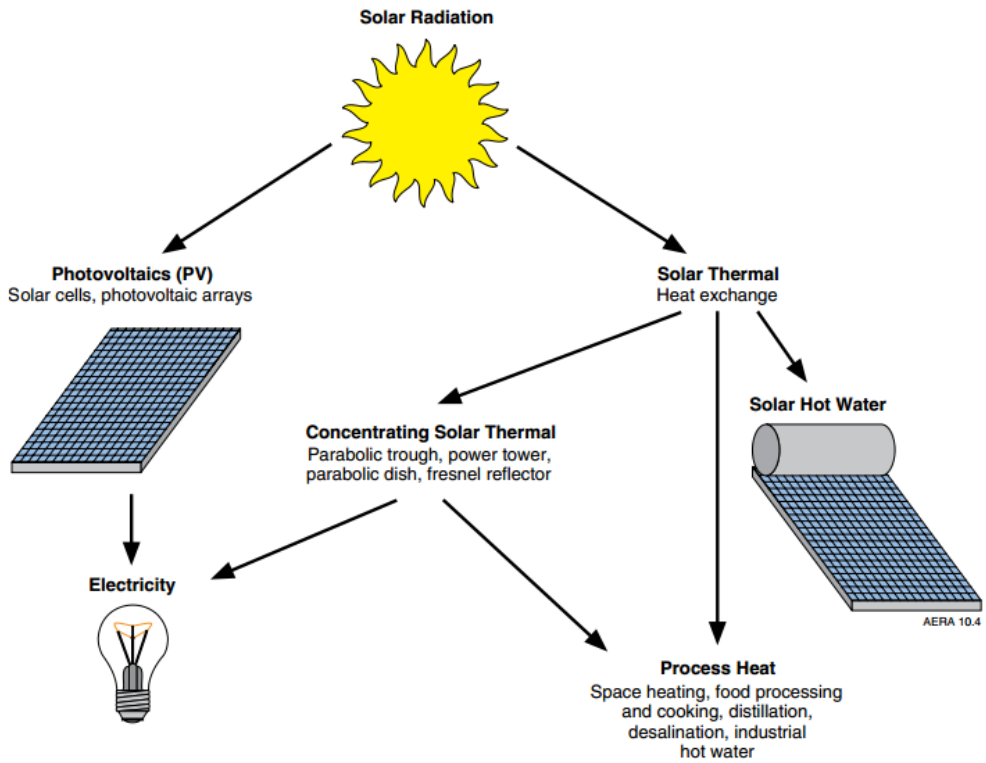


Figure 1. Summary of solar energy flows [64]; (a) both photovoltaics and solar thermal; (b) components of a concentrating solar thermal generating facility.

PV is a technology used for generating electrical power by converting sunlight into direct current electricity using semiconductor materials. PV system converts the solar radiation directly into electricity without any intermediate generator, hence is very easy to install and requires very little maintenance. The PV panels are normally installed on rooftops or on any large flat area, however, with the development of PV materials, new generations of PV panels can be integrated into building designs. PV electricity generation has been the fastest growing segment of the power production market in the last five years [68]. The STE is a technology for harnessing solar energy for thermal purposes. In recent year large-scale concentrating arrays have been developed to generate commercial or industrial electricity outputs, but the most common small application is the hot water collector, which absorbs solar radiation to heat the carrying medium (air, water or other fluid). Then the medium with thermal energy is driven to different terminals for space heating or domestic hot water supply or even to generate electricity using steam and turbines.

2.4.1 Solar-Electrical and Building Integrated Photovoltaic

The traditional way of installing PV panels on to buildings is by mounting PV modules to a separate metal support structure on the roof. This installation method relies heavily on the existing building structure and is more typically used in roof retrofits, thus it is named Building Applied Photovoltaic or Building Adopted Photovoltaic (BAPV). A typical BAPV system is shown in Figure 2. There are mainly two subcategories for BAPV systems, standoff and rack-mounted arrays [69]. Standoff arrays are typically installed on pitched roofs and panels are parallel to the roof slope. The rack-mounted arrays are normally suitable for flat roof conditions, where the modules can be oriented and tilted for optimal exposure and maximum annual electricity yield. The support structure is usually attached to the roof through series of brackets which are mechanically fastened to the roof structure. But in some cases, the BAPV arrays can also float over the roof without any mechanical connection to the roof. The PV modules in these cases are ballasted or designed to remain in place when subjected to wind or other loads that would cause the array to slide move or overturn.

Figure 2. An example of a BAPV system fitted on a tiled rooftop [70].

The BAPV systems have several positive features that have made this type of mounting method dominant in the market for decades. First, the installation process is simple [71]. There is no necessity to re-design or modify the building structure for the deployment of the arrays. The PV arrays can be simply mounted on the support structures. Second, the arrays are easy to maintain and replace when some parts of the modules are broken due to the weather or other external factors. Due to overlapping of the deployed arrays with the roofs, the building's function will not be disturbed by the broken PV parts. Moreover, the overlapping deployment can create a space between the PV arrays and the building's roof. This air gap is very important for both the modules and the building, because the gap will help the modules discharge the heat generated as a by-product of conversion of solar radiation into electricity [72]. The temperature rise in the module significantly affects its electrical performance [73, 74]. In general, temperature coefficients for power output of crystalline silicon PV arrays reduce by approximately 5% for each 10 °C increase in module operating temperature [75]. On the other hand, the overlapping mounted arrays will effectively reduce the heat gain to the building by shading the building roof from direct sunlight. The reduced roof temperature will thereby lower the heat transfer between the roof structure and the top level of the interior by heat conduction and convection. The corresponding radiation heat transfer will be also decreased by lowering the temperature of the underside of the roof.

In contrast to the conventional BAPV, Building Integrated Photovoltaic (BIPV) is defined as an architecturally integrated building component: the electricity producing modules are both a functional unit of the building and also part of the exterior building envelope, since these modules replace conventional building materials [61]. The fields of BIPV application are the roof areas of the building as well as facades such as vertical walls, skylights, windows and external shading devices depending to the particular features of the photovoltaic materials. The PV product, silicon wafer based crystalline cells (c-Si) is the most widespread and predominant in roof applications [76]. The subcategories, mono-crystalline and multi-crystalline modules both offer a good cost-efficiency ratio of 20% and 15% respectively, due to the relatively high photovoltaic efficiency. However, due to the specific material properties, the modules are mostly rigid, opaque and flat. In some cases, semi-transparent solutions can be obtained, typically achieved by means of a particular distance set between the arrays of solar cells. Figure 3 illustrates an example of semi-transparent c-Si skylight roof.

Figure 3. An example of semi-transparent c-Si skylight roof [71].

With the development of Thin-Film (TF) technology, several types of TF modules with varied photovoltaic materials, such as amorphous (a-Si), micromorph (μm-Si), copper indium gallium selenide (CIGS), organic photovoltaics (OPV) and dye-sensitized cells (DSC) are accepted by the market due to their advanced features. For instance, compared with c-Si, the efficiency decrease in the TF modules is less affected by high temperatures and there are less significant losses of performance under indirect and low solar radiation conditions when the sunlight is blocked by clouds, trees or other adjacent buildings [76, 77]. Moreover, by adding an encapsulating polymer of any colour or interferential coating, the TF modules can be tailor-made into any size and shape to satisfy the specific architectural requirements [78]. Figure 4 shows an example indicating the wide range of applications of OPV BIPVs due to its flexible property. In addition, the coating and printing techniques which are known as the roll-to-roll printing technology, employed for the manufacture of the TF PV products, the manufacturing costs are expected to be much lower than the crystalline silicon solar cells in the next few years [79]. The dye-sensitised cells (DSC) PV modules currently possess a relatively low level of efficiency of around 4-6% [80], however this disadvantage is offset by other properties. For instance, the cell can be produced in various colours on flexible, rigid or semi-transparent substrates in a cost-efficient way [81].

Figure 4. Flexible photovoltaic panels stretched across a tent gather energy for electricity generation while camping [82].

Compared to the previously mentioned semi-transparent BIPV products, which are installed by scattered module deployment or laminated frit-sealed modules with limited transparency, a prototype transparent photovoltaic cell with an ultrahigh visible transmission has been produced in the laboratory [83, 84]. By absorbing only infrared and ultraviolet light, letting visible light pass through the cells, the cell is able to reach a transmission of >55%±2%, which is sufficiently transparent for incorporation on architectural glass [83]. To highlight the transparency of the fully assembled device, the solar cell array was deployed in front of an LCD screen showing the "Teton mountains" as in Figure 5. Both picture-detail and colour clarity "blue-green" are minimally disrupted so that details of the cell array are even difficult to discern. Furthermore the PV cell series were tested under near ambient lighting environment and the result showed that it was able to power up a small LCD clock.

Comparing to the BAPV system, BIPV systems significantly extend the solar collecting area from roof only to the whole building skin, converting the largest vertical areas such as exterior walls and windows into electricity generators. They provide a vast vertical area directly exposed to the bright morning and early evening sunlight and hence the total electricity yield will be significantly increased [71, 85]. As an architecturally relevant component, the PV modules replace the conventional building facade materials, the initial cost can be offset by reducing normal construction costs of building materials and labour for parts of the building replaced by BIPV modules. Especially since BIPVs do not require additional assembly components such as brackets and rails. Apart from saving the initial costs, the integrated PV modules also contribute to the thermal comfort of the building [76]: they serve as a shell of the building, providing weather protection, heat insulation, noise protection, thermal isolation and electromagnetic shielding. The PV cells block much of the infrared solar radiation which is mainly responsible for the indoor heat gain. The reduced heat gain will result in a lower air conditioning demand, which further reduces energy use and operating costs in the building. It should be noted that these benefits are gained without modifying the look of the building or obstructing views for the occupants [86].

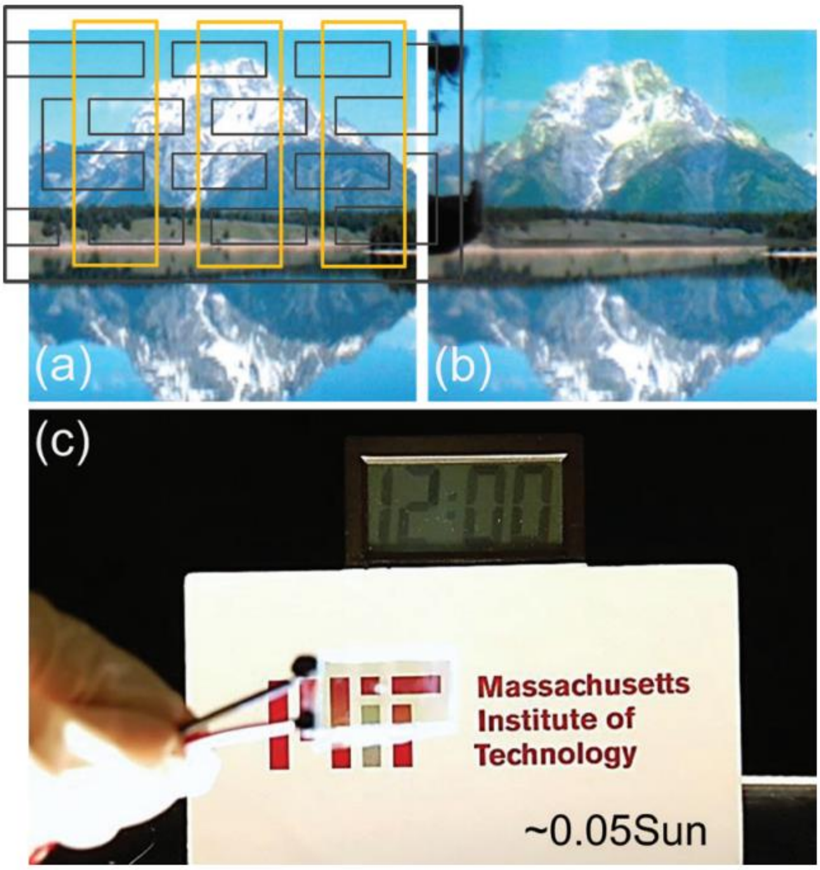


Figure 5. A prototype transparent photovoltaic cell with an ultrahigh visible transmission: a) Picture of the "Teton mountains" displayed on an LCD screen; b) with the fully assembled transparent solar cell in front of the picture; c) transparent cell powering an LCD clock illuminated with ~0.05 sun while allowing for high transparency [83].

2.4.2 Solar-Thermal Energy and Hybrid Air-Conditioning Systems

The solar energy collector is the most commonly used application of the Solar-Thermal Energy (STE) technology. The solar energy collector, shown in Figure 6, is a heat exchanger that converts solar radiation energy to internal energy of the carrying medium, which is usually water [87]. In the last century, the solar collector was usually used for providing domestic hot water (DHW) of less than 87 ^{0}C during the summer season [88, 89]. The hot water could also be stored in a thermal energy storage tank from where it could be drawn for use at night or on cloudy days. Compared to the electrical hot water supply system, the solar collector hot water system is a more economical alternative because there is no working ability loss in the energy conversion process [90].

Figure 6. Vacuum tube collector is one of the most efficient (and most expensive) types of collector on the market [91].

The energy consumed by the Heating, Ventilating, and Air Conditioning (HVAC) system in a building is usually two to four times the energy consumption of DHW [92]. But, the high solar radiation in summer is associated with the period of peak cooling demand, which offers an opportunity to exploit solar thermal technologies to drive heat-driven cooling technologies [93]. As a result, attempts have been made to apply solar energy collection into HVAC systems to achieve higher energy conservation rates [94-98]. The commercial use of the STE for air conditioning purposes is relatively new. Lamp and Ziegler [99] reviewed the development of solar-assisted air conditioning systems in Europe up to 1996. Li, et al. [100] and Concina, et al. [101] discussed the feasibility of solar cooling technologies from the aspects of energy, economic and geographic parameters. Rosiek, et al. [102] analysed a solar-assisted air-conditioning system which was installed in an educational building and confirmed a positive result in energy savings when the solar-assisted air-conditioning system is incorporated in the whole heating and cooling demand.

The solar assisted HVAC systems contain solar thermal collectors connected to thermally driven cooling mechanisms which consist of several main components, as illustrated in Figure 7. The HVAC system comprises a solar thermal collector, heat buffer storage tank, heat distribution system, heat-driven cooling devices, and an optional cold storage tank followed by the air conditioning system and the auxiliary subsystem for backup. Among these main components, the heat-driven cooling systems could be generally divided into two categories of open cycles (desiccant systems) and closed cycles (absorption, adsorption) [103, 104].

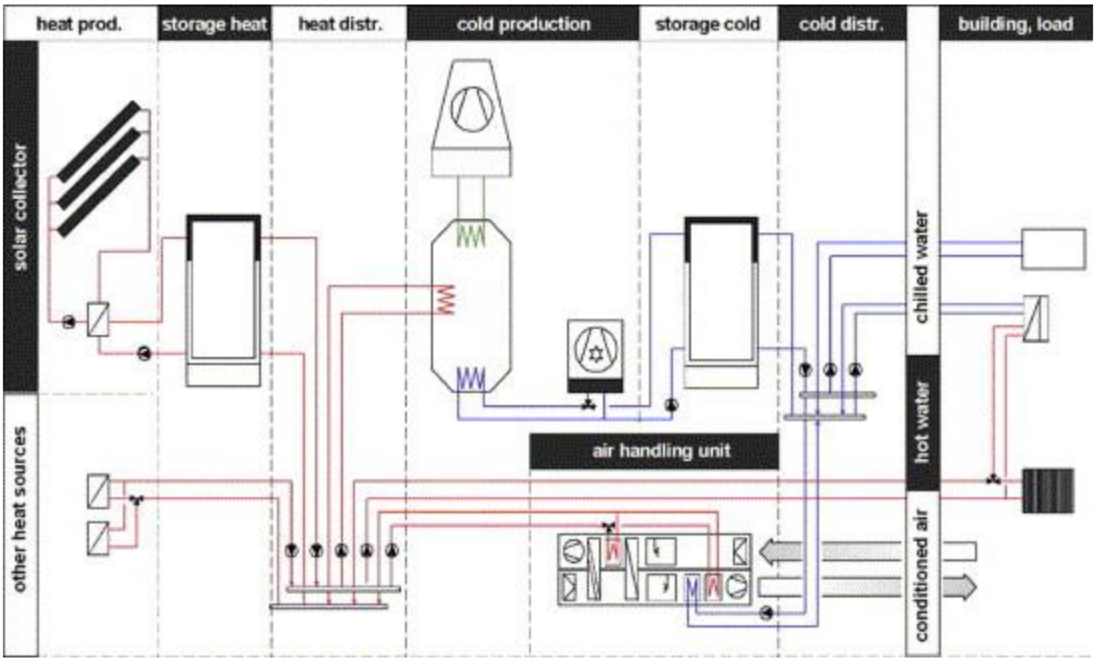


Figure 7. Schematic description of solar assisted air-conditioning system [105].

Open cycle systems refer to solid or liquid desiccant systems that allow complete conditioned air by supplying cooled and dehumidified air according to the living space comfort conditions [106]. In principle, desiccant systems transfer moisture from one airstream to another through two processes [104, 107]. In the first process which is known as the sorption process, the desiccant system transfers moisture from the inlet air into a desiccant material by using the difference in the water vapour pressure of the humid air and the desiccant. The moisture in the inlet air is attracted and absorbed to the desiccant material due to its relatively low surface vapour pressure comparing to that of the moist air. After the desiccant material becomes wet, the second process, which is called the desorption process or regeneration process is needed. In the regeneration process, the captured moisture is released to the exhaust airstream by increasing the desiccant temperature. After regeneration, the desiccant material is cooled down by the cold airstream, then it is ready to absorb the moisture again, hence forms the desiccant cycle. To drive the cycle continuously, thermal energy is needed during the desorption process which provides an opportunity to apply STE instead of an electrical-driven refrigeration cycle to transfer the moisture. The standard system commonly used at present is that of rotating desiccant wheels, shown in Figure 8, equipped either with silica gel or lithium-chloride as the sorption material [108].

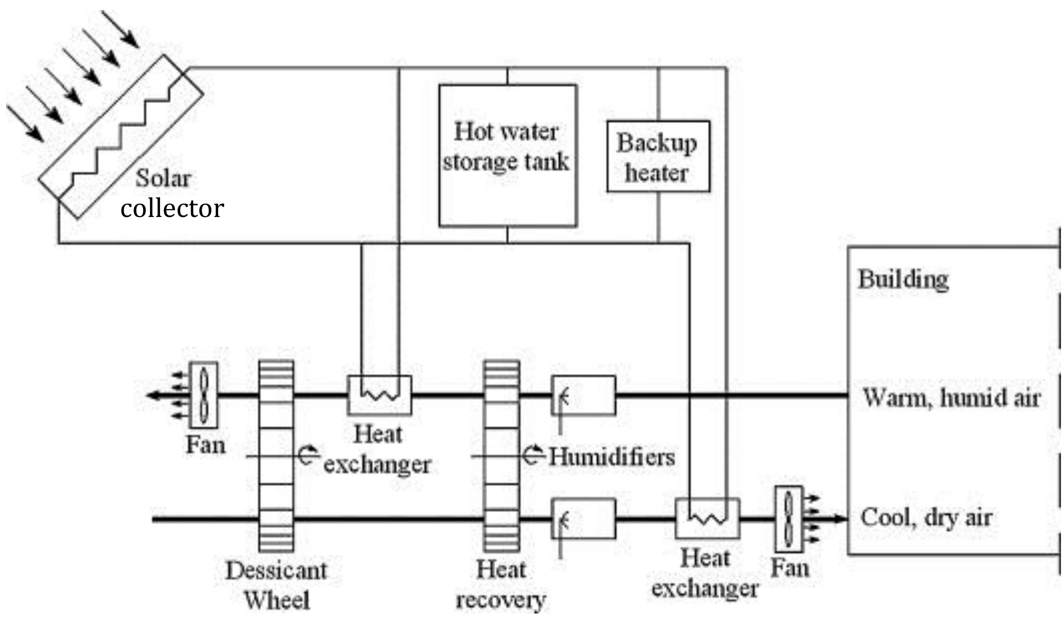


Figure 8. Schematic of a standard desiccant cooling cycle using a dehumidifier wheel with solar thermal energy driving the heat input [107].

Different from the open cycles directly supplying conditioned air, the closed cycles provide chilled water which can either be used in air handling units or in decentralised room installations, for instance, fan coils to supply a space with cooled and dehumidified air [106]. These types of systems are based mainly on the absorption cycle which is one of the oldest refrigeration technologies [104]. The refrigerant side of the absorption cycle essentially works under the same principle as the vapour-compression cycle. The electric-driven compressor used in the vapour-compression cycle is replaced by the thermal compressor in the absorption cycle. The thermal compressor consists of the absorber, the desorber, and the solution pump. The absorption cooling cycle starts in the evaporator, where the refrigerant evaporates in a low partial pressure environment to the absorber. In the evaporator, the refrigerant extracts heat from the surroundings and evaporates, which in turn cools down the chilled water. Then the phase-changed refrigerant is absorbed into the absorbent which causes the partial pressure to be reduced in the evaporator and allows more liquid to evaporate.

In the regeneration process, in order to separate the refrigerant from the solution, the liquid mixture of diluted refrigerant and the absorbent materials is pumped to the generator and then heated using a heat source. The refrigerant evaporates and then condenses on the condenser to refill the supply of liquid refrigerant in the evaporator through a circulation valve [109]. The advantage of the absorption cycle is that the power consumption of the solution pump is relatively small compared to that consumed by the electric-driven compressor. Moreover, the heat source required in the regeneration process can be replaced by the STE. Solar absorption systems use solar thermal energy from a solar collector to separate the refrigerant from the solution of mixed diluted refrigerant and the absorbent materials. The typical absorption cycle solar cooling system consists of an absorption chiller, solar collector, hot-water storage tank and an auxiliary heater, as shown in Figure 9.

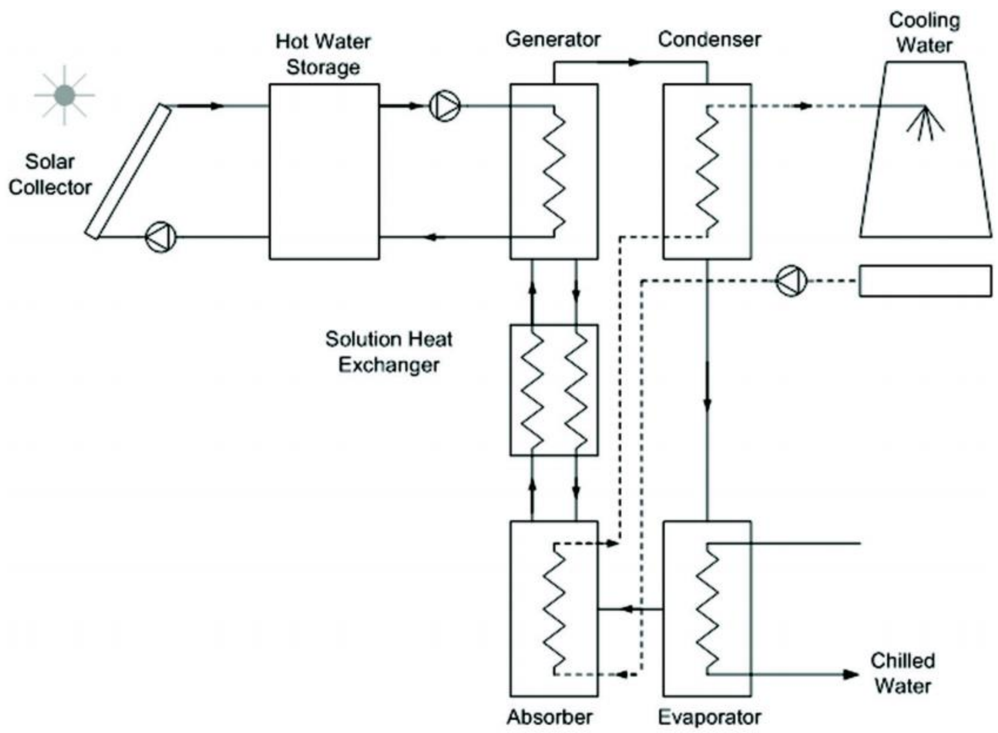


Figure 9. Schematic description of an absorption cycle solar cooling system [104].

2.5 Indoor Renewable Energy Alternatives

A number of indoor renewable energies, such as waste heat, flowing water in internal drainage systems, electromagnetic waves and vibration, may also become important energy sources for buildings.

2.5.1 Fundamental Piezoelectric and Characteristics of Piezoelectric Materials

The piezoelectric effect was first discovered by the French scientists Pierre Curie and Jacques Curie in 1880 when they were studying the physical properties of crystals [110]. They noticed that when the natural crystals of tourmaline, quartz, topaz, cane sugar, and Rochelle salt were subjected to pressure, a slight electric charge was generated at the crystal surfaces. This phenomenon was named the direct piezoelectric effect. After the discovery of the direct piezoelectric effect, the converse piezoelectric effect was mathematically deduced from fundamental thermodynamic principles by Gabriel Lippmann in 1881. This effect results in the mechanical deformation of the crystal located within the electric field [111].

Originally, piezoelectricity was only generated from natural single-crystalline materials, like quartz (SiO_2); however, artificial materials with piezoelectric properties have been developed in the recent decades. Piezoelectric ceramic is one of the artificial ferroelectric polycrystalline piezoelectric materials produced after polarisation treatment. The term polycrystalline refers to the material composition which is composed of multiple single-crystalline elements. Each of the single-crystalline elements can be seen as a single power domain. Before the polarisation treatment, each polar axis in the elements is arranged in different directions due to the lack of central symmetry under the so-called spontaneous polarised condition, as shown in Figure 10 a). The spontaneous polarisation effect in various directions neutralise each other, resulting in the zero polarisation intensity [112]. Therefore, the raw ceramic is initially isotropic. To break the isotropic properties, the polarisation treatment must be applied at a certain temperature [113].

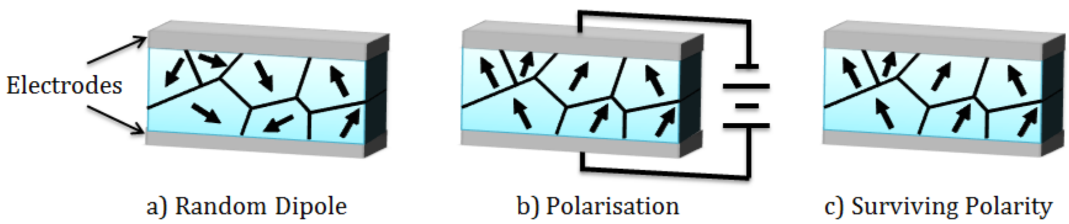


Figure 10. The polarisation process of ceramic material to generate a piezoelectric effect.

Polarisation treatment is the key process to initiate the piezoelectric effects in materials [112, 113]. In the treatment, the polycrystalline is subjected to a strong DC electric field and heated at a certain temperature as illustrated in Figure 10 b). The heat drives the molecules to move more freely and thus forces the direction of spontaneous polarisation of domain dipoles to be consistent with the direction of the applied electric field [114]. As the dipoles of each domain are lined up and facing nearly the same direction in order, the ceramic represents a certain polarity. Then the treating environment is cooled down and the electric field is removed. The direction of domain is substantially unchanged, retaining a relatively strong residual polarised electric field inside, shown in Figure 10 c). Hence the ceramic shows a piezoelectric effect as both ends of the ceramic sheet bind electrical charge, one positive and one negative on the other side. Due to the effect of bound charge, a layer of free charge is absorbed from the outside environment and attached on both ends of the polarised ceramic. The absorbed free charge is equal in the quantity with the bound charge but with opposite polarity. Therefore, the ceramic does not exhibit polarity in the ambient condition. However, when the piezoelectric ceramic is subjected to external pressure, the compressive deformation shortens the distance between the bound charges, which in turn weakens the polarisation density. Accordingly, part of the free charge, which is previously absorbed on the electrode surfaces is released and ultimately leads to a discharge phenomenon. Table 2 lists the materials that exhibit piezoelectric effects.

Table 2. Major piezoelectric materials.

Types	Material
Mono-crystalline	Quartz, tourmaline, $LiNbO_3$, $LiTaO_3$
Membrane	ZnO
Polymeric	Polyvinylidene Difluoride (PVDF)
Ceramics	$BaTi0_3$, Lead Zirconium Titanate (PZT)

The piezoelectric polymer foil of PVDF and the Lead Zirconium Titanate (PZT) ceramics are the most commonly used materials. Kawai firstly discovered the piezoelectric properties of PVDF in 1969 [115]. When the PVDF was subjected to simultaneous uniaxial stretching, some part of the polymer volume became semi crystalline and formed the so called β-phase molecule chain structure, which had a net dipole moment triggering the piezoelectric behaviour of the whole solid [116]. The efficiency of piezoelectric energy conversion of PVDF is determined by the overall thickness of the active material as well as the force that is applied on the surface, while the amount of charge is determined by the area of piezoelectric active material that is compressed [117].

PVDF has the advantage of being fast, easy and cheap to manufacture. The thin thickness of the foil allows the material to be stacked upon each other to increase the thickness to fit varied circumstances. By layering the energy generation ratio of the stacked energy harvesting modules can be enhanced by one single pressure pulse. PZT was developed at the Tokyo Institute of Technology in the 1950s and various versions of it, such as PZT-5A and PZT-5H, are today the most widely implemented piezoelectric ceramics [118]. This is because of its relatively high energy conversion efficiency comparing to the PVDF mentioned above. Apart from the high efficiency, PZTs offer the possibility of tailoring their behaviour to specific responses and applications by the use of dopants.

Furthermore, the fabrication of PZT is flexible and this ceramic can be manufactured into any required shape or size.

2.5.2 Kinetic Energy Harvesting

Through the application of piezoelectric materials, kinetic energy from the ambient environment can be converted into electrical energy [119]. The energy converting efficiency of the energy harvester depends significantly on the design of the piezoelectric system.

At present, a cantilever type vibration energy harvester is the most commonly used design due to its simple structure and the feature that can produce a large deformation under vibration [120, 121]. For this type of energy harvester, a beam structure is manufactured by laminating one or two layers of piezoelectric material to a substrate layer to produce monomorph or bimorph configurations [122, 123]. A proof mass is attached at the tip of the beam to adjust the structure resonant frequency of the energy harvester to match the ambient vibration of the surroundings. When the cantilever structure is operated at resonant frequency, the piezoelectric material has maximum stress and strain so as to produce the maximum electric power output [124]. Figure 11 a) shows a typical bimorph cantilever piezoelectric energy harvester.

The majority of the cantilever beam piezoelectric harvesters are used in micro-electro-mechanical system (MEMS) applications [125], aiming for vibration resources with high frequency and small mechanical stress. This is because of the limitations of the beam structure where the piezoelectric material is easy to break when bearing a strong impact force [126]. This design limitation led to the development of stack type piezoelectric harvesters.

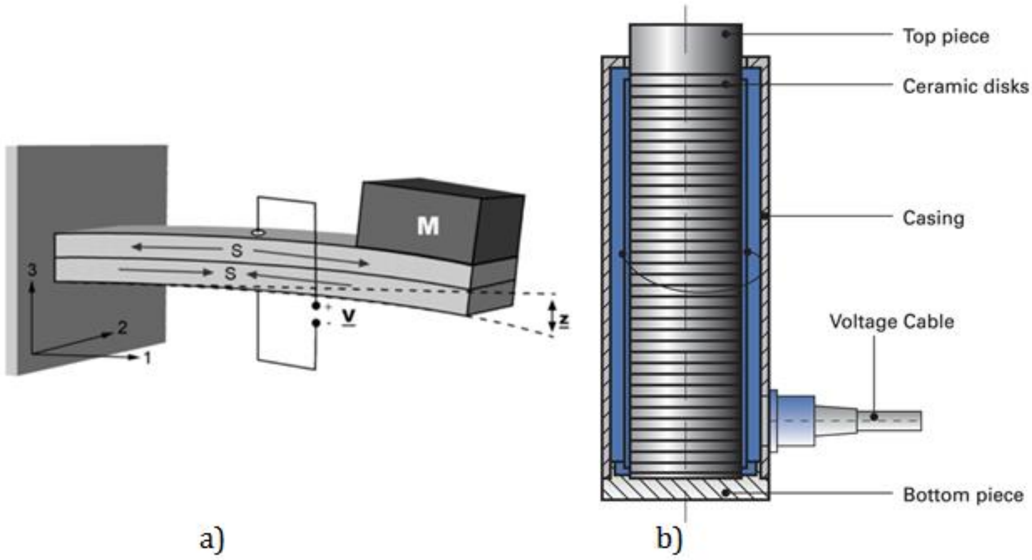


Figure 11. Two designs of the piezoelectric system: a) a two-layer bender mounted as a cantilever [123]; b) a stack type piezoelectric harvester [127].

A stack type piezoelectric harvester is produced by stacking multiple layers of piezoelectric materials [128], as shown in Figure 11 b). This results in a high mechanical stiffness in the stack configuration. Compared to the cantilever configuration, the stack type possesses a large capacitance and a higher capability of energy harvesting. It is suitable for a high force environment, such as a heavy manufacturing facility or in areas of large operating machinery [121]. With these features, the stack type piezoelectric harvester breaks the limitation from micro-scale energy harvesting in MEMS to macro-scale energy generation. In Israel, Innowattech has tested this type of energy harvester on highway to collect kinetic energy from passing cars as well as railways [129]. In the ideal conditions, the system is able to generate up to 200 kWh in every kilometre, which is enough to satisfy the energy demands from more than 800 families.

To date, several piezoelectric power generating products have been released to the market by different companies, such as Pavegen [130], Waynergy [131] and Powerleap [132]. The Pavegen piezoelectric energy harvester, Pavegen Tile, was demonstrated at the London 2012 Olympic Games. Twelve tiles were installed on a temporary walkway connecting the Station to the Greenway walking route at the Olympic Park. It was estimated that these tiles would receive more than 12 million impressions from footfalls, generating 72 million joules of energy, which equals to 21 kWh of electricity. This amount of electricity was enough to illuminate the walkway for eight hours at full power during the night, and 16 daylight hours at half power [133]. A similar test was conducted at the University of Beira Interior. The Waynergy People prototype was deployed in the pavement at the main entrance of the Engineering Faculty. It was confirmed that 525 Joules or 0.15 Watt-hours of electric energy was harvested from 675 human steps by the Waynergy system during a peak hour, between 9 am and 10 am [131].

2.6 From Waste to Energy, from Biomass to Biofuel

Biomass derived fuels are expected to be the major fuels in the future [134] and this is for three main reasons [135, 136]. First, biofuels have formidably positive environmental properties resulting in no net releases of carbon dioxide and very low sulphur content. During its lifecycle, a plant used as biomass absorbs CO_2 from the atmosphere by photosynthesis and converts it to organic carbon molecules in a solid state. When the plant is consumed as feedstock for energy, the carbon dioxide returns to the atmosphere, with no net change in the amount of carbon in the atmosphere, plants, or soils [137]. Hence the biomass energy does not contribute to climate change with greenhouse gases.

Second, the bioenergy is relatively easy to obtain in many different ways. Due to its availability worldwide, biomass energy has contributed around 10–15% which is approximately 45 EJ of world energy use in 2009 [138, 139]. This share is predicted to reach at least one-quarter of the world's projected energy needs by 2035 due to the great potential the bio-energy holds [140]. In many developing countries, biomass is the single most important energy source providing roughly 35% of energy demand [141]. In Brazil the internal supply of energy in 2006 was 226 million tonnes of oil equivalent (toe), among which 27.2% was from biomass [142]. In India, biomass fulfils 70% of the basic energy needs in rural areas, where almost 70% of India's population live [141]. Biomass also has an important role in certain industrialised countries. It currently provides 11% of the total energy consumption of Austria and 17% of the national energy supplies in Sweden [143]. In the U.S. the current biomass energy consumption is 4% (200 million dry tons) of total primary energy consumption [141].

Third, biomass is a renewable resource with abundant feedstock sources that can be sustainably developed in the future. In general, materials such as wood and wood wastes, agricultural crops and their waste by-products, municipal solid waste, livestock wastes, aquatic plants and algae, and even waste from food processing could be used as biomass resources [144]. The food wastes includes food processing leftovers and uneaten food from residences, commercial establishments, such as restaurants, institutional sources like school cafeterias, and industrial sources like factory lunchrooms [145]. According to a study of global food waste published in 2011 by the Food and Agriculture Organisation of the UN, it was revealed that nearly a third of all food produced for human consumption each year goes to waste, totalling 1.3 billion tonnes [146]. Socleary there is potential to produce a considerable amount of energy from the process of biomass conversion.

The utilisation of biomass energy in buildings has been investigated in various ways. Mazen, et al. [147] studied the energy generating potential of biomass to contribute to the energy demand of a high-rise building in Guangzhou, China. A 5% energy contribution to the building was achieved by the energy produced from biomass, which was almost equal to energy generated by photovoltaic modules installed on the building surface. Carpio, et al. [148] and Carlini, et al. [149] analysed the impacts of using a biomass boiler in residential buildings on the energy rating, CO_2 emissions and economic aspects, respectively. The biomass combusted in the boilers generated heat used to provide heating and domestic hot water (DHW) to the residential buildings. The results showed that the use of biomass in these residential buildings presents important advantages, such as: reduced environmental costs, significantly less CO_2 emissions provides a more favourable energy rating; and results in economic savings.

Huang, et al. [150] tested the possibility of using biomass to provide heat and power simultaneously for commercial buildings from the technical, environmental and economic analysis of two configurations. These were Organic Rankine Cycle (ORC) based and biomass gasification based combined heating and power (CHP) systems. It was found that neither system was economically viable for power only generation, due to their poor efficiency; however, the system efficiencies were greatly improved by recovering waste heat for building heating purposes. The ORC based CHP application was beneficial to buildings with a high heat to power ratio, while the biomass gasification based CHP system would be suitable for the buildings with a relatively lower heat to power ratio. It was also noted that the biomass fuelled CHP systems offer a significant CO_2 saving opportunity for the building energy supplies. By further exploiting the waste heat, Harrod, et al. [151] used a wood waste biomass-fired Stirling engine to power a combined cooling, heating and power (CCHP) system for a small office building. The factors which affect the system performance of the biomass-fired CCHP system were revealed.

Biomass can be efficiently converted into useful forms of energy using a number of different processes. The main process technologies can be classified into three categories: thermo-chemical, bio-chemical and mechanical extraction. As shown in Figure 12, there are three optional processes included in the method of thermochemical conversion: combustion, gasification and pyrolysis; while under the biochemical conversion category, there are two technologies available, which are digestion and fermentation. This thesis considers biomass pyrolysis as the main technologies that can be potentially integrated in a buildings' energy generation potential and compared the technique with combustion and anaerobic digestion.

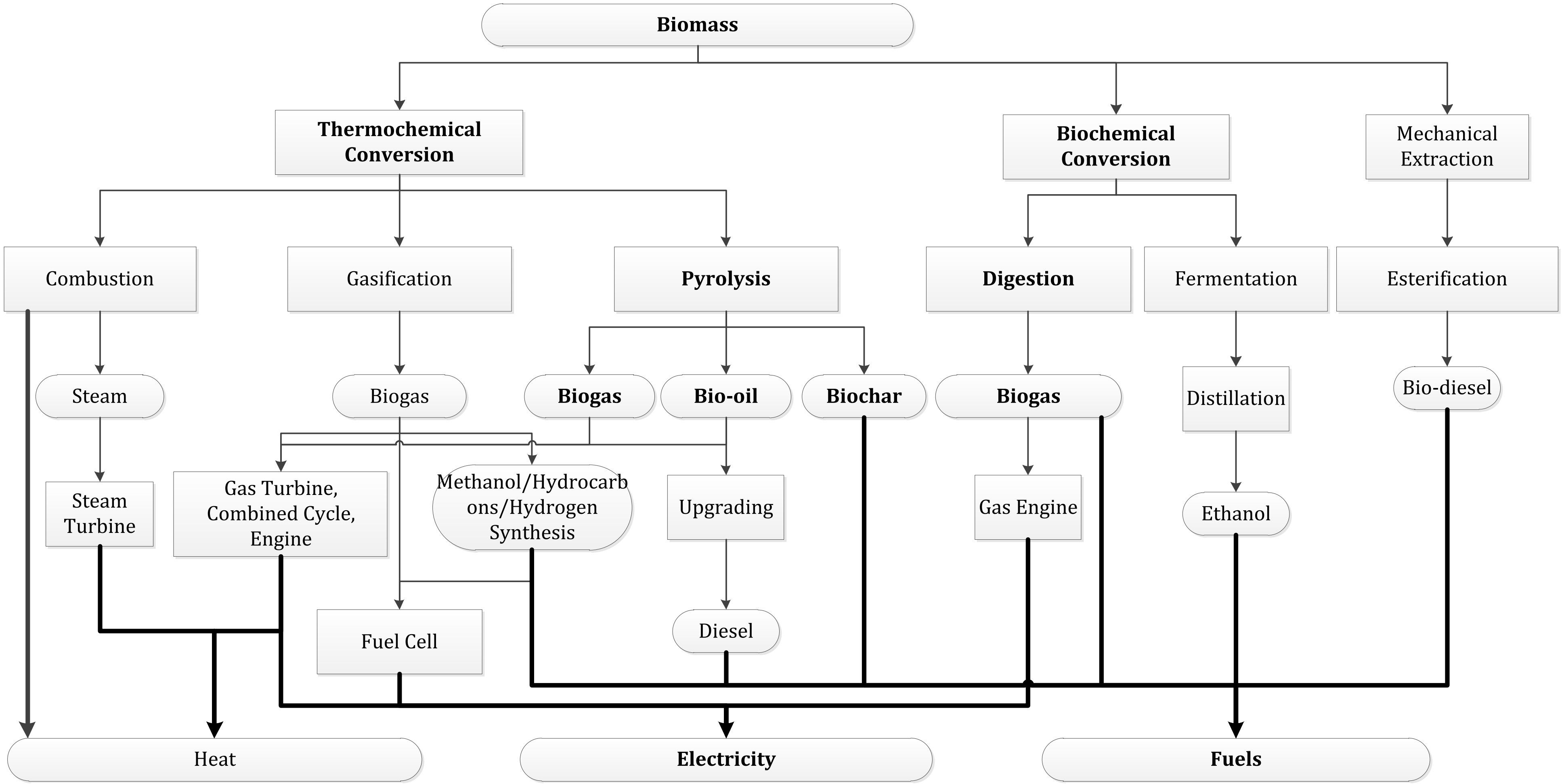


Figure 12. Main biomass conversion options, intermediate energy carriers and final energy products from biomass.

2.6.1 Pyrolysis - A Thermo-Chemical Conversion

Pyrolysis is a method that converts biomass to more useful fuel products [152]. Under pyrolytic conditions biomass is heated to maximum temperatures of 450–500 ^{0}C in the absence of oxygen to produce a hydrocarbon rich gas mixture (biogas), an oil-like liquid (bio-oil) and a carbon rich solid residue (bio-char) [153]. There has been a long history of using pyrolysis since the dawn of civilisation, though it was named wood distillation at that time [144]. During the industrial revolution in the 1800s, the wood distillation was applied to produce charcoal as a major industrial fuel until it was replaced by coal.

Modern pyrolysis processes can be adjusted to favour bio-char (otherwise referred as charcoal), bio-oil (pyrolytic oil), or biogas production with a 95.5% fuel-to-feed efficiency, depending on the varied temperature and different heating rates [153, 154]. For the production of bio-char, a low temperature, slow heating condition, which is also termed as carbonisation, is preferred. For the purpose of maximising the yield of bio-oil, a low temperature, and high heating rate process, known as flash pyrolysis, is required; while for high production of biogas, a high temperature, low heating rate, and long gas residence time process is required.

Bio-char is a light black residue of the biomass material obtained by removing highly volatile matter with temperature, typically when heating is limited to 550 ^{0}C. Bio-char is comprised of a carbon matrix of complex lignins and cellulose which contains the minerals and many of the nutrients that remain from the growth cycle of the biomass [155]. In addition to its very high surface area structure which can retain soil-water and nutrients for plant growth, bio-char is widely used as a soil amendment to improve crops yield [156]. Furthermore, bio-char has several other advantages in improving water quality, reducing soil emissions of greenhouse gases, reducing soil acidity, and reducing irrigation and fertilizer requirements [157]. Recently, with the growing realisation of the importance of constructing human shelters that better conserve energy and water through appropriate insulation and architectural designs, bio-char is used as a substrate material for green roofs due to its positive influences on both plants and roof heat insulation. Lin and Lin [158] investigated four types of plant substrates on thermal reduction of green roofs. These were sand, bio-char debris mixed with sand, organic matter mixed with soil, and burned reservoir sludge mixed with rice husks. A good reduction percentage of heat amplitude on the rooftop surface was detected when bio-char with sand was used as the substrate.

The bio-oil is the dark brown liquid fraction of biomass generated during the pyrolysis process. It is a complex mixture of water and organic chemicals which include acids, alcohols, aldehydes, ketones, esters, phenols, guaiacols, syringols, sugars, furans, alkenes, aromatics, nitrogen compounds and miscellaneous oxygenates [159]. Due to continuous concern for potential shortages of fossil oil and GHG reduction legislation, bio-oil is expected to play a dominant role as a substitute for crude oil – because of its CO_2 neutral and low sulphur content features. Czernik and Bridgwater [160] reviewed several options for bio-oil combustion, including as feedstock in boilers, diesel engines, gas turbines, and Stirling engines. However, due to the high oxygen content in bio-oil, the heating value is less than half that of petroleum liquid. Bio-oil needs to be upgraded for higher energy density before it can be economically used for energy production in standard equipment [161]. Bio-oil is not yet a commercial product due to other features as well. Poor volatility, high viscosity, coking, and corrosiveness all limit the range of bio-oil applications at present. But the potential of bio-oil to replace fossil fuels as an alternative fuel to generate power, reducing GHG emissions has been confirmed through life cycle assessments [162, 163].

Biogas produced by pyrolysis is a mixture of volatile gases that consist primarily of CO_2, CO, methane and higher hydrocarbon compounds [153]. The total amount of gas generated during the pyrolysis process is dependent on the temperature and heating conditions [164, 165]. An increase in temperature and heating rate leads to increasing yields for all gases up to 825–900 °C, where CO_2 and hydrocarbon yields show a clear tendency to stabilise, compared to other gas products such as CH_4, C_2 hydrocarbons and H_2. Due to these combustable components in the biogas, biogas can be used as a fuel. Raveendran and Ganesh [166] compared biogas with fossil fuels. They found that the heating value of biomass pyrolysis gases are much lower than those of natural gas, but are comparable with those of blast furnace gas and producer gas.

2.6.2 Anaerobic Digestion – A Bio-Chemical Conversion

Anaerobic Digestion (AD) is a chain of interconnected biological reactions, where the organic matter is transformed into biogas, which is a gaseous mixture of methane, carbon dioxide and small quantities of other gases such as hydrogen sulphides, in an oxygen-free environment [167, 168]. In the digestion process, the biomass is converted by bacteria in an anaerobic environment, producing a gas with an energy content of about 20–40% of the lower heating value of the feedstock [169].

The history of using AD has been recorded for centuries. The first documented anaerobic digestion plant built for generating energy from waste was in Bombay, India in 1859 [170]. In the 20th century, AD has become a widely used process due to its low cost and relatively low technical barriers. The small scale digesters can be easily found everywhere, including small farms in Africa and villages in India. The application of biogas digester is increasing rapidly in China. By the end of 2006, more than 22 million biogas digesters were serving over 250 million rural households [171]. In 2010, there were 30 million digesters established across the country [172], and increased to 41.68 million at the end of 2011 [173]. Previously, the biogas was generated in small scale digesters and predominately used for personal cooking or lighting purposes [174]. Now, decentralised middle scale reactors and centralised big scale digesters are being widely established as integrated networks for heating or energy generating purposes [175].

The methane component in the biogas produced from the AD process can be combusted in internal combustion engines or micro turbines for the production of electricity. Meester, et al. [176] compared electricity production from domestic organic waste and energy crop digestion with reference to electricity. They highlighted an effect of vaporisation brought about by the AD technology, as it is able to convert almost all sources of biomass, including different types of organic wastes, slurry and manure to a high calorific value biogas. Komatsu, et al. [177] proposed a mesophilic-thermophilic hybrid flow scheme which further enhanced the electricity production from municipal sludge, resulting in electricity production at a cost of 0.05 USD/kWh, lower than the market price of 0.009 USD/kWh. In relation to individual building heating, Esen and Yuksel [178] designed a hybrid system which integrated an AD reactor into a greenhouse. During a winter period the system maintained a constant self-sustained temperature of 27 °C within the reactor, while the greenhouse temperature was able to be maintained at about 23 °C.

2.7 Conclusion

In a future of potentially severe energy supply shortages and global climate change issues, with a continuously rising population and rapidly raised requirements of indoor living comfort, it is important to investigate every possible way to address or relieve the energy demands in a sustainable way. History has shown that it is not possible to cut down building energy consumption by ignoring the indoor environment quality, and dynamic energy neutral practise has been developed as a promising approach. Sustainability needs to be integrated into the building deeply from its early design and construction. Although more investors are attracted by the profitable features of sustainable buildings, the rating tools are not yet fully standardised to evaluate building performance, from both energy and occupant aspects, with global benchmarking.

However, there is a common acceptance among the worldwide building rating tools that the weight of the Energy category has significant importance. On one hand, the improvement in building energy efficiency directly reduces the building energy demand, leading to a lower GHG emission. On the other hand, the application of on-site renewable energy production provides the possibility to reduce dependence on fossil fuel and mitigates emissions. The utilisation of solar energy, including solar thermal and photovoltaic generation, has been given great attention over several decades. Although high energy conversion rate solar products are developed and available on the market, it has become harder for these solar energy harvesters to become more widespread. This is due to limited roof space, especially in urban areas where empty roof space is either shaded by high skyscrapers or utilised by varied building service equipment. Given these circumstances, the solar panels with suitable features for the integration on the building envelope are receiving considerable attention. However, there has been little quantitative analysis of the solar energy harvesting potential of vertically mounted photovoltaic modules on buildings, particularly on buildings with a bulky and over-complex appearance.

Retrieving energy from indoor environments is a relatively new approach emerging with the development of micro-electro-mechanical system applications. The possibilities of harvesting ambient energy from waste heating, flowing water, electromagnetic waves and vibration have been demonstrated. Piezoelectric material is used in energy harvesters to convert ambient vibration into usable electricity. By connecting the energy harvester with a remote sensor, the harvest can be seen as an eternal energy source to replace the conventional battery, therefore eliminating the need for long term maintenance. However, because this energy harvesting technology is fairly new, the energy yield scale is still within the range of μW to mW, which is only capable of powering micro sensors. In recent years, viable macro-scale piezoelectric harvesters have been developed and started to emerge in the market. However, since the macro-scale piezoelectric technology has not yet been fully established, much uncertainty still exists about the actual energy harvesting efficiency of the commercialised piezoelectric tiles. There is a lack of information on energy harvesting potential of piezoelectric tiles when applied in buildings, and particularly in green buildings.

Pyrolysis and anaerobic digestion processes are two approaches for biofuel production, and are particularly relevant for built areas as they use urban organic waste as feedstock. In addition to alleviating pressure on landfilling, pyrolysis and digestion can provide a critical solution to growing waste management problems while simultaneously reducing greenhouse gas emissions. So far this method has only been applied in the industry scale for waste management and biogas production purposes. The understanding of the sustainable building integrating approach, especially its energy recovering potential from the on-site bio-wastes, such as spent coffee grounds, was still very limited.

In accordance with trends in building development where modern buildings are becoming, complex and multi-functional, the green technologies discussed can either be integrated into pre-standing urban buildings or designed into new buildings as part of a shift toward a more renewable, sustainable future. While the ideas and technical developments are exciting, they remain as components of a concept that is yet to be fully and successfully demonstrated in practice. Further research needs to address their adaptability and their capabilities when integrated into buildings. A full scale case study is essential with the aim of increasing the energy production and maximising the reduction of the GHG emissions. A sketch of buildings beyond the green ratings should be drafted by the energy diversification approaches to neutralise energy consumption and GHG emissions.

Chapter 3 A Qualitative Study of Motivation and Influences for Academic Green Building Developments in Australian Universities

3.1 Introduction

With the establishment of the World Green Building Council (WGBC) in 2002, the energy efficiency and associated environmental issues from construction and maintenance of the building sector have been considerably improved. Green technology has become a mainstream solution to reduce greenhouse gas emissions and improve the national environmental footprint [179]. Since early 2011, there are over 60 Green Building Councils at various stages of development in different countries mentoring the emerging sustainable building construction projects around the world [180].

The main factors affecting wider application of green buildings have been studied in the past. Hakkinen and Belloni [35] outlined the barriers in promoting sustainable buildings from five aspects – steering mechanisms, economics, client understanding, process and underpinning knowledge. The authors believe the barriers to increasing green building infrastructure can be transformed into drivers if these obstacles can be properly handled. According to Syace [45], the drivers for building green infrastructure can be divided into market factors and imposed drivers. Market-led drivers mainly refer to the economic benefits generated by sustainable buildings, for instance, reduced operating costs, reduced maintenance costs and increased building value [181, 182]. Besides the obvious economic benefits, a greater tenant attraction and reduced vacancy periods, potential enhanced returns on assets and increased property values have been identified as drivers that potentially impact across the stakeholders [25, 45, 183]. For the imposed drivers, regulations established by country or local government can undoubtedly trigger sustainable building adaptation. Therefore, many scholars advocate achieving the purpose of promoting the development of green building through formulating and improving relevant policies [35, 184].

Compared to enforced regulations, an environmental sustainable policy promoted at the internal decision-making level of an organisation shows better environmental responsibility. Arkesteijn and Oerlemans [185] state that the tendency of adopting sustainable technology has a high correlation with the levels of basic prior knowledge and pro-environmental behaviour of the consumers. This implies that a commitment to green behaviour from an organisation, that takes environmental protection as its responsibility, can be a driver for green building adoption [186]. Universities and academic institutions are organisations that traditionally lead a vanguard of thought with demonstrated practical solutions in sustainability [187]. The academic institutions do not want to be laggards, especially when it comes to green innovation and building standards [188].

Compared to commercial buildings, educational buildings have different aims and purposes, therefore the policies for investing in educational green building infrastructure differ from the commercial buildings. Yudelson [182] lists the recruitment of high-achieving students and faculty, attracting a new donor pool for campus buildings as speculative business benefits for higher education. Nicolaides [189] argues that a university which promises commitment to environmental protection will enhance its publicity and ensure its competitive position among other institutions. At a policy level, Richardson and Lynes [190] claim that the internal university green policy plays a significant role for the successful implementation of the green projects and demonstrates the adverse effects caused by weak administrative leadership for sustainability. Cupido [191] believes that policy development and application is a significant component of sustainability in universities and institutions, but the facility professionals should be also responsible for the development of policy and guidelines with institution's decision makers [192].

The objectives of this study are to examine the drivers affecting the implementation of green buildings, investigate the benefits gained by the green educational buildings in universities from a holistic perspective and review the factors that are important to promote the benefits from building green into drivers for investing in the green university projects. More broadly, this research seeks to highlight the contribution that higher educational institutions make to the overall implementation of green buildings within Australia.

3.2 Methodology and Approach

3.2.1 Trend Analysis

Historical trends in green building development in Australia was studied in this work from two data sources, the Australian Bureau of Statistics [193] and the Green Star Project Directory of the Green Building Council of Australia [194]. The number of building activities carried out monthly in Australia for the period of eleven years from July, 2000 to May, 2011 was identified by building function and value using the statistical information collected through the Australian Bureau of Statistics. The Green Star Project Directory contains a comprehensive list of all green projects evaluated by the GBCA. In this work, all of the green building projects for a 7-year period, starting from the first green building in Australia approved in October 1, 2004, through to the most recent dating in June 15, 2011, were identified. For the purpose of this study, the information analysed from this database comprised of the certified date, green star rating result, building function and respective district of the project. All of the university green building projects were identified from the Green Star Project Directory, where the educational building projects are divided into three categories according to the progress of the project - Educational Design, Educational as Built, and Educational Pilot. In this study, the stage of the project progress was not a criterion for either inclusion or exclusion from the research. All these three categories were considered to have equal importance to the motivation of the corresponding university's administration to register, design and develop green buildings.

3.2.2 Motivation Analysis

The second stage of the analysis was to determine the motivation of the university's decision makers to invest in green facility. The motivation analysis comprises of a collection of data consisting of official promotion of the green building projects by academic decision makers and discourse analysis of the resulting data using grounded theory.

3.2.2.1 Data Collection and Sampling

Based on the fact that news media can reach a large audience and exert great influence on them, the motivation analysis was performed using the articles published on the internet and local media. The textual image of what constitutes "green buildings" mediated by the decision makers may have been influenced by their values about green infrastructure [54], hence it could be the ideal source to investigate their motivation for complying with pro-environmental behaviour. However, due to the feature of press releases that are usually written by internal communication officers and as such may provide favourable evaluation towards the developments, the articles for analysis were carefully searched and filtered from several types of media articles, such as government statement, university publicity, and organization press release to avoid possible bias. During data collection, web searches were carried out for all published articles mentioning the educational green projects in the universities. The name of the building and its relevant abbreviation were used as the specific search terms. For the reasons that the opinions of specialists and recognized authorities are more likely to be reliable and to reflect a significant viewpoint [195], the primary data collected for the analysis consisted of the official statements announced by the high-authorities responsible for the green project, such as Innovation Minister, Executive Directors, Presidents of Universities, Vice Chancellors, Deputy Vice Chancellors, and Facility manager of the university. The relevant materials are shown in Appendix D.

Furthermore, in order to confirm validity of information published in the news articles used for this study, interviews with selected individuals was arranged. A group of twelve participants from Macquarie University consisting of university decision makers related to the news releases, and 10 students, users of the green star building, were interviewed. The decision makers were asked to clarify the drivers and barriers for university to invest in green facility as well as their expectations from the green building. Their views on the higher education news releases, and the reliability of the message delivery were also examined through the interviews. The decision makers confirmed that the news articles were constructed with honesty prior to their release. The student participants were then asked to express their personal opinion of the green facility and rank the difference between the green building and other non-green facility that they had used.

The data collection procedure for the news article analysis was driven by theoretical sampling to ensure that a sample size is fully adequate to support particular qualitative analysis [196]. Theoretical sampling plays a pivotal role in the theory construction. It is a process of gathering data guided by concepts derived from the evolving theory for the purpose of comparing the concepts and densifying emerging categories [197-199]. Following this perception, all educational projects listed in the Green Star Project Directory are initially designated as a data pool. However, due to projects' data accessibility and the diversity of the introductory materials, only 24 green projects which are located in urban areas were selected as observation objects and their related articles were collected to generate an initial hypothetical theory. Based on the hypothesis, the follow-up data gathering were then refined to obtain the data necessary to further the development of the evolving theory [197].

The sample size of this study was decided based on the 'theoretical saturation' approach [197, 200]. According to this approach, the data collection continues until (a) no additional data reveals new category, (b) categories are well developed and (c) the relationships among categories are well validated [196, 197, 201]. For this work, 68 related media articles were collected after all of the above conditions were satisfied. These articles were then imported and analysed using a computer-assisted qualitative data analysis software application (NVivo 9.0).

3.2.2.2 Data Analysis

The media articles were analysed in line with the grounded theory approach that simultaneously develops an inductively derived theory about a phenomenon with application of a systematic set of data gathering procedures [200, 202]. The aim of this method is to identify theory out of concrete data rather than testing hypotheses with existing theory. The core strategy of analytical phrase is based on three types of coding processes, open coding, axial coding and selective coding, to define and categorise data [203]. The data analysis procedure is described in detailed below, and a chart that illustrates the coding process is provided in Figure 13.

Open coding is the first stage of analysis where the text data is fractured and conceptualised [197, 202]. In this process, noticeable statements were identified and those with similar meanings were extracted from the content and then labelled as a node [204]. To verify and ensure the nodes were grounded in the data, each following statement was examined carefully to compare with other nodes coded previously before a new node is assigned [200, 202]. Following this, the nodes that are discussing the same points in different aspects were assigned to categories, which were more substantial than the initial nodes [197, 199]. Furthermore, conceptual annotation and memos were also noted in order to set up internal links between the categories.

Axial coding is the second process of the conceptual data analysis in which categories are connected by a combination of inductive and deductive thinking in the grounded theory [197]. During this process, the categories fractured during the open coding analysis were connected with their subcategories in a set of conceptual relationships, thus forming core categories [203]. The content of the core categories identified and condensed their relationships so that the conceptual linkages between each of the categories become more specific [204]. These categories and their connections formed a framework that give rise to a theory's occurrence.

The final process of the analysis was performed by selective coding which is used to refine and focus the data collection and analysis [197, 200] The text data was screened by moving back and forth these three analytical coding processes to discover all possible interrelationships between the core categories. Thus the framework of the theory was filled-in with descriptive details [204]. These processes were reiterated until theoretical saturation was reached in which every connection was well validated and no category needed further refinement. By doing so, a well-developed and validated theory was established.

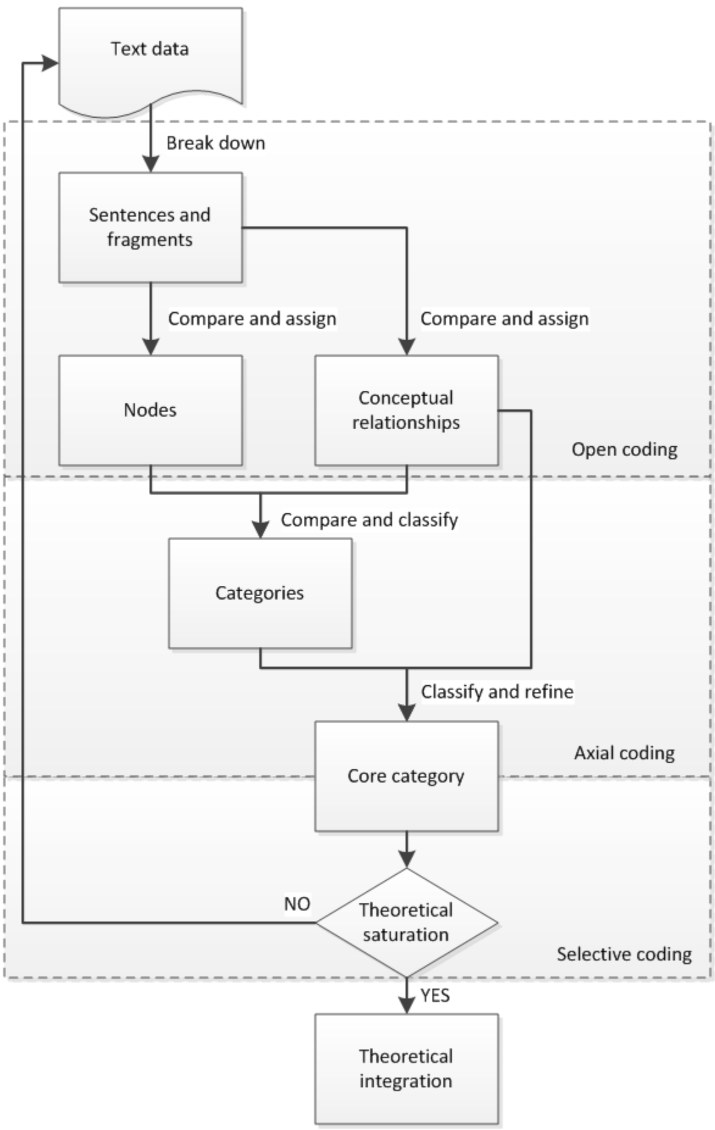


Figure 13. Data analysis procedure: steps from text data to well-developed theory.

3.3 Result and Discussion

3.3.1 Trend Comparison

Figure 14 shows the number of green buildings compared with total building projects approved in Australia between 2004 and 2011. In 2008 the total building number remained steady while the green projects rapidly increased, possibly stemmed from the rapid growth in public awareness of climate change and the need to reduce GHG emissions [25]. By 2008, the awareness of climate change and propensity for action had been bolstered by films, reports and the frequent media coverage of extreme weather events, and hence a fundamental shift in the building industry towards sustainable practice [25].

After five-year continuous increase, the number of annual certified green projects seems reduced from 2010. The recession of green projects due to the reduction of the number of total building approvals in Australia, which began to decrease from 2009 as one of the negative hysteretic consequences of the financial crisis in 2008 [205]. While the total number of green building projects decreased, the ratio of green buildings to total buildings increased during the same time period. This highlights the importance of development of green building industry in Australia.

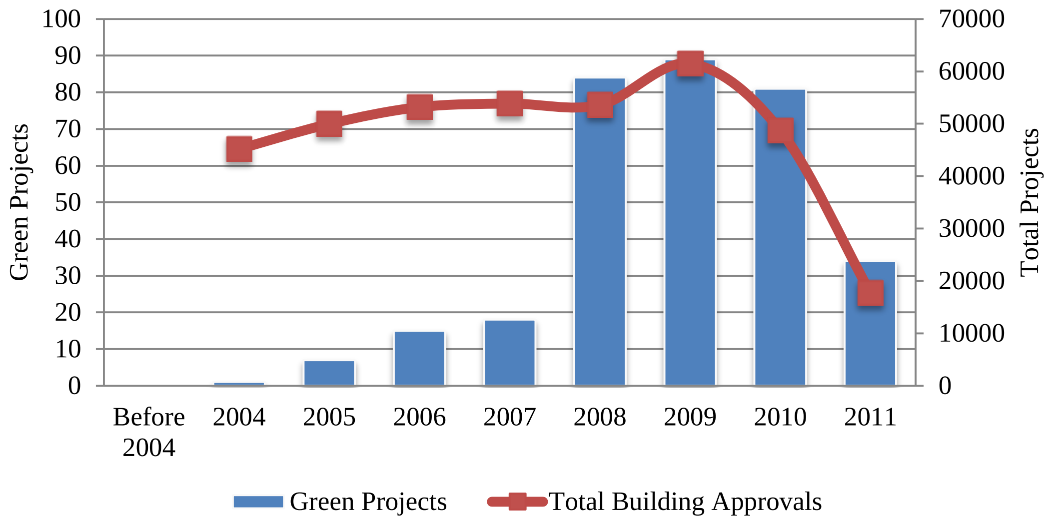


Figure 14. Application trend of green projects compare to total building approvals.

More specifically, if building functions were considered in the trend analysis, the increasing demand of educational green building in universities presents a sharp contrast with the application trend of green non-educational buildings (Figure 15). The first educational green building project was recorded in 2008, accounting for 2% of all the green projects approved in that year. Although the number of green projects decreased annually in the following years, the number of educational buildings increased at double the rate. Up to the first half of 2011, the educational green projects have reached a ratio of 15% of the total green building project applications.

According to Guellec and Wunsch-Vincent [206], the financial crisis in 2008 could partly explain this rapid growth in the investment of the educational sector. In the consideration of sustainable recovery, the government is more inclined for long-term investments, such as education and research infrastructure[207], as a strategic response to the crisis [208]. The financial situation and the investment strategy in difficult economic times could be seen as extrinsic factors that foster the development of educational green buildings in universities. However, this does not explain the popularity of green building on Australian campuses unless the intrinsic motivations of decision-makers are analysed.

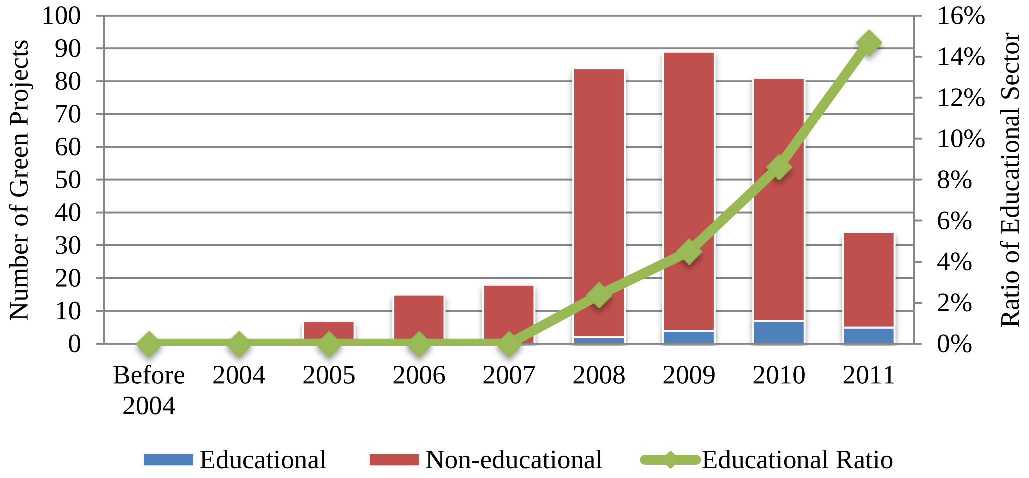


Figure 15. Application trend of educational vs. non-educational buildings.

3.3.2 Frequency Statistics

On the basis of the coding processes, 68 articles of all 24 green projects were fractured into sentences and examined carefully. Thirty different statements with frequent appearance in context were labelled as nodes in open coding. The nodes that described similar topics were then classified into four main categories as *Reputation and publicity*, *Specific needs*, *Environmental consideration* and *Financial condition* of the universities. The node categories, their total occurrences and number of buildings in which each node was addressed, are listed in Figure 16.

A total of n=158 sentences relating to the university's reputation and publicity were discussed in 13 different ways. The category of reputation and publicity of the university appeared to be the most frequently used and is therefore considered to be the most significant to invest in academic green building projects. Meeting the specific needs of research through green facility had the second most frequent appearance at n=96 times in four nodes. Environmental consideration and financial condition were shown to be the third and fourth most important with frequency of appearance at 65 and 35, respectively.

From the total counts of specific node shown above the x axis in Figure 16, seven nodes were identified with a high occurrence rate over 20 times. The high occurrence of *A platform of collaboration, Enhance university's capacity, Maximum use of natural resources* and securing *Government funding* indicates the realistic goals and the most urgent expectations from the universities. Some nodes with very low frequency of appearance, such as *Making difference*, *Sustainable effect*, *Demonstration effect*, etc., are used in this assessment in order to set up the connections between related nodes in the second part of the study.

Below the X axis, the figure shows the number of green buildings covered by a specific node among the 24 building projects. Nearly half of the projects highlighted the nodes of *Aim and core values of university*, *Attractive social and working environment* and *Multi-function building*. When these nodes were synthesised together to analyse in a holistic way it was found that a green building with multi-functions in a university is built as a platform of collaboration to meet the special needs for education or research. The highly integrated platform and its property maximises the use of natural resource thereby creating an attractive social and working environment which can greatly enhance university's capacity. With the outstanding example of a sustainable educational building, the university is qualified to be a leader among its competitors. In the following these emergent findings are validated by motivation analysis.

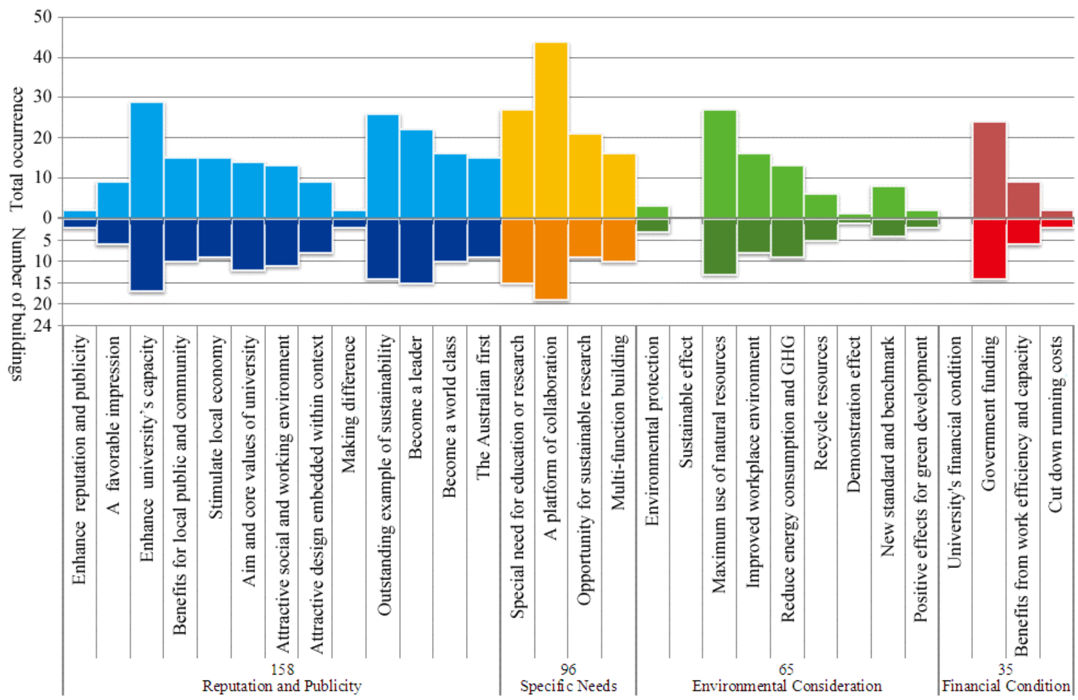


Figure 16. Classification and frequency of nodes.

3.3.3 Motivation Analysis

The second stage of the analysis comprised of a study of motivation of the university decision-making officials to invest in green facility as a long term strategy for the academic development. The analysis in this stage is important to define the strategies of the universities in Australia and project further developments in this field. For this purpose each of the classification groups identified in the frequency analysis was further studied to define the inter-relation between the categories and nodes.

3.3.3.1 Enhance Reputation and Publicity

According to the conceptual pattern that emerged from the data analysis, green projects influence university publicity by presenting a favourable impression on society and making a difference with other educational competitors.

A favourable impression. Since any positive media coverage will give public a favourable impression, the green projects approved by the university apparently create this opportunity and increase its public identity. In the situation of aggravating environment problem, an environmentally sustainable educational building which represents the aim and core value of the university will establish a lofty image for the university among its competitors. Professor James McWha, Vice Chancellor of the University of Adelaide's comment offers an example of the University of Adelaide's motivation to invest in green building:

> Achieving a 6 Star Green Star rating demonstrates the University of Adelaide's environmental aspirations and commitment to world leadership in providing sustainable learning spaces for our students.[i]

From the above claim it is apparent that a better impression could also be gained by providing sustainable learning spaces for students. During the validation interview, the facility manager of Macquarie University also acknowledged that "… (The green facility) it is an iconic building on the Campus. The students love it." The statement was then confirmed by the student participants. Nine of the ten students admitted that they prefer to study in a green learning space, ranking the green facility at much higher level than any other non-green building they had used before. Because of the attractive research environment provided by the green buildings, the university could achieve additional benefits. These benefits are outlined by promotion of the green project of Medical

Sciences 2 (MS2) at the University of Tasmania[ii]. According to Professor Foote's prediction, the project will greatly enhance university's capacity not only by assisting in accommodation of staff and research students, but also by creating a collaborative platform for national and international research communities.

The platform of collaboration and attractive research environment as motivations for investments in green buildings are mutually dependent and promoted jointly. A highly integrated research institute may enhance the research capacity in its particular area by sharing knowledge, specialist equipment and facilities. This in turn, will strengthen the attraction, resulting in rising of university's national and international profile. The following comment from University of New South Wales - Lowy Cancer Research Centre is an example of this connection.

> …By combining adult, children's cancer research, the Lowy Centre would continue to attract top researchers and trial funding…It provides a beacon if you like for other great cancer researchers and gives them a reason to come here and work in Sydney.[iii]

The universities are focusing on promotion within the academic area, but more so on promotion within the local public and community. During the data analysis process, it becomes evident that several green projects[1] are extensively analysed in the design process to assess the history of the site, visual amenity, how the building would sit on the site and what impact the new building would have on the city.

> …The new Life Sciences Building is sited to enclose and terminate a new landscaped pedestrian avenue connecting many of the existing buildings and capable of expansion eventually back towards the centre of the campus.[iv]

---

[1] National Centre for Health and Wellbeing of Australian Catholic University, National Life Sciences Hub of Charles Sturt University, Design Hub of RMIT University, Medical Sciences of University of Tasmania, Economics & Commerce Faculty of University of Melbourne

> …These stations are all accessible at ground level without any security access and therefore provide an open resource for the community.[v]

Besides the attractive design embedded within its urban context, green educational buildings are sometimes intended to connect with the other existing buildings, providing the locals with a good opportunity to experience an outstanding example of sustainability. In contrast with the commercial green buildings, educational green buildings are usually designed with the aim of offering benefits to the public and community with access links to other main streets and suburbs located nearby. The public has the opportunity to experience the benefits and superior comfort brought by green technologies when they enter or walk through the green building without any restrictions. The demonstration effect will stimulate the public both awareness of environment protection and university's reputation.

Stimulating local economy is another effective way to improve university's impression. These over million dollar green projects can boost local economy as a catalyst, providing hundreds of job opportunities in construction phase as well as additional accommodation for academic and administrative staff. This positive effect is evident in the following comment from Queensland University of Technology (QUT) Science and Technology Precinct:

> The Science & Technology Precinct and Community Hub will create around 300 local jobs during the construction phase, and when completed will house at least 1,000 scientists, researchers, teaching staff and students.[vi]

Making difference. Distinguished features of one university are perceived as an opportunity for the university to outshine the other competing education institutes.

Therefore, some of the fundamental expectations of the universities in Australia when approving green projects in their campuses are for the university to become a “leader”. A world class research institution provides an attractive research environment supported by advanced green technologies which promote integration with the world class research communities, who then reflect to creating university’s world class identity. Hence, the national status of the university will be promoted and strengthened in specific research areas. Benefits brought by green projects become favourable external publicity material, as shown in Table 3.

Table 3. Selection of statements for promotion of university's national status by approving green projects.

University	Example Comment
Bond University	"The Bond University Mirvac School of Sustainable Development building on the Gold Coast is the first Australian university to attain 6 Star 'World Leadership' status from the GBCA. It is now regarded as one of the greenest education buildings in the world."[vii]
Charles Sturt University	"CSU's Albury-Wodonga Campus is Australia's first environmentally friendly university campus and is a developing, dynamic model of how communities can address environmental concerns and create sustainable environments."[viii]
Macquarie University	"The Australian Hearing Hub will be a unique, world-class facility purpose-designed to facilitate collaborative research into hearing and related speech and language disorders."[ix]
Queensland University of Technology	"The research to be undertaken here will add to the State's reputation as a world class contributor to solutions that will underpin sustainable development and community living in coming decades."[vi]
University of Melbourne	"The Centre for Neuroscience has achieved a 5 Star Green Star – Education v1 rating, making it the first 5 Star rating for a University Laboratory project."[x]
University of New South Wales	"The new facility, opening on the 19th August 2010, is the first centre in Australia to bring together childhood and adult cancer research at the one site…"[xi]
University of Tasmania	"Australia's most imposing medical science precinct will be created in Hobart when the $90 million second stage of the Menzies Research Institute is completed in December 2012."[ii]

3.3.3.2 Special Need for Education or Research

The special needs of each university for education and research are evident through three characteristic nodes, identified as below.

Multi-functional building. Nearly half of the 24 university green buildings projects are designed to be multi-purpose facilities. These buildings commonly comprise of spaces for learning and teaching, such as lecture theatres and classrooms; research areas which include meeting rooms and laboratories; the break out areas and exhibition areas including café-bookshop, indoor garden and public gallery respectively.

In the education and research perspectives, multifunctional green buildings can provide a modern and open working environment. The open areas and galleries encourage the public to visit and experience the green concept, which potentially benefits the local community. The following comment from La Trobe University highlights the relationship between the multi-function building and the enhancement of the university's reputation and publicity:

> The internal design will facilitate contemporary approaches to learning and teaching with flexible teaching spaces…The staff and students at La Trobe are thrilled at the prospect of working and studying in this wonderful new building, which gives a 21st Century identity and feel to higher education study in Shepparton.[xii]

A platform of collaboration. According to the specific need of university or research institution to increase their academic capabilities, 19 of the 24 green projects are built as a platform of collaboration. World leading research teams could be brought together to foster innovation and collaboration by transcending traditional disciplinary boundaries. As shown in Table 4, these teams with alliances have complementary superiority and the cooperation facilitated through the green building will position them as a world leader in the specific profession.

These statements claim that the collaboration platform provides benefits to the academic institutions, but also to the local public and communities, especially in the medical research area. For instance, the Australian Hearing Hub from Macquarie University which integrates the Federal government research organisation Australian Hearing, Cochlear Ltd, and groups from the Sydney arm of the Hearing Cooperative Research Centre to provide research in hearing and related speech and language disorders:

> One in six Australians has hearing loss and thus the Hearing Hub has enormous potential to advance research of benefit to the Australian community.[ix]

Another example is the Peter Doherty Institute of the University of Melbourne, which allied four World Health Organization (WHO) collaborating centres to "fight against infectious disease". As Deputy Vice-Chancellor (Research) Professor Peter Rathjen's comments:

> As a frontline organization in the fight against infectious disease, the Institute will be an excellent example of aligning University and State Government education and research facilities to serve the people of Victoria.[xv]

Table 4. Statements that triggered the relationship between *a platform of collaboration* and becoming a *world class* institute.

University	Example Comment
La Trobe University	LIMS will be a world-class facility for molecular science, biotechnology and nanotechnology research and research training. The Institute will align with the broader Northern Melbourne Science precinct and support growth in the burgeoning Australian biotechnology industry.[xiii]
RMIT University	…The Design Hub will be a centre for collaboration – a place to develop world-class concepts and initiatives that will raise this city's and Victoria's international profile.[xiv]
University of Melbourne	The Institute will also house four World Health Organization (WHO) collaborating centres, and will integrate teaching, training, research and public health activities in human infectious disease at the University of Melbourne and the Royal Melbourne Hospital (Melbourne Health) to create a new world-class centre.[xv]

Apart from integration with related research organisations, the green buildings are seen as an opportunity to encourage industries to lease closely and establish linkages with the students and lecturers. According to Curtin's Pro Vice-Chancellor for Science and Engineering, Professor Andris Stelbovics's comments, the university will profit by the innovation and collaboration:

> The industry and careers space will enable students and lecturers to better interact with industry, while the exhibition area is intended as a multi-purpose space that can be used to exhibit design projects and research papers and for industry fairs, conferences and seminars…[xvi]

Opportunity for sustainable research. The green projects on the campus are posited as a learning opportunity for the students who specialise in research for sustainability, by demonstrating cutting edge sustainable technologies that are applied in the building. During the design, construction and use, green projects are expected to enhance students' understanding of sustainable concepts and allow them to gain real world experience. This opportunity is seen as unique and attractive research environment for the university to gather future research fellows to enhance its reputation and capacity in the respective research area. Moreover, when the students graduate with their personal experience of green technologies, they will be in a privileged position to enhance the profile of green buildings from planning, design and operation of these facilities. Thus could ultimately push forward the sustainable development of the future.

> The School's graduates will be much needed industry leaders in implementing responsible and practical sustainability management initiatives in the business world and in the communities in which they will live.[xvii]

3.3.3.3 Environmental Protection

The universities strive to address the important individual responsibility for achieving greater environmental protection. This can additionally offer increased reputation and identity, which are discussed here.

Improved sustainability. The green buildings are largely perceived as facilities which offer improved sustainability thereby and environmental protection assurance [209]. Material and resources recycling technology are readily used to reduce the ecological footprint. High efficiency heating, ventilating and air-conditioning systems and smart control lighting systems are applied to reduce the building's energy consumption and greenhouse gas emissions. Green buildings may also maximise the use of natural resources by solar collection and rainwater harvesting systems which further reduce the carbon emission footprint. The Business and Economics building in University of Melbourne quantifies the environmental benefits:

> …sustainable design features that result in a 50% reduction in energy use and 83% less water compared to the average office building.[xviii]

A significant number of researches have begun to document the impact of a working environment on building occupants. The research consistently indicates that, across all academic fields, students in classrooms with access to natural light perform better than students who are studying in classrooms without natural light [210, 211]. Studies also show that a pleasing research environment in symbiosis with nature ensures a substantial increase in productivity, as well as increase in achievement rates, reduced fatigue, and improved occupant health condition [212-214]. This can be seen from the statement by the Australian Catholic University Education and Science Sector Director, Mark Kelly[xix]:

> The building section is organized with all academic offices on the northern side of the atrium with excellent access to natural light…which means better air flow, more sunlight and a happier, healthier workplace.

As a result, the university's research capacity could be indirectly improved by the increasing efficiency and the reduction of absenteeism associated with sick leave. Meanwhile, a working environment that guarantees pleasure and health helps the university to gain a competitive edge in attracting research staff:

> According to the Bond University online staff survey having a green building is likely to have a positive effect on attracting and retaining employees as 93% of employees said it is important to work in a green office [25].

This statement was also confirmed by the validation interviews. More than half of the student participants claimed that they would consider the green facility as one of the factors that influences their decisions for selecting a University for their future study.

Furthermore, reduced lighting loads, passive solar heating and water conservation measures all lead to savings in operational costs. In the comments of Business and Economics Building in University of Melbourne, this point is highlighted:

> The building's rating is part of a pilot for education institutions designed to improve the health and wellbeing of students, as well as to lower absenteeism and operational costs.[xviii]

Demonstration effects. In the engineering practice, majority of the leading sustainable concepts require testing and approval. The prototype of sustainable building project is then shaped as a new standard and benchmark to promote future designs and green industry developments. The Mirvac School of Sustainable Development building is one such example:

> It has been a wonderful opportunity to create a building that sets a new environmental standard for universities throughout the world. We will continue to set high benchmarks and to pursue innovative sustainable development solutions with relentless initiative.vii

3.3.3.4 University's Financial Condition

Green building projects offer direct and indirect financial benefits that universities can expect to improve their financial conditions. One of the direct financial benefits is access to the competitive development grants. In fact, 14 out of the 24 green educational projects in Australia received government funding assistance for the development of these projects. All of the funded green projects received Australian Education Investment Fund (EIF), which is a four rounds fund to provide capital expenditure in higher education and strengthen research facilities to create a world-leading higher education and research sector for Australia [207]. According to the statistics, nearly 75% of the higher education projects successful with the EIF were green buildings or buildings that address improved environmental performance [215]. The government funding was applied by the universities to support their special needs for education and research, and to enhance their capacity, which is evidenced from the following statement:

> …Our investments in that vital research will support high-wage, high-tech jobs for Australians in our emerging biotechnology sector. The Government is proud to give the researchers of La Trobe the kit they need to remain at the forefront of their field, Senator Carr said.[xiii]

The green projects supported by government funding directly boost the local economy and increase the number of employment opportunities [207]. They also indirectly offer benefits to the local public and community, as well as enable green developments to proceed.

Additionally, the university officials expect intangible benefits, which include productivity, staff and student attraction, reduced absenteeism, improved research capacity and enhanced reputation and publicity, as shown by the following comment from Medical Science 2 in the University of Tasmania:

> The new development will attract further high-quality professionals to Tasmania, enable us to expand our research by covering more disease areas, increase our collaborative links throughout Australia and internationally, and provide more opportunities for employment and professional development for researchers and medical professionals.[xx]

By synthesizing the direct and indirect financial gains, it is evident that the green building plays a pivotal role in stimulating the university's financial condition.

3.4 Conclusion

This paper analyses the application trend of the total and educational green projects across Australia and reveals the motivation of university executives and decision-makers to promote educational green buildings. The number of total building approvals was used as a background data to compare to the number of educational green projects applied over the years. Unlike the shrinking shown by the building industry after the 2008 financial crisis, the proportion of green projects has maintained stable growth rate. The educational green buildings were found to have a doubling rate of construction in the last four years.

The reasons for the fast-growth of green projects in universities and higher institutions were analysed using a qualitative approach, termed Grounded Theory. During this approach, the motivations for educational green building investments were identified from four aspects as university's core values and responsibilities, which were increasing university's reputation and publicity, meeting specific needs for education or research, ensuring environmental protection and strengthening the university's financial condition. The factors of enhance universities' reputation and meet the specific needs for research, were the major influencing parameters responsible for the decision-making to invest in green buildings. The factors that deal with enhancing university's financial condition and the environmental protection were found to be only minor influencing factors, which is contrary to the current situation of economic recession and increasingly serious global climate risk concerns.

The green projects offer direct benefits to the universities. The green identity of the well planned building and its favourable impression to both the academic area and beyond, directly boosts the university's reputation and publicity. The well-designed building which meets the specific needs for education or research purposes also enhances university's teaching and research capacity.

The grounded theory approach applied in this study also exposed the indirect benefits to the universities offered by the green buildings. The environmentally sustainable property of the green project reveals the great efforts that the university makes to fulfil its responsibility, as well as supplying technical verification opportunity for education or research. Moreover, the environmental protection consideration guarantees a higher possibility for the university to compete for the government funding which can be used for its expansion.

The findings of this study have a number of important implications for future practice. It proposes a convincible approach to deal with the complex network of vague and subjective concepts in people's comprehension of green buildings. It supplies researchers powerful tools for analysing abstract concepts and determining their interactions. However, due to the specific feature of media, the outcomes of this research are limited in education building sectors. For better understanding of the drivers responsible for approving green projects in other sustainable industry sectors with high priority for marketing, further investigation may be needed.

Chapter 4 Energy, CO_2 Emission Assessment of Conventional and Solar Assisted Air Conditioning Systems

4.1 Introduction

The increasing concerns over rapid growth of energy consumption and the need for reduction of greenhouse gas emissions in building services has become one of the priority objectives when planning design of new buildings [216, 217]. However, the increased living standards, occupant comfort demands and building architectural characteristic trends, such as the increasing application of transparent rather than opaque surfaces in the building envelope or even glass buildings, drive the growing energy demand for air-conditioning [108]. This situation occurs not only in residential and commercial buildings, but also in the educational building sector. In higher education institutions of Australia, previous study has shown that the majority of the universities are willing to invest in green technologies to improve environmental sustainability of their service [218].

Due to the unique geographical advantage of Australia, solar technologies seem to be a promising renewable energy source to power the individual buildings. First of all, Australia has the highest average solar radiation per square metre of any continent in the world. The annual solar radiation falling on Australia is nearly 58 million petajoules (PJ), which is 10000 times of Australia's annual energy consumption [219]. Secondly, the Australian government has introduced a number of grants and passed incentive programs in favour of solar energy development [220]. Moreover, the intermittent feature of solar energy is highly in accordance with the human activity pattern in the commercial, government or educational buildings. The cooling demand occurs in the daytime when the activities are occurring in the building, and the demand reduces to the background level after the sunset.

There are two main types of solar energy technologies conceivable for the utility of solar radiation in cooling based on the electrical and thermal process [108, 219]. The electrical process is achieved by supplying the electricity which is converted by photovoltaic panels to a conventional motor driven vapour compression chiller. Because the classical motor is used in this process, the main focus of research is based on renewable energy generating studies and development of integrated photovoltaic (BIPV) panels. Peng [71] compared the function, cost and aesthetics of the BIPV technology with traditional photovoltaic panels and proposed a novel structural design scheme to solve the maintenance and replacement difficulties for the PV panels. Miyazaki [221] and Wong [222] verified the application potential of semi-transparent PV panels as facades in office buildings, but they pointed out that the PV cell density could influence the efficiency of the power generation due to the increase of panel temperature. Chel [223] proposed a methodology to evaluate size and cost of BIPV system components through a case study.

The thermal process used for cooling applies solar collector to provide heat for the cooling process. Zhai [224] reviewed the traditional solar single-effect absorption cooling systems and introduced several new design options. The cooling efficiency of solar cooling systems was assessed by Chemisana, he claimed that a solar concentrating system will effectively increase the efficiency of the chiller [225]. Besides the main solar cooling technologies listed above, a new product based on both electrical and thermal process, the hybrid solar air-conditioning (HSAC) system has now emerged to the market. Ha and Vakiloroaya [226] analysed the working mechanism of this product and provided computer modelling in order to optimise its control .

The aim of this study was to compare the cooling efficiency and the environmental burden of the different air cooling systems, the solar powered conventional cooling systems, the hybrid solar air-conditioning system and a conventional system using an existing educational building as a case study. A detailed computer model was developed simulating the actual building used in this case study. The comparison work in this paper aimed to estimate the techno-environmental properties of the three cooling systems using a variety of different energy sources.

4.2 Methodology

4.2.1 Building Description

The newly built library at Macquarie University in Sydney, Australia was selected as a case study. The building is located at the centre of the campus and at the south side of seven existing multi-story buildings. The new library building, which is currently undergoing assessment for Five-Star Green Building Rating [25], is comprised of five stories, equal to a total of 16000 m^2 in Gross Floor Area. The building has a capacity of 3000 seats able to accommodate nearly 3000 students and 150 library staff. The underground level and ground level of the library are the largest floors and provide access to the exhibition spaces, the main collection section with open shelves and some special areas for presentation practise. The upper ground level, 1, 2, 3 provide staff, students and postgraduate researchers highly adaptive personal and collaborative learning spaces. The design of the building was following the architectural trend with large glazing area and metal slabs for shading. The detailed building information is presented in Appendix B section. Figure 17 presents a 3-D view of the new library with its adjacent buildings. The 3-D building model was firstly constructed in the AutoCAD environment based on the architectural drawings and field measurements. Then the model was exported to the simulation software for specified analysis. The envelope materials and thermal properties of the building are displayed in Table 5.

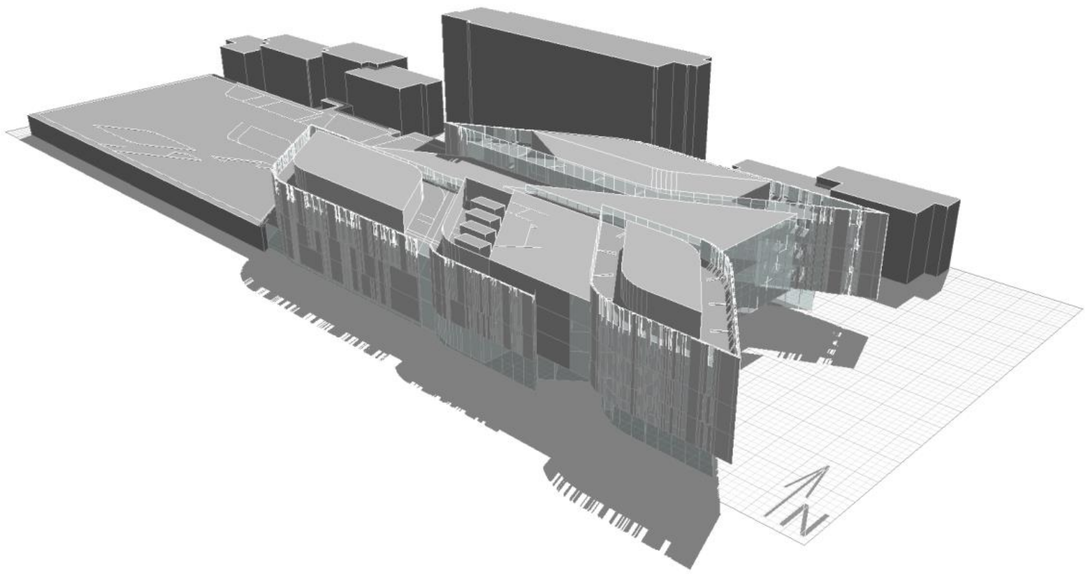


Figure 17. 3-D view of the new library building.

Table 5. Envelope materials and thermal properties, including thermal resistance (R-value), overall heat transfer co-efficient (U-value), visible light transmission (VLT) and Solar Heat Gain Coefficient (SHGC).

Constructions	R (m^2K/W)	U (W/m^2K)	VLT (%)	SHGC
External wall (lower ground and ground level)	1.78	0.56	-	-
Roof (flat roof and metal roof)	3.28	0.311	-	-
Glazing (windows and curtain walls)	-	1.69	62	0.29

4.2.2 System Description

Total of six different computer modelling scenarios of potential air conditioning systems were developed, as shown in Table 6. This study involved assessment of conventional cooling methods based on water and air cooled chillers, and the emerging hybrid solar air-conditioning system. Each of these systems were assessed based on two different power supply scenarios, the first where the electricity was supplied from the grid and the second when the electricity was produced from photovoltaic PV cells installed to the maximum capacity on the same building.

In this study, the HSACs case covered in Scenarios 5 and 6 were based on simulation using the data provided by the prototype testing results from Ha and Vakiloroaya [226]. The deduced model for the HSAC in our work assumes the same Coefficient of Performance (COP) working under similar environmental conditions but 200 times magnified, comparing to the testing data presented in [226].

Table 6. Energy modelling scenarios and cooling system types.

Building	Cooling Method	Cooling Equipment	Energy Source	Scenario
Cooling Demand	Conventional System	Water Cooled Chiller (WCC)	Grid	1
			PV	2
		Air Cooled Chiller (ACC)	Grid	3
			PV	4
	Solar Assisted System	Hybrid Solar Air Conditioner (HSAC)	Grid + Solar Thermal	5
			PV + Solar Thermal	6

4.2.3 Solar Simulation Description

A model was developed using Autodesk Ecotect Analysis 2011 [227] to simulate potential for generating solar power in this building. Ecotect is a visual building design and environmental analysis tool that links 3D modelling with a wide range of simulation and analysis functions [228].

In this study, the function of solar radiation calculations was applied to predict the annual accumulative solar radiation that falls on the surface of the library building selected for this case study. The detailed geometrical model of the library as well as the buildings which could potentially influence the library's solar exposure was created in the software, as shown in Figure 17. The North, East and West sides of the library were set as the main analysis objects due to the direct sunlight (southern hemisphere). Refined mesh was then mapped over the building surfaces on these sides. When simulation begins, Ecotect uses hourly recorded direct and diffuse radiation data from the weather file obtained from the United States Department of Energy to calculate the insolation amount. After the simulation, the analysis results can be overlaid on building surfaces in addition to the standard graph and table-based reports [229].

4.2.4 Energy Simulation Description

The energy simulation was carried out using EnergyPlus software [228]. EnergyPlus is building energy analysis and thermal load simulation program which is capable of running dynamic analysis based on the instantaneous measured weather data [230, 231]. With the input of building's geometrical and thermodynamical properties associated with mechanical and other systems, the cooling loads necessary to maintain thermal control set points of the investigated building could be calculated. The predominant method used to simulate the dynamic cooling loads is the heat balance method. Along with Table 5, Table 7 lists simulation parameters adopted for the building loads calculation. According to the table, the internal heat gains were mainly from three parts, occupancy, lighting and equipment, and infiltration.

Table 7. Simulation parameters of the building at different levels (lower ground level, ground level and the subsequent 3 floors).

Parameters	Units	Design Value	
		LGL, GL	L1, L2, L3
People Density	people/m^2	0.2	0.1
Metabolic Heat	W/person	135	123
Equipment Heat	W/m^2	5	15
Lighting Heat	W/m^2	12	10
Cooling Set Point	^{0}C	25	25
Relative Humidity	%	60	60
Ventilation/Infiltration	V/h	0.3	0.3

The metabolic heat generated from the occupancy of the building at the building's peak occupancy level was estimated according to the Australia Standard 1668.2-2002. The standard states that each person should have space allocation of at least 5 m^2 in the general library area (Lower Ground Level and Ground Level) while in the study areas (Level 1, 2 and 3) the space allocation should be minimum of 10 m^2 per person. The number of occupants in the library varies in a typical academic year according to the learning sessions. Figure 18 represents the fraction of building occupancy throughout the year with three semesters, indicating clearly high usage exam weeks, mid-semester breaks and holidays.

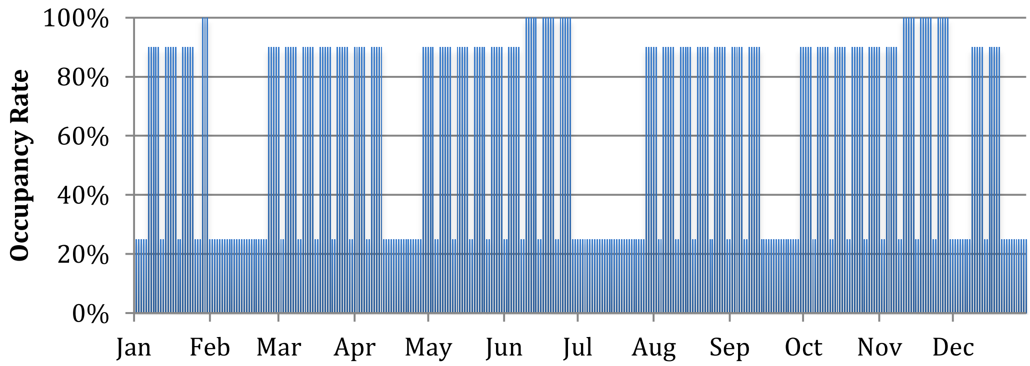


Figure 18. Annual occupancy schedule for the library building.

The occupancy rates of a typical week, weekend and exam day were estimated based on the actual occupancy door counts measured at the entrance of the library. The hourly data of the number of occupants was collected during daytime from 8:00 AM to 18:00 PM and in night time from 19:00 PM to 22:00 PM, over an investigation span period of 14 days, including nine weekdays, four weekend days and one session break day. The investigation results are shown in Figure 19.

The library opens at 8:00 AM and closes at 10:00 PM on weekdays, while it opens at 9:00 AM and closes at 9:00 PM on weekends and holidays. For a normal semester day (shown in blue in Figure 19), some students arrive at early morning to occupy a study place for the remaining of the day. Other students and staff enter the building to borrow books and leave before the start of their course. At noon, the number of fixed students in the library drops as the students leave for lunch, but the number of borrowers entering the building is stable. After lunchtime, the students are back to study until the closing time of the building. The number of borrowers meets a sharp decrease at 5:30 PM after the lectures finish. For an examination day, students arrive in the library earlier and leave the building later than the normal days. For the weekends and holidays, there are a smaller number of borrowers, but those who use the library for study remain in the building.

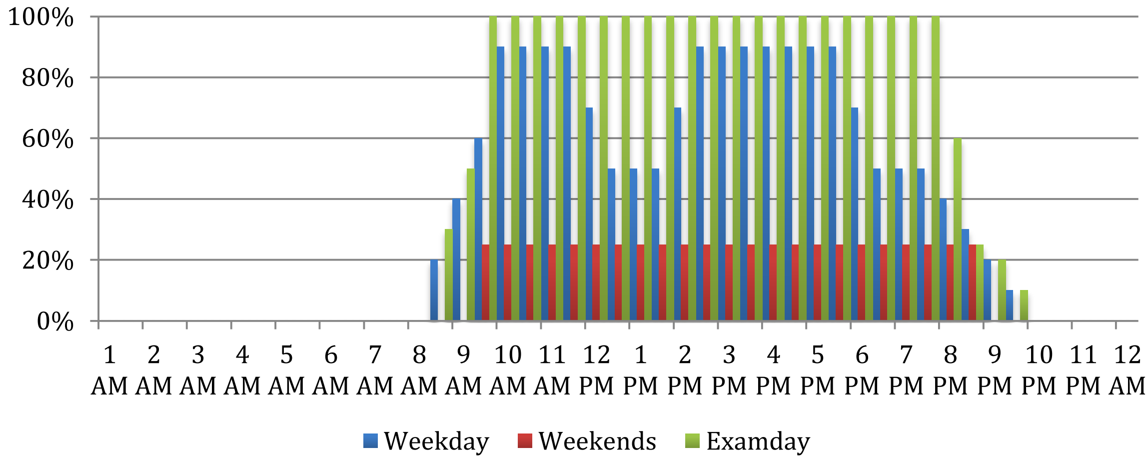


Figure 19. Occupancy profiles for weekdays, weekends and examination days.

Artificial lighting and the usage of office equipment are the two additional sources of internal heat gains. The lighting and equipment running hours are assigned according to the occupancy schedule. When the building is occupied, the lighting and equipment are on and stay at high levels to satisfy demands. The lights and equipment are back to standby model after the building is empty. Figure 20 represents the detailed schedule and power density as determined according to field investigations. There is no difference between examination days and typical weekdays.

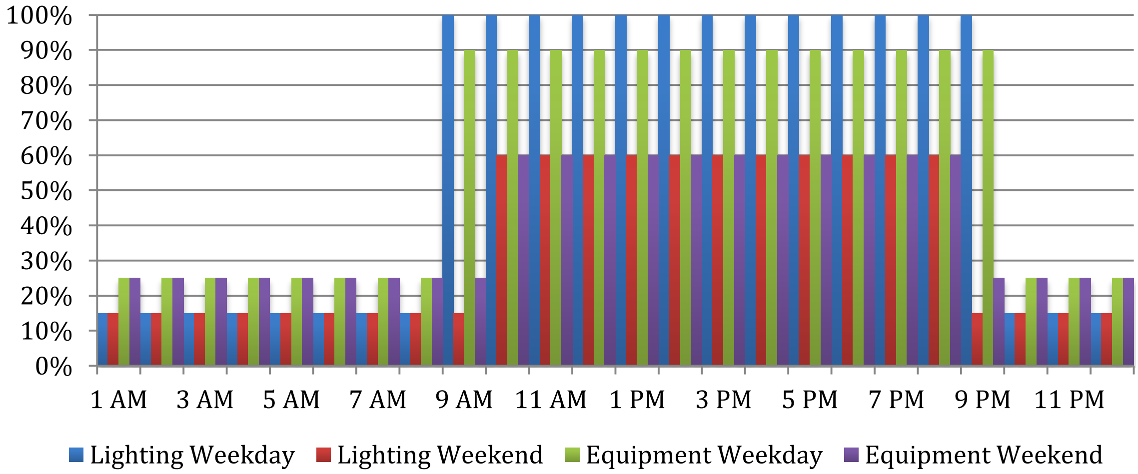


Figure 20. Lighting and equipment profiles for weekdays and weekends.

4.2.5 Greenhouse Gas Emission Prediction

The greenhouse gas emissions of cooling systems in the six scenarios are calculated using the following equation:

$$GHG_{Total} = g_{Grid}E_{Grid} + g_{PV}E_{PV} - (g_{Grid} - g_{PV})E_B \quad (1)$$

Where, g_{Grid} and g_{PV} are the specific CO_2 emission factors for electricity from the grid and PV panels respectively; E_{Grid} stands for the cooling systems' electricity consumption supported by the grid while E_{PV} represents the consumption share covered by PV generation; E_B represents the electricity balance left from the electricity generated by

PV panels subtracting the electricity consumed by the cooling systems, $E_B = T_{PV} - E_{PV}$, in which T_{PV} is the total electricity generated by the PV panels. The emission factors in the equation are found in [232, 233] and listed in Table 8.

Table 8. Average greenhouse gas emissions expressed as CO_2 equivalent for individual energy generation technologies.

	g $CO_{2\text{-}e}$/kWh
New South Wales Electricity Grid	900
Photovoltaic	90

4.3 Results

4.3.1 Solar Energy Potential

The solar energy potential of the library building selected for case study in the work was further modelled with Ecotect 2011. The results, shown in Figure 21 reveal that the solar radiation falls on the roof areas of the library building across the entire year. The majority of the exposed area received around 1687 kWh/m^2/year of radiation, while parts of the roof reached 1020 kWh/m^2/year due to the shading effect from adjacent building components. This effect where horizontal surfaces receive more solar radiation than vertical surfaces was previously discussed in [234].

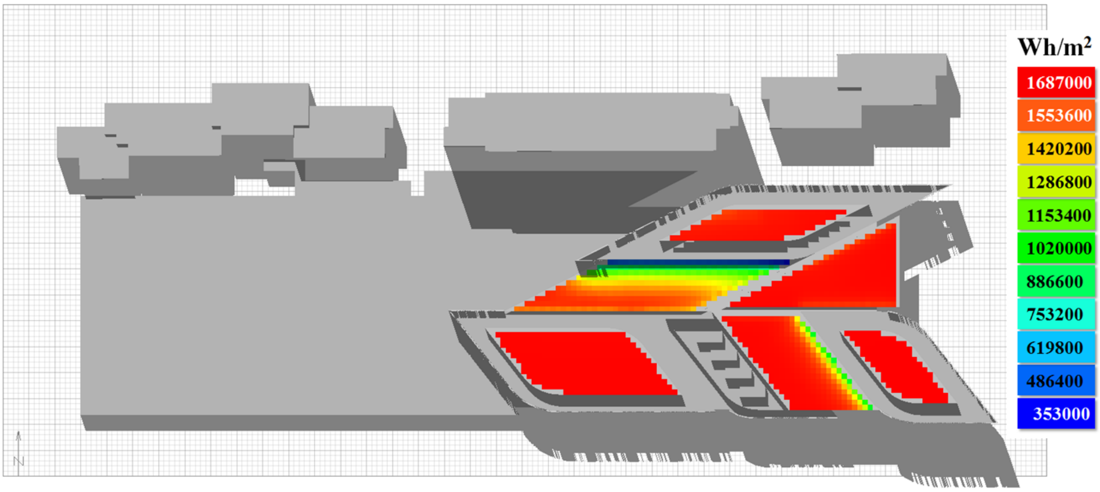


Figure 21. Annual cumulative solar radiation on the roof of the building.

With the advent of third generation PV panels, the envelope of the building, including the windows can be used as solar electricity generators. Figure 22 illustrates the power generation potential using transparent PV panels on the East, North and West building surfaces. The colourful stripes on the building envelope represent the varied cumulative amount of the solar radiation, from the lowest at 49 kWh/m^2/year in the darkest area to the highest 910 kWh/m^2/year on the Northwest glass curtain wall. The dark blue areas are the surface parts behind the vertical shading blades, which are rarely exposed to sunshine. Due to the different angles of the blades fixed on the external walls or windows, the shading effects to the building envelope vary. Although the shading slabs nearly cover all the building surface area, the effective radiation area (over 80 kWh/m^2/year) still reaches a total of 1500 m^2.

Dust accumulation on photovoltaic module surface is an issue of concern. Deposited particles and dust on the surface of module reduce the glass cover transmittance and thus decrease the amount of solar irradiation reaching the cells [235]. It should be noted that the energy generating degradation caused by the dust effect is a complex phenomenon varying by climate, geographical location and the installation of the photovoltaic module [236]. Depending on these factors, a wide range of power output reductions from 5-40% could be experienced if the modules are not cleaned for a period of time [236, 237]. However, the impact of dust can be effectively minimised by optimised installation and regular maintenance of the modules. More specifically, the vertically installed window solar collecting area is expected to be less affected as the modules titled with larger angles less susceptible to dust accumulation on surfaces, leading to lower reduction in transmittance [238]. Moreover, the degradation of power generating performance can be further mitigated by periodic cleaning of the photovoltaic panels [235, 236].

In this study two types of PV panels were selected for estimating the potential of the solar power harvesting, an ideal condition without the efficiency decrement caused by the cell temperature increase and dust cover were considered for the maximum power output. The results were compiled in Table 9.

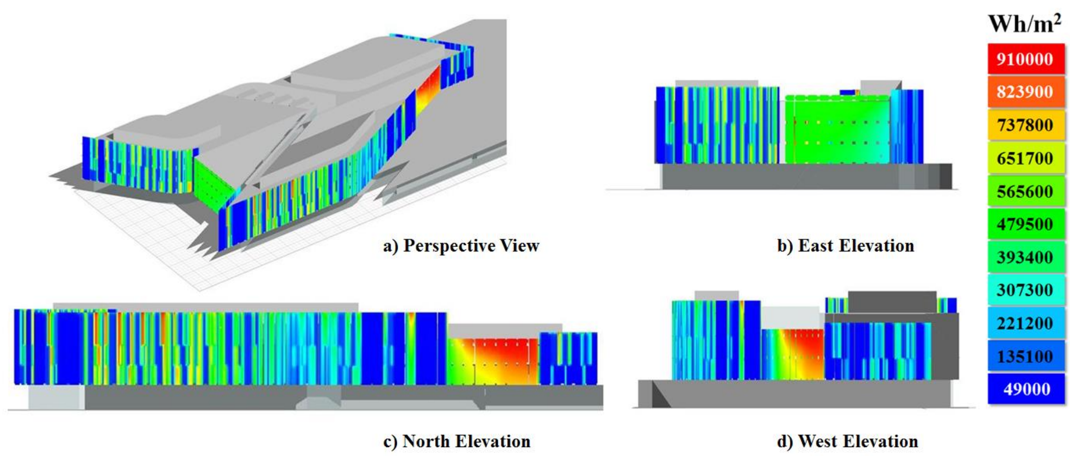


Figure 22. Annual cumulative solar radiation on the envelope of the building.

Table 9. PV panel attachment and energy production analyse results.

Building Surfaces	PV Cell types	Efficiency	Area of Panels (m^2)	Available Solar Radiation (MWh)	Electric Power Generated (MWh)
Roof	Multicrystalline	15%	1474	2311.7	346.8
East Side	Amorphous	8%	708	204.7	16.4
North Side	Amorphous	8%	609	174.9	14.0
West Side	Amorphous	8%	744	206.1	16.5
SUM			3535	2897.4	393.7

4.3.2 Cooling Demands of the Building

The first stage of simulation comprised of a pilot run on a summer day to determine the size of the cooling system. The cooling demand was calculated based on the design day information of the EnergyPlus IWEC weather file. According to the file, the 21st of February was selected as the summer design day and the dry bulb temperature of the day was 33.5 ^{0}C while the wet bulb temperature was 23.3 ^{0}C. Figure 23 shows the outdoor temperature and its relevant cooling demand through the whole day. The outdoor temperature reaches peak of 33.5 ^{0}C at 15:00 in the afternoon when the cooling demand rises to the maximum value of 1138 kW in the following hour 16:00. This lag is caused by the thermal storage property of the external walls. More specifically, the cooling demand between 12:00 and 13:00 experiences a temporary decrease due to the students who study in the building leaving for lunch. When lunch time is over, the cooling demand rises again until the end of the classes. Based on this calculation, two equal sized, 850 kW water cooled or air cooled central chillers were selected to fit the building demand as a conventional cooling plan, and the capacity of an ideal HSAC was assumed to be 1200 kW for the solar assisted system.

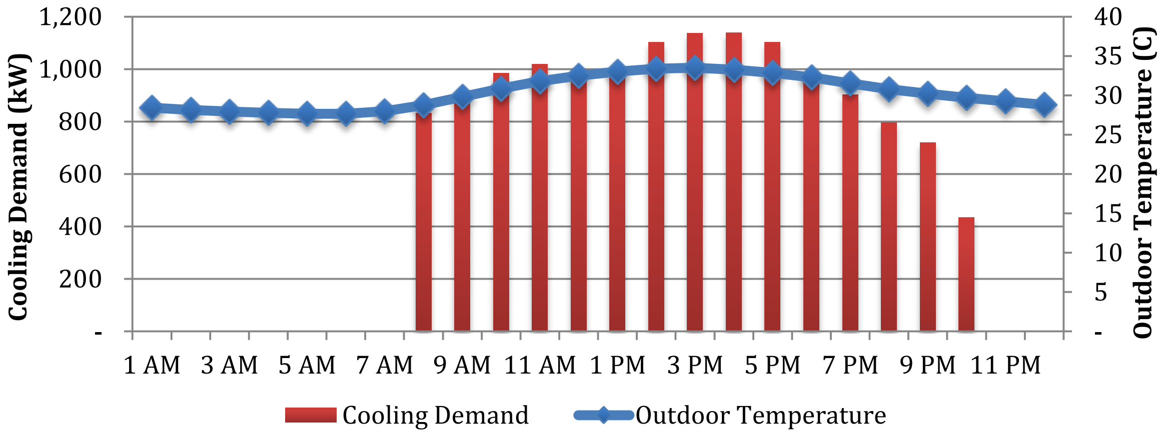


Figure 23. Cooling demand of the library building on the summer design day.

The hourly cooling loads of the building throughout the whole year were then carried out based on the annual weather data to determine the load distribution. As shown in Figure 24, the cooling load density during the winter period is relatively low compared to the summer period. The average hourly loads during winter periods are estimated at only 200 kW. The cooling load density from January to April is higher than from October to December. The majority of the cooling loads fall on the space interval between 250 kW and 500 kW. The extreme high load conditions, which is over 850 kW, only occur for several hours on the day with extreme hot outside temperatures or full occupancy, such as on the examination days. Table 10 lists the detailed cooling hour distributions under part load conditions.

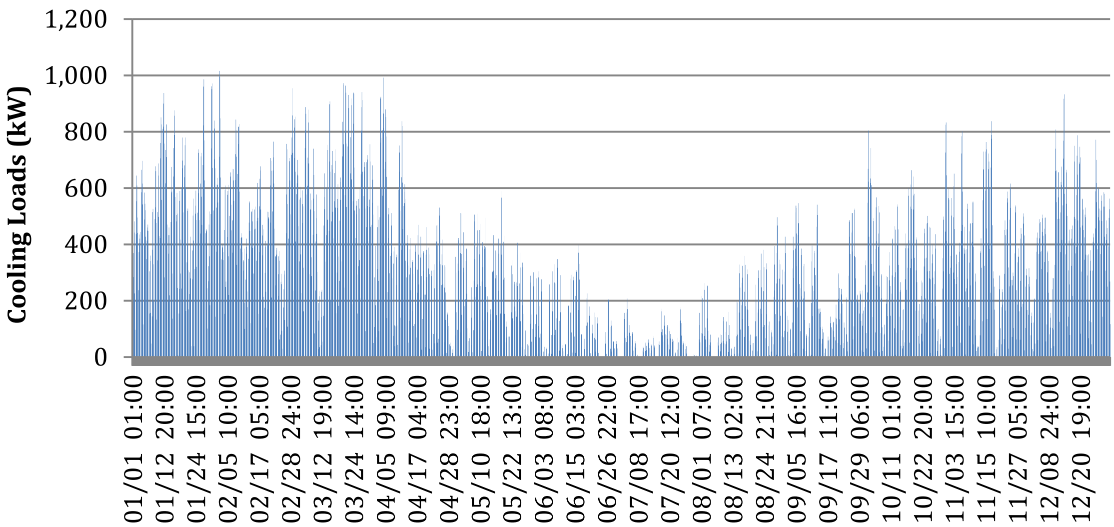


Figure 24. Hourly cooling loads of the library building throughout the whole year.

Table 10. Accumulative cooling hours under part load conditions.

Part loads (%)	100%	75%	50%	25%
Cooling Hours (hr)	487	985	1448	2060

4.3.3 System Performance Comparisons

For the conventional cooling systems, regression analysis was performed to plot a curve which can describe how the chillers' performance change with the varied cooling loads, based on the part loads performance data of the cooling units at rated standard conditions. Figure 25 illustrates the performance of specification of the water cooled and air cooled chillers. If Table 10 and Figure 25 are examined, it is obvious that the cooling systems are mainly working on their high performance interval which is from 25% to 50% load ratio.

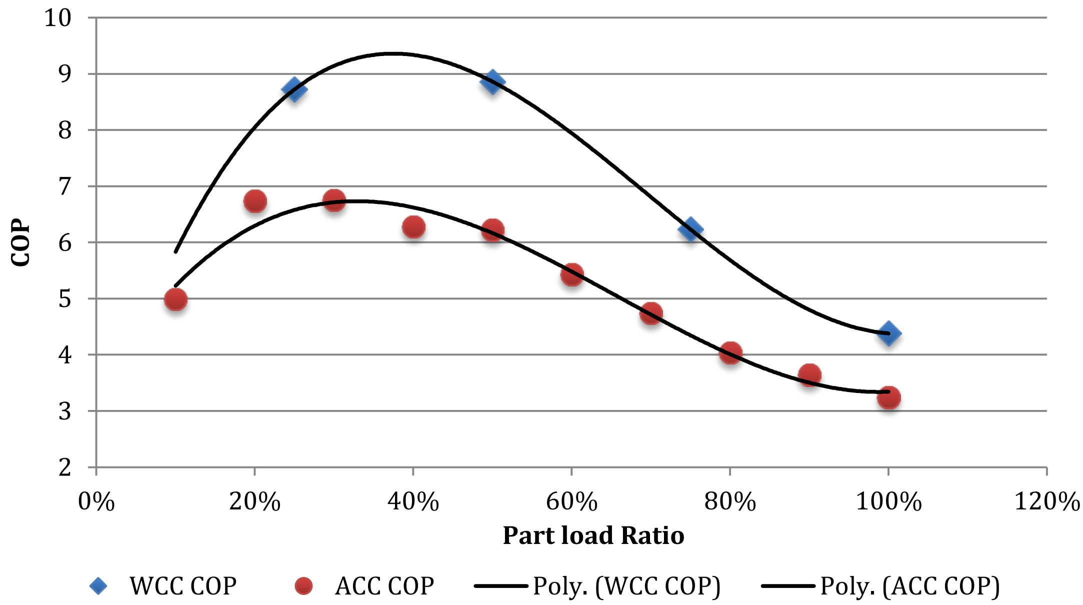


Figure 25. Performance of plant units under different part loads.

For the solar assisted system, the dependence of COP from the ambient temperature was established accounting for several assumptions, which were: a) the solar energy absorbed by the HSAC is constant during the day; b) the temperature difference between the ambient temperature and the temperature of refrigerant leaving the condenser is stable at 3^{0}C [239]; c) the influence of ambient temperature fluctuation is more significant than the cooling load variation on system's COP. Figure 26 demonstrates the performance changes of the HSAC with outdoor temperature.

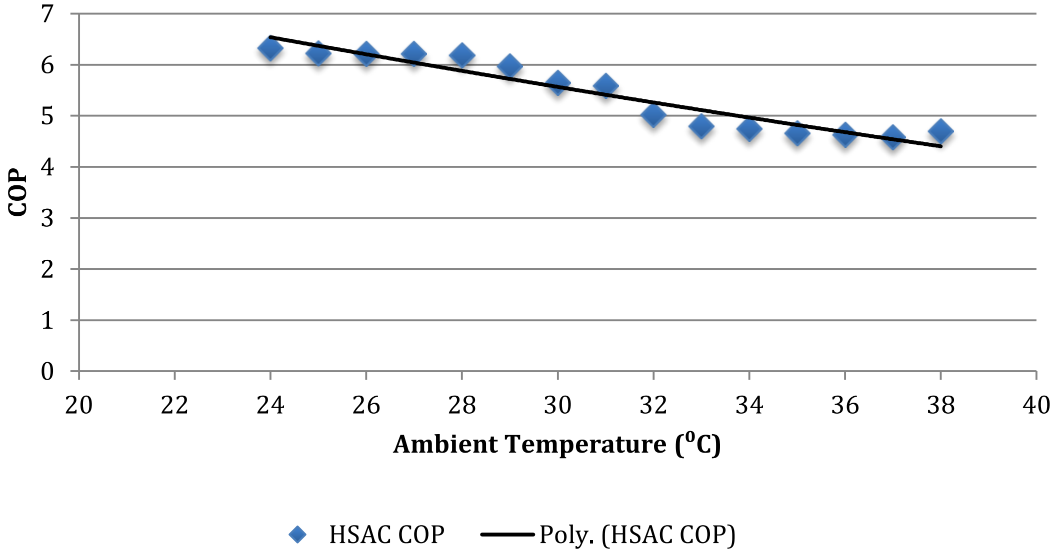


Figure 26. Performance of HSAC under different ambient temperatures.

The polynomial function of the fitting curves can be explicitly established as:

$$y = a_0x^3 + a_1x^2 + a_2x + a_3 \qquad (2)$$

where y is the dependent variable which is the coefficient of performance of cooling units; x is an explanatory variable which represents the part load ratio of cooling equipment; the coefficients from a_0 to a_3 are constant values determined by curve-fitting the manufacture's data. The R^2 values of the function indicate good fit. The coefficients obtained from the regression are listed in Table 11.

Table 11. Coefficients describing COP curves of cooling systems.

Cooling Unit	a_0	a_1	a_2	a_3	R^2
WCC	37.867	-78.960	43.213	2.260	1.00
ACC	23.693	-46.786	23.074	3.362	0.973
HSAC	-	0.001	-0.227	11.295	0.914

With the three regression functions from Table 11, the variation in the Coefficient of Performance (COP) of each cooling unit during entire year was calculated (Figure 27). It can be observed that the water cooled chiller has the highest COP which oscillates from 4.3 to 9.3 while for the hybrid solar air conditioner exhibits slightly lower COP and fluctuates between 4.2 and 9.8, followed by the air cooled chiller with COP varying from 3.3 to 8.9. Although these three units have varied performance, they represent a similar trend in the summer time. The units work at high efficiency in the early morning and late in the evening when the cooling loads are relatively low. As the cooling loads increase during daytime, the performance decreases for each unit. For example, the largest decrease in COP is predicted for 16:00 of the hottest day. Besides the extreme conditions, the HSAC exhibits a much more stable performance than the other two cooling units. During the winter time from June to August, the trends become quite different. The COP of the HSAC increases because the ambient air temperature in winter is lower than that in summer. Similarly for the WCC, the daily COP decreases significantly due to the lack of high part load running during daytime. However, in the hours of early morning and late evening, the cooling loads are very small, sometimes even below the manufacturer's recommended minimum cooling capacity limits. Adjustments had to be done for the WCC and ACC to ensure the units are not working below the limits. This explains the straight lines between the cooling periods from June 13th to August 17th.

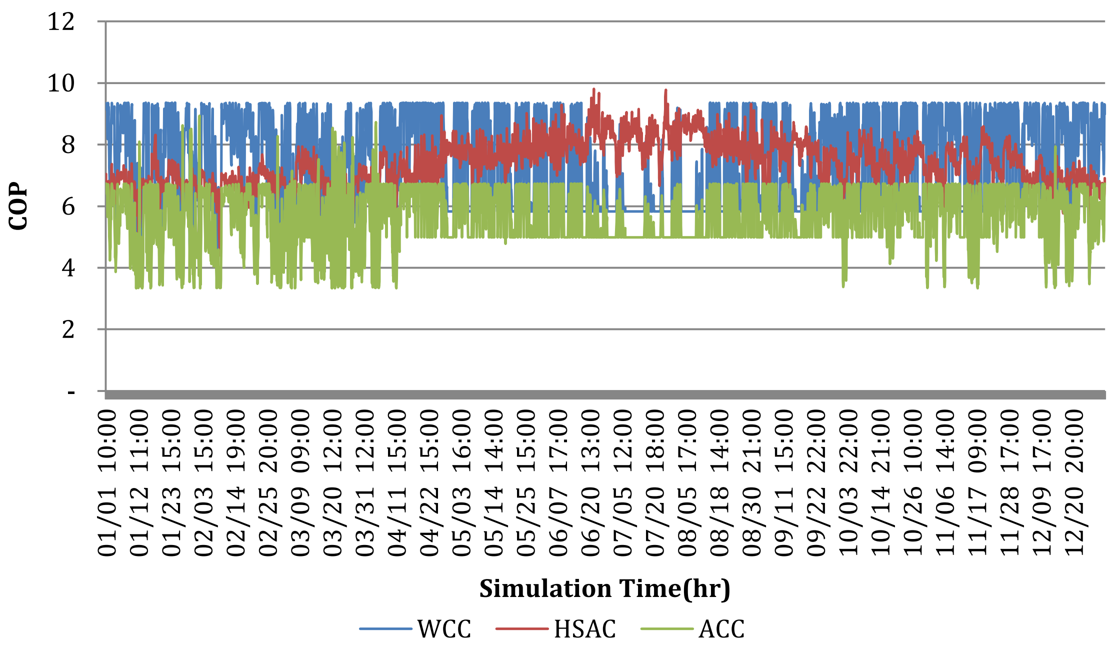


Figure 27. Hourly COP of the cooling units throughout the whole year.

4.3.4 Energy Consumption and Energy Saving Potential

Based on the cooling demand simulation and the cooling unit performance analysis, the energy consumption of these three systems were obtained and shown in Figure 28. The results show that the ACC system needs more electricity to cool the building than the other two systems. The HSAC consumes more energy than the WCC in the summer time but is more economical in the winter periods. In total, the annual consumption of HSAC 212,564 kWh is significantly lower than ACC 266,186 kWh but slightly higher than that of WCC 198,855 kWh.

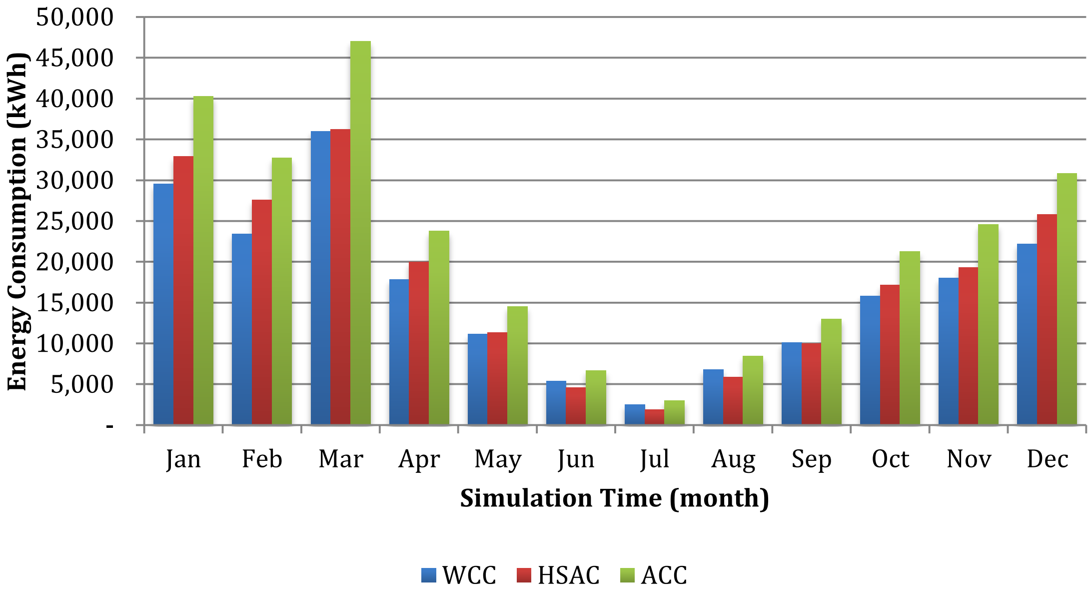


Figure 28. Monthly energy consumption results.

Accounting for the results from Table 9 and Figure 28, the energy consumption profile of the six scenarios are analysed and compared in Figure 29. Scenario 1, 3 and 5 are the annual consumption of grid electricity of WCC, HSAC and ACC respectively, while 2, 4 and 6 are the ideal cases that apply PV electricity at the building's full PV installation capacity in order to substitute for the demand from the grid. The results show the PV panel production has the potential that not only to cover all of the building's cooling electricity consumptions in Scenario 2, 4 and 6, but can also have surplus electricity of 194750 kWh, 181040 kWh and 127419 kWh respectively. Scenario 2 in which water cooled chiller and integrated PV panels in the building structure provides the most energy efficient solution for cooling of the selected library building for the investigated yearly weather conditions in Sydney.

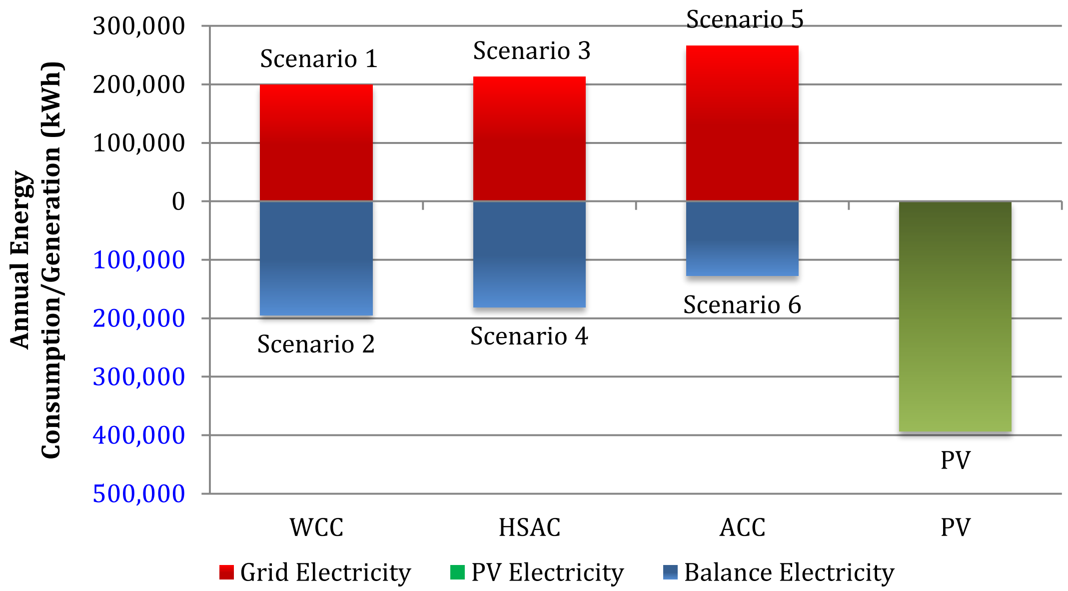


Figure 29. Comparison of annual electricity consumption and the energy structure among six scenarios.

4.3.5 Greenhouse Gas Emission Comparison for Cooling Systems

Based on Equation (1) and the annual energy consumption results from Figure 29, greenhouse gas emissions were compared among the six scenarios in Figure 30. For the cases without PV support, the cooling systems of the building emit more than 150 tonnes of greenhouse gases each year. However, the calculation results of scenario 2, 4 and 6, indicate that the PV technology can reduce greenhouse gas emissions effectively. The surplus renewable electricity has an equivalent over 140 tonnes of CO_2 mitigation in the best case. However, it is important to emphasise that this calculation did not take into consideration the embodied energy and greenhouse gas emissions from production of the air-conditioning units and solar panels.

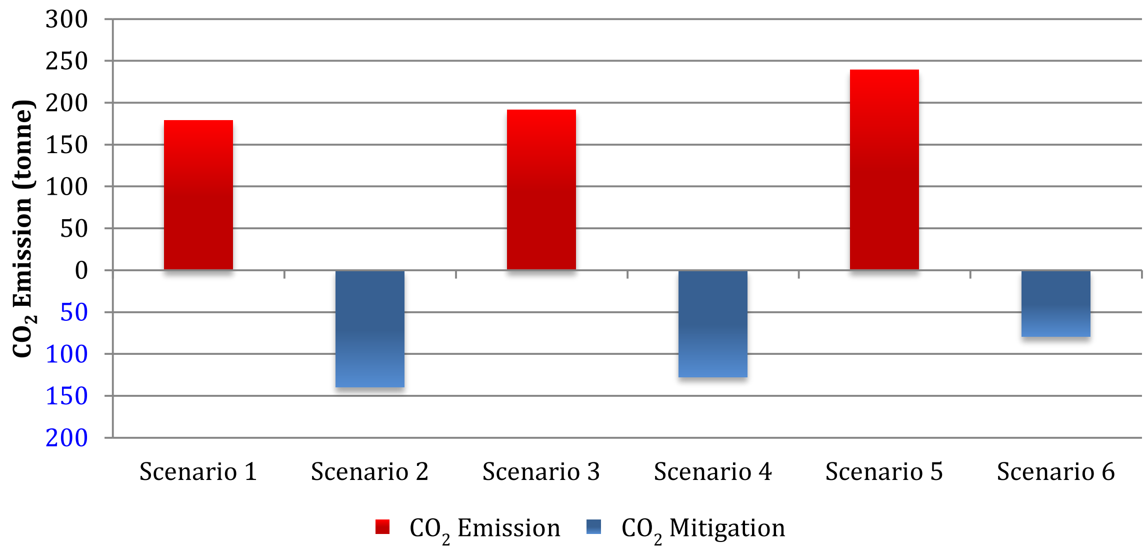


Figure 30. Comparison of annual greenhouse gas emissions among six scenarios.

4.4 Conclusion

This research evaluated three types of cooling systems in a complex educational building, including water cooled, air cooled chiller system and Hybrid Solar Air Conditioning system for the cooling demand, power consumption requirements and greenhouse gas emissions based on the local weather conditions. To test the potential of the solar power that could be used by the building, an annual cumulative insolation analysis was performed in the first place, using a building model and accounting for the nearby shading elements. Then the cooling demand of the building throughout the whole year was simulated. The findings of this research are as follows:

- The simulation results indicate that under ideal conditions, if PV panels are installed on the investigated building, they will entirely cover for the annual electricity consumption for cooling of the building.
- The overall performance of the Hybrid Solar Air Conditioner (HSAC) is higher than the Air Cooled Chiller (ACC) but lower than the Water Cooled Chiller (WCC).

- The annual energy consumption of the HSAC was found to be lower than the ACC while it consumes more electricity than the WCC system. By applying the BIPV technology, it effectively reduces the electricity demand on peak load period.
- Additionally, the greenhouse gas emissions caused by cooling the building could be completely offset by the production of renewable energy. The surplus electricity could be also used by other electronic appliances in the building to mitigate the greenhouse gas emissions further when the solar based PV technology is integrated in the building.

Chapter 5 Potential Analysis of Piezoelectric Energy Harvester and Development Strategy Exploration in an Educational Building

5.1 Introduction

The increasing energy demand in the building sector, which results from the growth in population, enhancement of building services and comfort levels, together with the rise in time spent inside buildings, is significant contributor to the overall energy use [92]. To minimise the impact of growing energy requirements by the building sector, integrating alternative energy sources is of paramount importance.

In the last few decades, a wide range of renewable energy sources have been considered as the possible solution, including but not limited to solar, wind and hydroelectric power [232, 240]. Recently, there has been an increasing interest in the exploration of indoor energy harvesting sources. The indoor energy sources are believed to be an important component in the energy diversity and reliability when the weather related energy resources are minimal [241]. Inside a building, a range of harvestable ambient energy sources exist, e.g. waste heating, flowing water, electromagnetic waves and, particularly, vibration [121, 242]. The vibration-based energy harvesting, termed as piezoelectric energy generation, has received the most attention due to its ability to capture the surrounding ambient energy and then directly convert the applied strain energy into usable electrical energy and the ease at which they can be integrated into a system [121, 243-245].

The piezoelectric material in the piezoelectric system has several modes of operation. These modes are characterized by the piezoelectric strain constant d_{ij}, which is the strain to the electrical field [119]. The subscript i represents the direction of the applied electrical field, while the subscript *j* indicates the direction of deformation. When an electrical field is applied in the poling direction, normally along the vertical axis, the material contracts in the poling direction (3-axis) and extends in other directions (1 and 2-axis), as shown in Figure 31. The deformation along the 1 and 2-axis is called the d_{31} effect, and the shape change along the 3-axis is defined as the d_{33} effect. These two effects predominate in the application of power harvesting. The piezoelectric materials are capable of generating power from the nano-Watt to the Watt range, depending on the piezoelectric materials and system designs [124, 246-248].

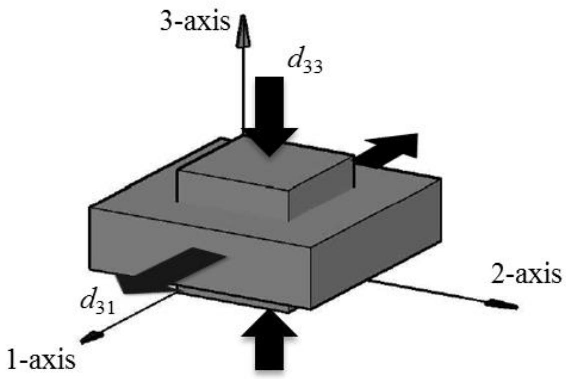


Figure 31. Operation modes of piezoelectric material and its axis reference system.

The initial research driver in this field was reduction in power requirement of small electronic components which would ultimately release the sensors used in remote passive and active monitoring applications from the constrain of complex cable wiring and periodic battery replacement [249-252]. Under this context, Roundy and Wright developed a piezoelectric generator as well as an analytical model for the design validation [123]. This generator had been successfully used to power up a radio transmitter from a vibrational source of 2.5 m/s^2 at 120 Hz. Similar piezoelectric generator was further proved to be functional in a much broader vibrational frequency from 40 Hz to 1000 Hz [253, 254]. To extend the piezoelectric technology over micro-scale, relative energy storage devices were developed to accumulate sufficient amount of energy to power the intended electronics [124, 249].

In recent years, several attempts at the macro-scale application of the piezoelectric technology have emerged [117, 130, 255, 256]. The piezoelectric floors have been trialed since the beginning of 2007 in two Japanese train stations, Tokyo and Shibuya stations. The electricity generated from the foot traffic is used to provide all the electricity needed to run the automatic ticket gates and electronic display systems [257]. In London, a famous nightclub exploited the piezoelectric technology in its dance floor. Parts of the lighting and sound systems in the club can be powered by the energy harvesting tiles [258]. However, the piezoelectric tile deployed on the ground usually harvests energy from low frequency strikes provided by the foot traffic. This working condition may eventually lead to low power generation efficiency.

In order to improve the power generation efficiency, a two-stage energy harvester design was suggested for the very low frequency vibration environment in the 0.2–0.5 Hz range [259], as shown in Figure 32. This design contains two main components, a mechanical energy transfer unit linked with a vibration platform and secondary vibrating units composed of additional piezoelectric elements and vibrating beams fixed on one side. Ideally, when the initial impact effects on the platform, the mass attached on the mechanical energy transfer unit starts to vibrate in low frequency. The low vibration energy is then transferred to a much higher natural frequency vibration in the piezoelectric elements as the mass passes over and excites the piezoelectric beams.

Based on the proposed design, a piezoelectric cantilever stream structure was adopted by Wu et al. [260]. In their research, the two-stage design is called the plucked method and the design was validated with experimental tests. It is claimed that the plucked method can enhance the efficiency of the energy harvesting system by 900% [260].

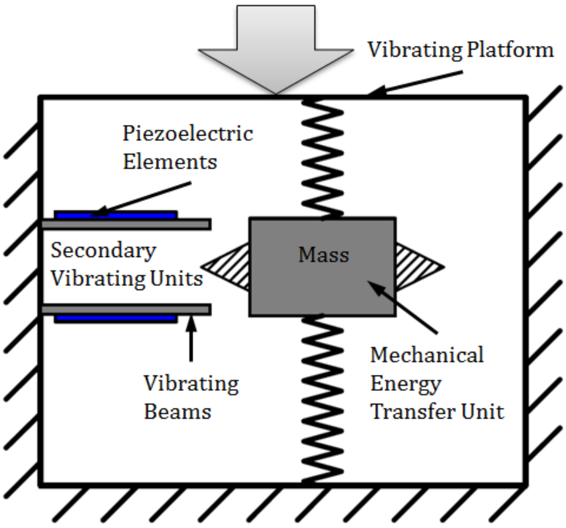


Figure 32. Schematic of an enhanced piezoelectric energy generator based on the two-stage energy harvesting approach based on [259].

However, since the macro-scale piezoelectric technology has not yet been fully established, much uncertainty still exists about the actual energy harvesting efficiency of the commercialized piezoelectric tiles. There is a lack of information on energy harvesting potential of piezoelectric tiles when applied in buildings, and particularly in green buildings. In this work, a novel approach to estimate piezoelectric harvesters' power generating potential and their adaptability in buildings is developed. The analysis was conducted based on the data provided by a manufacturer of a commercial piezoelectric energy harvester to examine its adaptability in a central hub building at Macquarie University in Australia. In order to evaluate the full potential of this harvester, the high traffic areas inside the building were located by a mobility analysis approach. Based on the mobility pattern, a deliberate tiles deployment strategy was then selected. Along with modelling the amount of electricity converted from the footsteps, the energy generating potential of a possible improvement with plucked method was also determined. The study then proposes an evaluation indicator to calculate and predict the most efficient areas for tile deployment.

5.2 Methodology

5.2.1 Building Description

The building considered for the piezoelectric power generation study in this research was a newly built library at Macquarie University, Sydney, Australia. The new library is a flagship building located in the center of the Campus, aiming for a Five-Star Green Rating under the criterion of the Green Building Council of Australia [261]. The building comprises of five stories, equal to a total of 16,000 m^2 in Gross Floor Area with capacity of 3,000 seats available for students and 150 working staff.

The ground level of the library, as shown in Figure 33, is the largest floor area in the building. Near the main entrance, there is a cafeteria providing food and drinks for the library users. Lobby meeting areas, including concourse spaces, are located after the main gates and the central cross area. They provide access to the exhibition spaces and the main collection section with open shelves. The lower ground floor and upper ground levels, 1, 2, 3 provide undergraduate and postgraduate students and research personnel collaborative learning spaces. With these features, the new library becomes a new hub for not only students but also staff members in the university. It makes the area the busiest spot on the Campus, making the library one of the target areas for deploying the piezoelectric tiles.

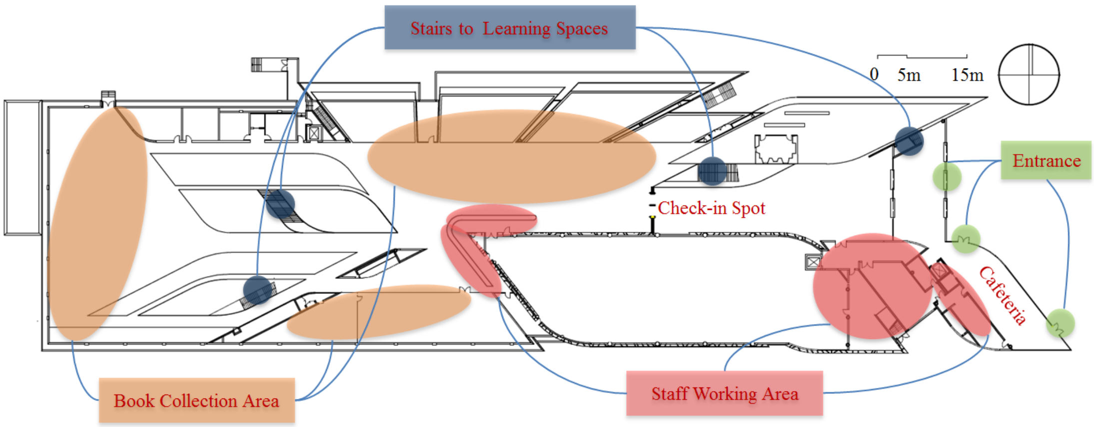


Figure 33. Main function areas of the ground floor of the new library.

In order to facilitate students' learning, the library building is open seven days a week during the entire year, except for the third session period from 30 November to Tuesday, 24 December when the library is closed on Sundays. The library is also closed from 25 December to 1 January. The actual operating days of the library throughout the year, according to the library schedule, are 353 days.

5.2.2 Location of High Traffic Areas

The high cost of the piezoelectric power generation tiles ($3850/per tile) is the limiting factor in their deployment. For this reason, high traffic areas in the building should be identified in order to maximise the energy harvesting efficiency.

There are three broad functional groups of users of this library. The first group consists of book borrowers, who generally aim for borrowing books from the main collection areas. They spend short time in the library and are with high mobility per time unit. The second group consists of "fixed students" who occupy the learning spaces. Although they spend longer periods of time in the library, their mobility per unit time is low. The last category is the librarian professional staff as well as other employees in the cafeteria, with variable mobility. The mobility pattern of these three groups of users can be predicted according to users' aim and behavior. More specifically, the route of book borrowers is estimated based on the shortest route from the entrances of the library to the main book collection area. The routes for the fixed students and the staff are determined based on the shortest route from the library entrances to the location of the specific functional districts, such as the stairs to the learning spaces and the staff working areas in the library building. Based on these assumptions, Figure 34 provides hypothetical examples of the mobility of each category of library users with the interest in this study of identifying the areas of the highest mobility. Qualitatively, the overlapped areas represent the places with the highest mobility.

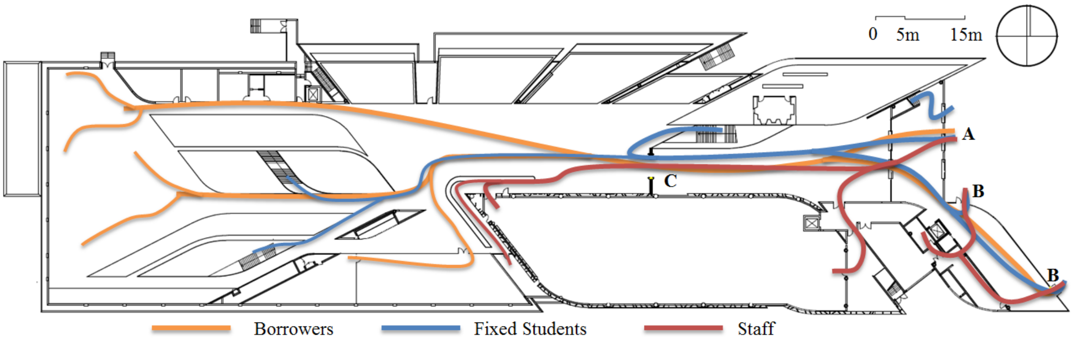


Figure 34. Library ground floor and examples of paths followed by the library users and staff.

The first specific area of the highest mobility is the main entrance (A) of the library building. The library has only one main entrance door, unless emergency occurs. As a result, this area could be considered as one of the high frequency hot spots. As the library has a cafeteria on the ground floor near the main entrance gate, both students and university staff members may use the adjacent cafeteria to enter into the library building through the points (B) identified in Figure 34. The library cafeteria is considered as the second hotspot in this study. The third high traffic spot is the security path (C) to the collection area, as the library users have to walk through the path to enter the book collection area. The self-check in/out stations are also nearby, hence this area provides a good potential where piezoelectric floor tiles can be laid.

Based on the assumptions listed above, the actual student mobility was measured with door counts at these three spots in the library over a 10 day period, which covered seven typical semester days, two typical weekend days, and a public holiday. The tests started from 8:00AM in the morning and ended at 5:00PM in the evening for the working days, while for the weekend days and holidays, the test ran over an investigation span period of 8 hours starting from 10:00AM.

5.2.3 Electricity Generation Potential

There are several piezoelectric power generating products released to the market by different companies, such as Pavegen from the UK [130], Waynergy from Portugal [255] and Soundpower from Japan [262]. Pavegen Tile is one of the commercial products designed for harvesting kinetic energy from footsteps. According to the Pavegen Company, the paving unit, with a dimension of 600mm × 450mm × 82mm, is able to generate up to 7 Watts electricity per footstep [130], which is higher than the products from other companies, for instance, 0.1 Watts per step for the Power Generating Floor [262] and 4 Watts per step for the Waynergy Floor [131, 255]. In our research, the Pavegen Tile was selected as the power harvesting system in the selected building to examine the building's piezoelectric power generating potential.

According to the introduction of the Pavegen Tiles, the energy yield is strongly dependent on the accumulative time when the piezoelectric elements are activated. If the piezo-element is activated once per single footstep, the power generation (W) then can be calculated as a function of the number of pedestrians and the number of tiles that are stepped on by a single pedestrian along the pathway. The function is defined as follows:

$$W = M \times n \times E \times R \tag{3}$$

Where M is the number of pedestrians; n represents the number of tiles that are activated; E is the electricity generated from single step; R is the enhancement rate when the plucked method is used to improve the harvesting efficiency.

In this study, the Daily Power Generation of the library is firstly calculated based on the door count statistics using Equation (3). Due to the working mechanism of the piezoelectric energy harvester, the enhancement rate R is the default amount 1.0 as the single impact effects on the tiles. Based on the daily energy harvesting potential, the Annual Generation can be obtained by multiplying the Daily Power Generation with the building's actual running days throughout the year.

The model then considers the effect of enhancement of the piezoelectric tile's energy productivity by applying the plucked method. Although this technology is still in development, in order to model the full potential of the piezoelectric energy generation, it is important to predict its effect when the technology reaches the required maturity. For this purpose, in this study it is assumed that the plucked method could be integrated in the tiles and an efficient enhancement rate R=9 is achieved based on the tile's default status. The Enhanced Annual Generation of the piezoelectric power was further modelled based on the Enhanced Daily Generation and the actual running days of the library through the year.

5.2.4 Tiles Deployment Strategy

It should be noted that the number of tiles along the pathway (variable n in Equation 3) can differ according to the size of the tiles and their deployment method. In general, the most efficient pavement is when the pedestrian steps on every tile one by one to maximise the impact caused by the footsteps. Hence the length of the pathway and the size of the tile have to be considered by applying Equation (4).

$$n = \frac{L_l}{L_T} \tag{4}$$

Here L_l means the length of the pathway, while L_T represents the length of the tile side which is in line with the pathway. Figure 35 demonstrates two different tile arrangements, depending on the tile orientation. Twelve tiles with the same size are assumed to be deployed to cover a specific area. The lengthwise arrangement is applied in Figure 35a) while the widthwise arrangement is used in b). It can be seen that only four tiles could be potentially activated in the first type of arrangement, while in case of the second type of arrangement, it would be six. Thus the arrangement of the piezoelectric tiles is a variable that affects the piezoelectricity production in the main walking direction.

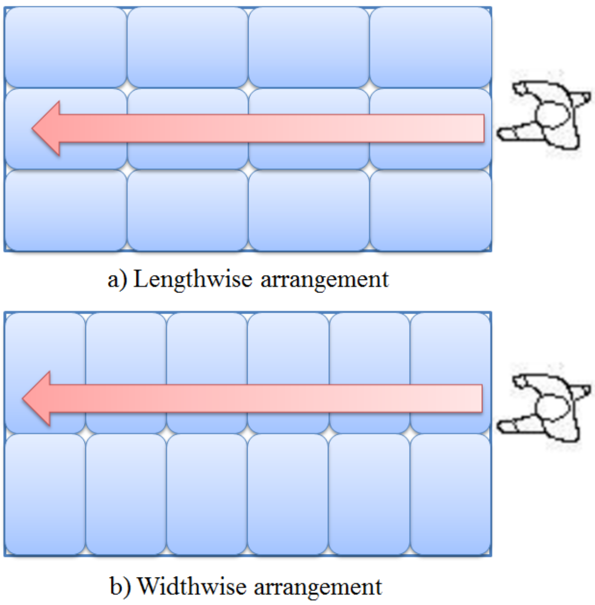


Figure 35. Two types of piezoelectric tile deployment.

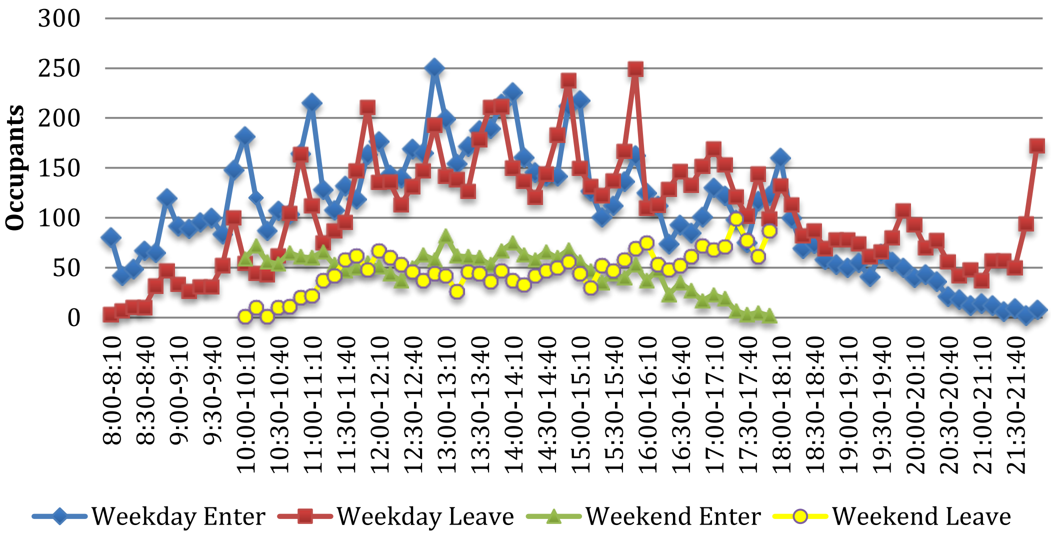
In this study, the tile deployment strategy is employed to optimize the design of piezoelectric harvester pavement for estimating the maximum energy harvesting potential. The direction, length and width of the pathways in the library building were determined by measurements of the actual building. The information was then used as input data into AutoCAD software to generate an optimized deployment scenario with the maximized n variable.

5.3 Results and Discussion

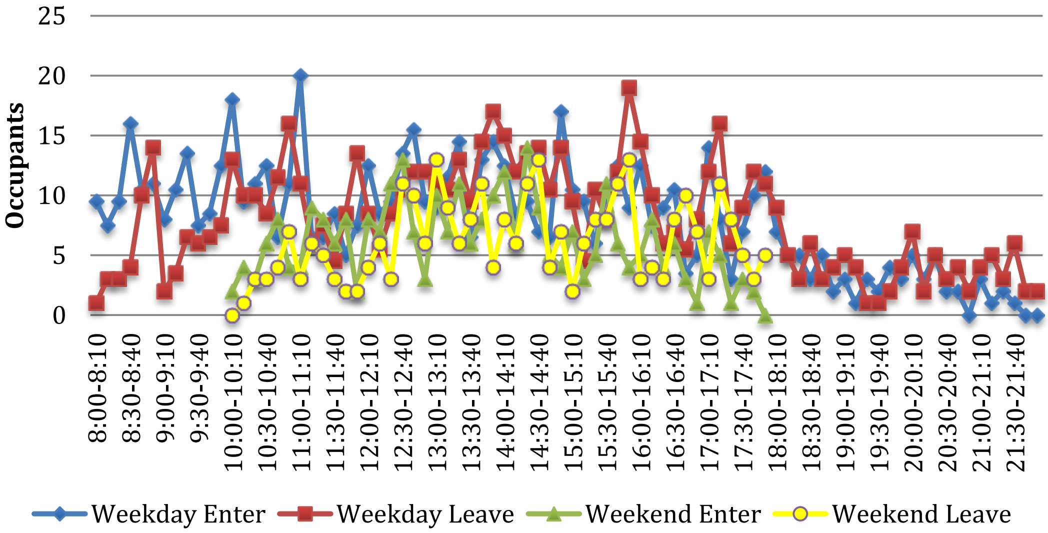
5.3.1 Mobility Pattern of the Library Users

Using the data collected from the door counts, the student mobility graphs were constructed. Figure 36(a) shows the number of library users that walk through the Main Entrance (A in Figure 34) of the library building on a typical weekday and a typical weekend day. The peak periods with over 250 entrances were identified for the period from 12:50PM to 1:00PM, and nearly 250 people left the building at the end of the lecture hours (from 15:50PM-16:00PM). However the number of occupants using the building fluctuates during the day. Several peaks appear on the hour while the population decreases in the middle of each hour. This is due to students' use of the library between classes over the weekdays.

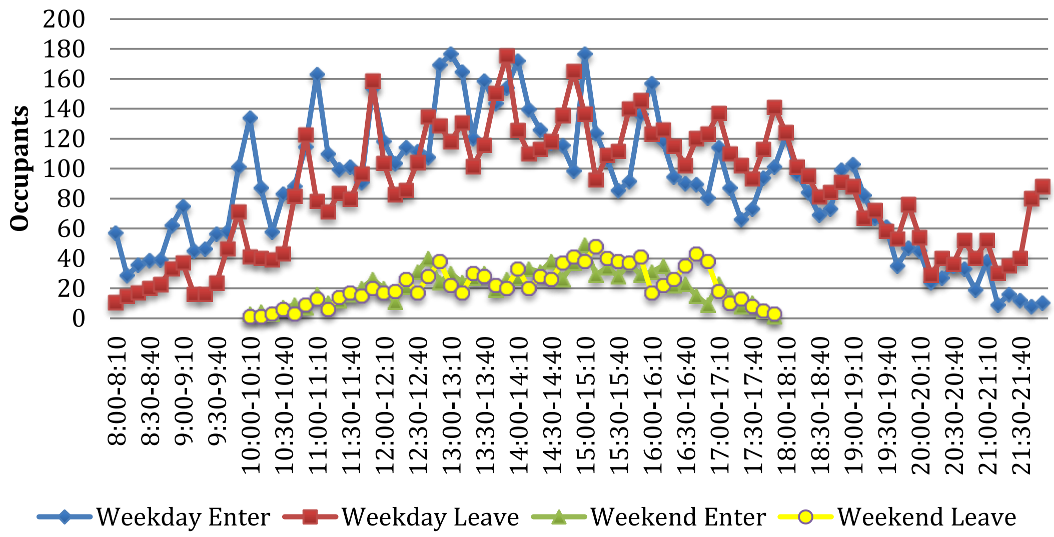
However, the number of occupants shows a difference in weekend use patterns. The overall total number of occupants is lower and the relatively flat occupancy curve comparing to the weekday trend indicates fixed students' use of the library as a study area. The fixed students have limited mobility in the library with low contribution to the overall foot traffic.



a) Main Entrance



b) Cafeteria



c) Check in Spot

Figure 36. Student mobility pattern on weekday and weekend at different locations

The foot traffic results at the Cafeteria (points B marked in Figure 34) are presented in Figure 36(b). The overall traveling population in this location was found to be considerably lower comparing to the main entrance, with the average occupancy reaching 2 persons per minute. In general, the cafeteria is more crowded in the morning than in the afternoon. There is no obvious difference in the weekend and weekday occupancy frequency. This is partly due to the size of the cafeteria which restricts the number of customers entering this area.

Figure 36(c) shows the pattern of library users at the check-in point C marked in Figure 34. The weekday pattern represents strong regularity similar to the trend observed at the Main Entrance. If the peaks in mobility are compared between the two areas, it can be seen that the trend at the check-in point is related to the Entrance peaks, although with lower value. The reason for this difference is due to the students that use the library for other purposes rather than borrowing books.

The results of daily mobility in the new library are summarized in Table 12. First of all, the reliability of the door count method is approved by the small differences between the Enter and Leave numbers, within an average tolerance of 2.6%. This variation is due to the measurement error mainly during the high occupancy density periods during the peak hours in the Main Entrance and Check-in Spot areas.

Secondly, from the Table it is obvious that the overall population over the weekend days at the three considered spots decrease rapidly comparing to the weekdays. Moreover, it can be seen that the Main Entrance area is the busiest spot receiving over 17,000 crossings on a typical weekday, followed by the Check-in area with approximately 14,600 crossings. The Cafeteria contributes little to the overall library mobility.

Table 12. Student mobility statistics on a typical weekday and a typical weekend day.

	Weekday				Weekend Day			
	Enter	Leave	Tolerance	Total Crossing	Enter	Leave	Tolerance	Total Cross-ing
Main Entrance	9004	8823	2.01%	17827	2297	2259	1.65%	4556
Cafeteria	673	671	0.30%	1344	296	297	0.34%	593
Check-in Spot	7434	7165	3.62%	14599	1031	1056	2.00%	2087

5.3.2 Potential Piezoelectric Power Generation

Based on the mobility statistics and the results of high traffic area location, an optimized pavement design is proposed for the tiles deployment strategy. The areas with high energy harvesting potential are highlighted in Figure 37.

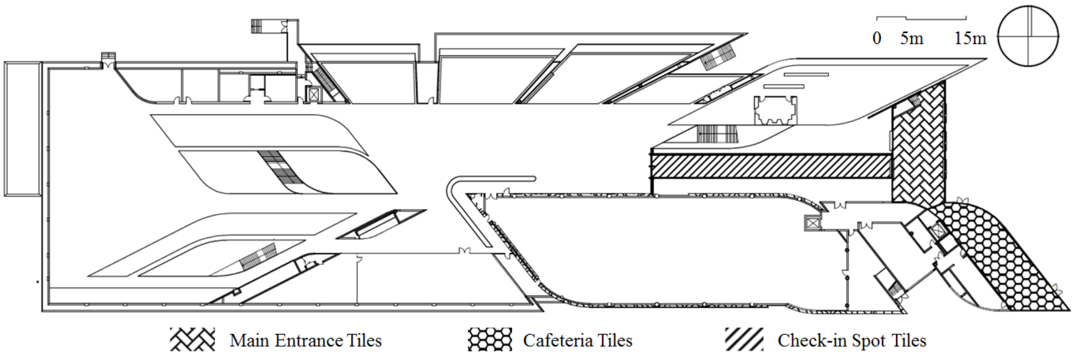


Figure 37. Ground level Floor Plan of the new library with highlighted piezoelectric tiles deployed areas.

These areas include the central cross between the Main Entrance and the gates towards the hall, the two doors in the cafeteria and the pathway linking the hall and the check-in spot. The Pavegen Tiles are selected as the piezoelectric generator to cover all the nominated areas. The parameters of the highlighted areas, as well as the tiles are listed in Table 13.

Table 13. The parameters of the energy harvesting areas and the piezoelectric generator.

	Path Width[a] L_w (m)	Path Length[b] L_l (m)	Covered Area A (m^2)	Tile Length L_T (m)	Tile Width L_T (m)	Tile Area A_T (m^2)	Total Tiles N
Main Entrance	9.2	18	165.6	0.6	0.45	0.27	614
Cafeteria	7.5	22	165	0.6	0.45	0.27	610
Check-in Spot	4	40.2	160.8	0.6	0.45	0.27	596

[a] An equivalent width due to the irregular covered area.

[b] An equivalent length calculated from Path Width and Covered Area.

According to the tile deployment strategy, L_T is defined as the Tile Width measurement since the widthwise arrangement provides higher possibility of footstep impact. Hence the value of n is further determined as the number of Activated Tiles deployed along the pathway based on Equation (4), rather than the total amount of tiles paved on the nominated harvesting area. Using Equation (3) the electrical power produced by the piezoelectric generator can be calculated and the results are listed in Table 14.

Table 14. The daily piezoelectric power generating potential of the library.

	Activated Tiles n	People Count[a] M	Energy Generated per Step E (w*s)	Enhance-ment Rate[b] R	Daily Power Generation W (kWh/day)
Main Entrance	40	14035	7	1	1.09
Cafeteria	49	1129	7	1	0.11
Check-in Spot	89	11024	7	1	1.91

[a] An average number of student mobility in 7 days including 5 weekdays and 2 weekend days.

[b] No enhancement occurred as the Single Impact Method is used.

The calculation reveals that the average daily energy harvesting potential through the deployed piezoelectric tiles is 3.11 kWh per day. An important parameter for consideration is the total versus active tiles that could be activated by a single pedestrian. In this study, a total number of 1820 Pavegen Tiles were assumed for deployment but only a maximum of 178 tiles are predicted to be activated by a single pedestrian, leaving nearly 90% idle tiles per pedestrian.

With integration of the plucked method in the piezoelectric tiles, the enhanced piezoelectric energy generations with the annual energy generating prediction are shown in Table 15.

Table 15. The enhanced piezoelectric power generation and the annual energy generating potential.

	Daily Power Generation W (kWh/day)	Annual Generation W_a (kWh/year)	Enhance-ment Rate R	Enhanced Daily Generation W' (kWh/day)	Enhanced Annual Generation W_a' (kWh/year)
Main Entrance	1.09	385	9	9.8	3463
Cafeteria	0.11	39	9	1.0	353
Check-in Spot	1.91	671	9	17.2	6072
SUM	3.11	1095		28.0	9888

5.3.3 Energy Demand Offset and Greenhouse Gas Mitigation

The economic contribution of piezoelectric energy harvesting on the building's energy demand offset is further estimated based on the renewable power generating potential. According to the library's energy consumption profile, the Enhanced Annual Generation of piezoelectric harvesters is able to replace 0.5% of the total energy usage of the library, which is supplied by the New South Wales power grid. When the running stage costs are considered, the application of piezoelectric harvesters will save AU$540/year, as shown in Table 16.

On the other hand, the greenhouse gas mitigation potential of the piezoelectric harvesters that are applied to the library is investigated based on the clean energy production and the emission factors obtained from the National Greenhouse Accounts (NGA) Factor Workbook. The results in Table 16 indicate that more than 10 tonnes of greenhouse gas emissions can be reduced by the piezoelectric energy harvesting approach.

Table 16. The potential economic and environmental benefits obtained by integrating 1820 piezoelectric energy tiles in the library building.

Enhanced Annual Generation	Economic Benefits		Environmental Benefits	
	Energy Price[a]	Running Costs Saving	Emission Factor[b]	Greenhouse Gas Mitigation
(kWh/year)	(AU$/kWh)	(AU$/year)	$kgCO_2$-e/kWh	$kgCO_2$-e/year
9888	0.055	543.84	1.07	10580.16

[a] Average annual electricity prices of New South Wales, Australia [263].

[b] Greenhouse Gas Emission Factors for New South Wales in Australia from National Greenhouse Accounts (NGA) Factors Workbook [264].

5.3.4 Density Flow Evaluation Indicator

Considering the observation revealed through the model of this study, an evaluation indicator termed as Density Flow, that reflects the power harvesting capacity of a nominated area, is proposed. Density Flow is the total number M of pedestrians passing through a given pathway width L_w at a given time T. This indicator can be presented with the following formula:

$$\varepsilon = \frac{M}{L_w T} \tag{5}$$

With the proposed indicator, the location of high frequency areas for piezoelectric energy harvesting can be addressed simply and qualitatively. A comparison of the Density Flow indicator between the Main Entrance area and the Check-in Spot area for a 14 hour time period is shown in Table 17.

Table 17. Qualitative comparison of high mobility places with varied Path Width using Density Flow.

	Total Crossing M	Path Width L_w (m)	Time Span T (hour)	Density Flow ε
Main Entrance	17827	9.2	14	138
Cafeteria	1344	7.5	14	12.8
Check-in Spot	14599	4	14	261

The higher Density Flow at the Check-in Spot reveals that the energy generating potential here is higher than the Main Entrance even though the Check-in area receives smaller traffic and have fewer tiles covered. The smaller amount of mobile population does not necessarily lead to fewer footsteps, because the path to the Check-in Spot is much narrower (4 m) than the Main Gate (9.2 m) of the library, as presented with the highlighted areas in Figure 37. This results in potentially more effective use of the pedestrian footsteps on the Check-in path comparing to the Main Entrance area under the condition that deploys comparable number of piezoelectric tiles.

Apart from the width of the pathway, time could also affect the evaluation of the piezoelectric power harvesting potential. The piezoelectric generator would be activated more frequently during a short period of time. Another example is provided in Table 18 to show the varied Density Flows of the same deployment area on different days.

Table 18. Qualitative comparison of mobility in Cafeteria with varied Time Span using Density Flow.

	Total Crossing M	Path Width L_w (m)	Time Span T (hour)	Density Flow ε
Weekday	1344	7.5	14	13
Weekend Day	593	7.5	8	10

In the Cafeteria, the Total Crossing number in a typical weekday is more than twice higher than during a weekend day. However, the shorter opening hours on weekend days (8 hours) than weekdays (14 hours) narrows the difference of the power harvesting capacities between the weekday and weekend day.

5.4 Conclusion

In this work a prospective study is performed to model optimisation of piezoelectric tile pavement in a library building and examine the energy harvesting potential. The building was a newly built library at Macquarie University with more than twenty thousand daily crossings. During the model analysis, the key findings are:

- The number of pedestrians, the number of tiles that are activated along the pathway and the energy harvesting efficiency from a single step are the main parameters that affect the piezoelectric energy harvesting potential.

- Locating high traffic areas is critical for optimisation of the piezoelectric energy harvesting efficiency. Mobility analysis should be applied when determining the optimised tile deployment districts.
- The study involved energy potential modelling using 1820 Pavegen tiles paved at 491.5 m^2 area in three identified hot spots with high frequency pedestrian traffic with a daily total average of 26,188 crossings. The tiles occupy 3.1% of the total floor area of the library.
- The total annual energy harvesting potential of the pedestrian crossing energy for the proposed optimised tile pavement model is estimated at 1.1 MWh/year.
- With integration of the plucked method in the piezoelectric tiles which is still under development, the total energy potential of the tile arrangement considered in this study can potentially increase to 9.9 MWh/year, which will be approximately 0.5 % of the total energy usage of the library building.
- Under the modelled tile arrangement, the piezoelectric energy harvesters can save AUS$540 of the annual running costs of the library building and reduce over 10 tonnes per annum of greenhouse gas emissions by replacing the electricity from the power grid.
- A simplified density flow evaluation indicator is proposed, which can qualitatively evaluate the power harvesting potential of the considered area based on the number of pedestrians per unit time. This indicator can be used to compare the piezoelectric harvesting potentials among different districts and provides benchmark for optimisation plans.

Although the piezoelectric energy harvesting products are still not competitive than other renewable energy harvesting techniques, such as solar and wind energies, the piezoelectric power harvesting technology is of great interests in the development of indoor energy harvesting approaches. This technology is expected to make more contributions for the future exploitation and with further reduction in its cost, due to the rapid breaking through on material developments, design innovations as well as the manufacturing revelations. The work we presented here draws a solid starting line for the wide spread use of piezoelectric harvester in the near future.

Chapter 6 Energy Recovery Potential Analysis of Spent Coffee Grounds Pyrolysis Products

6.1 Introduction

The conflict between the increasing energy demand and the fossil fuel depletion, coupled with mounting evidence of climate change, place the need for diversification of energy sources in a significant position to secure our energy supply [167, 178, 265]. Biomass, as one of the most promising alternative energy sources, offers many attractive features for fossil resource displacement, including zero net releases of carbon dioxide [136], and abundant feedstock sources [144, 266]. Biomass can be efficiently converted into useful forms of energy using a number of different processes. The main process technologies can be classified into three categories: thermo-chemical, bio-chemical and mechanical extraction [167].

Pyrolysis is one of the most developed thermochemical conversion techniques that can be applied to achieve thermal decomposition of biomass in the absence of oxygen to derive bio-char, bio-oil and biogas [267, 268]. The yields of these pyrolytic products are able to be adjusted by controlling the pyrolysis temperature and heating rates with a 95.5% fuel-to-feed efficiency [269, 270]. For the production of bio-char, a low temperature, slow heating condition, termed as carbonisation, is preferred, while the maximum yield of bio-oil is achieved in a low temperature and high heating rate process, known as flash pyrolysis. The process conducted in a high temperature but low heating rate condition with long gas residence time, is favourable for the high biogas production [153].

Utilisation of pyrolysis products has been performed by many studies [157, 158, 271-273]. Bio-char is widely used as a soil amendment to improve crop yields due to its very high surface area structure, which can retain soil-water and nutrients [156]. Its positive influence on plants, as well as heat insulation property, made bio-char a substrate material for the green roofs [158]. Bio-oil is expected to play a dominant role as a substitute for the crude oil due to its significant potential for the production of energy through direct combustion. Czernik and Bridgwater [18] reviewed several options for bio-oil combustion, including the feedstock in boilers, diesel engines, gas turbines, and Stirling engines [160]. Bio-oil can be further upgraded for a better quality to make it suitable for engine applications [274]. As a mixture of volatile gases, which consist primarily of CO_2, CO, CH_4 and higher hydrocarbon compounds, pyrolytic biogas can also be used as a combustible fuel.

Biomass can also be combusted directly to produce heat or heat and power simultaneously. However, the efficiency of biomass combustion in conventional stove can reach only 10-20%, depending on feedstock properties [275]. In the case of standalone power plants the efficiency for electricity production typically varies around 20-30% [276]. According to Huang, et al, [150], the energy conversion efficiency can be greatly improved by providing heat and power simultaneously (CHP).

Coffee is a global favourite interactive beverage prepared from roasted coffee beans, with approximately 500 billion cups consumed every year [277]. At Macquarie University alone, nearly 900,000 cups of coffee were consumed annually with substantial quantities of waste generated as coffee grounds from this beverage [278]. Currently, spent coffee grounds have no significant market and hence are problematic for disposal. In addition to its large amounts of organic compounds, such as fatty acids, lignin, cellulose and hemicellulose, the disposal of coffee grounds in a landfill or by incineration potentially present serious environmental problems [279]. However, the high organic compounds make spent coffee grounds highly attractive as biomass for obtaining biofuel and valuable products [280, 281]. Moreover, the use of coffee wastes avoids competition with food crops compared to conventional lipid feedstock, such as soybeans and rapeseed [282].

The energy recovery processing of spent coffee grounds has been performed in previous studies. A complete utilisation approach of spent coffee grounds was conducted by Vardon, et al. [282] using slow pyrolysis to produce biodiesel, bio-oil and bio-char. Catalytic pyrolysis of coffee grounds was intensively investigated by Kan et al. [283] with a coupled TG–FTIR analysis. The study confirmed that the addition of catalysts increased the concentrations of CO_2 and CO in the produced gas evolved during coffee grounds pyrolysis. Co-pyrolysis of coffee wastes and polypropylene was performed by Zanella, et al. [284] at different volumetric fractions of each feedstock. The effect of polypropylene fraction in the mixture on pyrolysis product distribution was investigated. So far the studies have been limited to only combustion and pyrolysis of the coffee grounds. A comparative analysis of the energy potential of coffee grounds through different processing technologies has still not been performed.

In this work, the spent coffee grounds were collected as biomass feedstock from a coffee shop in a sustainable building at the Macquarie University Campus and were subjected to different biomass conversion processes. The energy property of the decomposed products were analysed to examine the energy generating potential of the coffee grounds. The objective of this work was to evaluate and compare the bio-energy production potential of coffee grounds, so that they can be applied as a renewable energy source to offset the building's overall carbon footprint from energy consumption.

6.2 Experimental Section

6.2.1 Biomass Materials

Spent coffee grounds were collected from a cafeteria in the library building of Macquarie University, Sydney Australia. The spent grounds were first air dried in room temperature for 48 hours. The sample was then milled and sieved to produce samples with a diameter range between 0.18-0.21 mm. The moisture content (MC) of the sample was measured by weight difference after 1 g of sample was heated to 105 ^{0}C in N_2 atmosphere for 3 hours. The ash content was determined by firstly heating 1 g of sample to 500 ^{0}C in a furnace with air supply and maintained at this temperature for 30 min. The heating was then ramped to 815 ^{0}C and held for another 60 min with a constant flow of air. The weight of the solid remainder was measured to calculate the ash content. The volatile matter (VM) was analysed according to the weight difference between 1 g sample before and after heating at 900 ^{0}C in N_2 environment for 7 min, excluding the moisture content. Fixed carbon (FC) was then obtained by subtracting the percentages of moisture, volatile matter and ash from the sample. The proximate analysis results, ultimate analysis results and the gross calorific value (HHV) of the sample, are listed in Table 19. These analyses were performed according to AS1038 part 5.

Table 19. Proximate and ultimate analysis of spent coffee grounds.

Proximate Analysis (wt %)[b]				Ultimate Analysis (wt %)[b]					HHV (MJ/kg)
MC[a]	Ash	VM	FC[c]	C	H	N	O[c]	S	
8.1	1.7	82.0	16.3	54.5	7.1	2.4	34.2	0.1	23.2

[a] Air dry basis. [b] Dry basis. [c] Calculated by difference.

6.2.2 Pyrolysis of the Biomass

6.2.2.1 Fourier Transform Infrared Spectroscopic (FTIR) Analysis.

FTIR analysis was used to identify the functional groups on the sample. The spectra of the unprocessed spent coffee grounds, in addition to the pyrolysis liquid and bio-char were recorded using a Nicolet 6700 FTIR spectrometer applying an Attenuated Total Reflectance (ATR) method with a diamond crystal. The FTIR spectra were measured in the 4000 to 400 cm^{-1} range by a total number of 32 scans with a spectral resolution of 4 cm^{-1}. Omnic Spectra software was employed to assist with interpretation of some of the data.

6.2.2.2 Thermogravimetric Analysis (TGA).

In order to analyse the mass loss of the spent coffee grounds during heating, TGA (TGA/DSC 1 STAR^e system, Mettler Toledo, Ltd.) was applied to heat the samples continuously from room temperature to 1000 ^{0}C at two different heating rates, 10 and 60 ^{0}C/min. Nitrogen gas with a flow rate of 20 mL/min was fed to the reaction chamber as the carrier gas. Differential thermogravimetric curves (DTG, in units of wt %/^{0}C) were obtained through differential calculations of the thermogravimetric (TG, in units of wt %) data.

6.2.2.3 Computer-Aided Thermal Analysis (CATA).

Specific heat of the spent coffee grounds sample during pyrolysis was determined using a CATA technique. The analysing apparatus consisted of an infrared image gold furnace and arrangement of internals for heating of a packed bed of sample, as described in previous studies [285-287]. The biomass sample was manually packed at a standard volume (approximately 2.4 cm^3) in a silica glass tube, where the outer surface was coated with carbon soot for a uniform emissivity through the glass. Argon gas with a flow rate of 5 mL/min continuously flowed through the glass tube as carrier gas to carry the pyrolytic volatiles out of the glass tube. Then the glass tube with the sample was inserted into the centre of a graphite heating element. The assembly was also kept under an inert argon atmosphere with a separate flow rate of 50 mL/min in the sealed sector of the furnace. Three chromel-alumel (K type) thermocouples were placed in the graphite tube, on the surface of the sample and in the centre of the sample respectively to control and measure the heating process. The temperature-programmed heating process was conducted at heating rates of 10 and 60 ^{0}C/min from the ambient temperature until the graphite heating element reached 1000 ^{0}C. The logging of the temperatures was obtained at 1 Hz logging rate and the data was applied in an inverse numerical model to calculate the specific heat.

The principle of the calculation was to sub-divide the sample into a grid with an assumed number of nodes across its radius and calculate the heat balance for each node [288]. The heat balance for the node was determined as the accumulated heat, which equals the difference of input and output heats from the node. The estimated specific heat had apparent values that showed corresponding increases or decreases when an endothermic or exothermic heat of reaction evolved during the pyrolysis [289].

6.2.3 Analyses of Products from the Pyrolysis

6.2.3.1 Gas Chromatographic (GC) Analysis of Volatiles.

The pyrolytic volatiles evolved from the biomass sample were analysed using an MTI Activon M200 series micro gas chromatograph instrument. In each run, 50 mg spent coffee grounds sample was packed inside the silica tube using the similar assembly method with the CATA analysis. Helium gas at a flow rate of 25 mL/min controlled by a mass flow controller was passed through the sample as the carrier gas while the sample was heated from the ambient room temperature to 1000 ^{0}C at constant heating rates of 10 and 60 ^{0}C/min. As the volatiles evolved during biomass pyrolysis were mainly comprised of H_2, CO, CO_2, CH_4 and other light, such as oxygen-containing compounds with a low carbon number [290], a calibration gas mixture of 3% CO, 3% CO_2, 1% CH_4, 1% C_2H_4, 1% C_2H_6, and 1% H_2 in ultrahigh purity argon was used to calibrate the instrument prior to the experiment. During the experiment, the produced off-gas from the reactor was first condensed by an ice-water coil to remove moisture and condensable organic volatiles before it was subjected to the micro GC for analysis. The GC equipped with thermal conductivity detectors consisted of a molecular sieve 5A column heated at 60 ^{0}C and used to determine H_2 and CO, while a Poraplot U column, kept at 40 ^{0}C, was employed to measure CO_2, CH_4, C_2H_4 and C_2H_6. The evolution rate of each gas species was illustrated as a weight percent of the initial sample mass per minute. The gross calorific value (HHV) of the biogas was determined based on the standard HHV of each component of gaseous volatiles with their relevant evolution rates at 500 ^{0}C.

6.2.3.2 Gas Chromatograph – Mass Spectrometric (GC-MS) Analysis of Bio-oils.

The pyrolysis liquid bio-oils were produced by heating 1 g of spent coffee grounds. The sample was heated from room temperature to the sample temperature of 500 ^{0}C with different heating rates of 10 and 60 ^{0}C/min, in an inert argon (5 mL/min) insulated environment. The sample temperature was determined as the average value of temperatures measured at the sample surface and centre. Glass wool was fully packed at the down-stream end of the reactor tube (in relation to the direction of gas flow), to capture the condensable volatiles at room temperature. Once the pyrolysis process was complete, the retained bio-oil held by the glass wool was dissolved using dichloromethane (DCM) solvent to obtain bio-oil-DCM solution. N,O-bis (trimethylsilyl) trifluoroacetamide with 1% trimethylchlorosilane (BSTFA+1% TMCS) was added to solutions to derivatise the bio-oil products [291]. The prepared sample solutions were then analysed by an Agilent 7890A gas chromatograph with a 60 m DB5-MS column coupled to a Pegasus 4D time-of-flight mass spectrometer. Before the analysis, the instrument was auto-tuned using perfluorotributylamine (PFTBA) as a calibrator. Then the gas chromatograph started in isothermal mode at 40 ^{0}C for 2 min, ramped at 4 ^{0}C/min to 310 ^{0}C, and maintained in isothermal mode at the temperature for 40 min. Through the derivatisation process, the hydroxyl functions, as well as other labile groups of bio-oils, were derivatised into relatively stable trimethylsilyl groups for analytical purposes by GC-MS. In the report stage, molecules were reported as underivatised if original compounds were identified, otherwise were listed as trimethylsilyl derivatives.

To determine the HHV of the bio-oil, a massive bio-oil production method was employed. A big pyrolysis reactor was used to heat 130 g coffee grounds samples in argon (50 ml/min) insulated environment at 500 ^{0}C for four hours. The gaseous volatiles were then trapped and condensed in a glass bottle, where the condensation temperature was maintained by an ice-and water bath. The moisture content and the ash content of the bio-oil were determined via ASTM D95 and AS 2438.8, respectively. The HHV of the bio-oil was analysed according to ASTM D240 and was carried out on a Leco AC600 calorimeter.

6.3 Results and Discussion

6.3.1 Changes in Chemical Bond Structure with Pyrolysis Temperature

The FTIR spectra obtained for the coffee grounds sample and its subsequent pyrolysis liquid and bio-char are shown in Figure 38. The stacked transmittances indicated that some of the detected functional groups were common across the pyrolysis processes of the sample while others were broken during the heating, representing the signature by-products of thermal degradation.

In both the raw and liquid products, the presence of a broad band at between 3400 and 3200 cm^{-1} expressed the existence of vibration modes, mainly attributed to O-H functional groups and a minor contribution of N-H groups. Similarly, the C-H stretch vibrations for methyl and methylene groups were evident in both the raw and liquid fractions between 2970-2845 cm^{-1}. The two sharp peaks during this range had been previously identified in roasted coffee and attributed to the presence of caffeine and lipids [292]. The existence of caffeine was further corroborated by the appearance of two characteristic bands lying at about 1700 and 1655 cm^{-1}, which were identified as markers of caffeine [293, 294]. The stretching vibration of C=C-C bond in aromatic ring structure was visible in both raw sample and bio-oil, as bands falling in the frequency range of 1510-1450 cm^{-1}. The strong aromatic nature of the compounds is further confirmed by a series of peaks within the 900-670 cm^{-1} range, signalling the possible presence of additional C-H groups with aromatic out-of-plane bend. Phenol or tertiary alcohol with O-H bend was observed by a reading of 1410-1310 cm^{-1}. A range of peaks in the raw sample and bio-oil between 1050-1270 cm^{-1} were indicative of ether compounds, specifically a C-O stretch and a likely aryl-O stretch. The peak detected in the raw material between 1055-1000 cm^{-1}, which was absent in the bio-oil spectra, suggested existence of cyclohexane ring that is necessary for lactone formation [295].

Both charcoals produced at heating rates of 10 and 60 ^{0}C/min had no remaining significant peaks, suggesting that the organic compounds were degraded or removed from the char during the heating process. The cleavage of these functional groups likely contributed to the higher mass losses during thermal decomposition and gas product evolution. The weak peaks between 1610-1550 cm^{-1} corresponded to carboxylate or carboxylic acid salt. Other peaks detected below 1055 cm^{-1} represented the presence of silicates found in the ash.

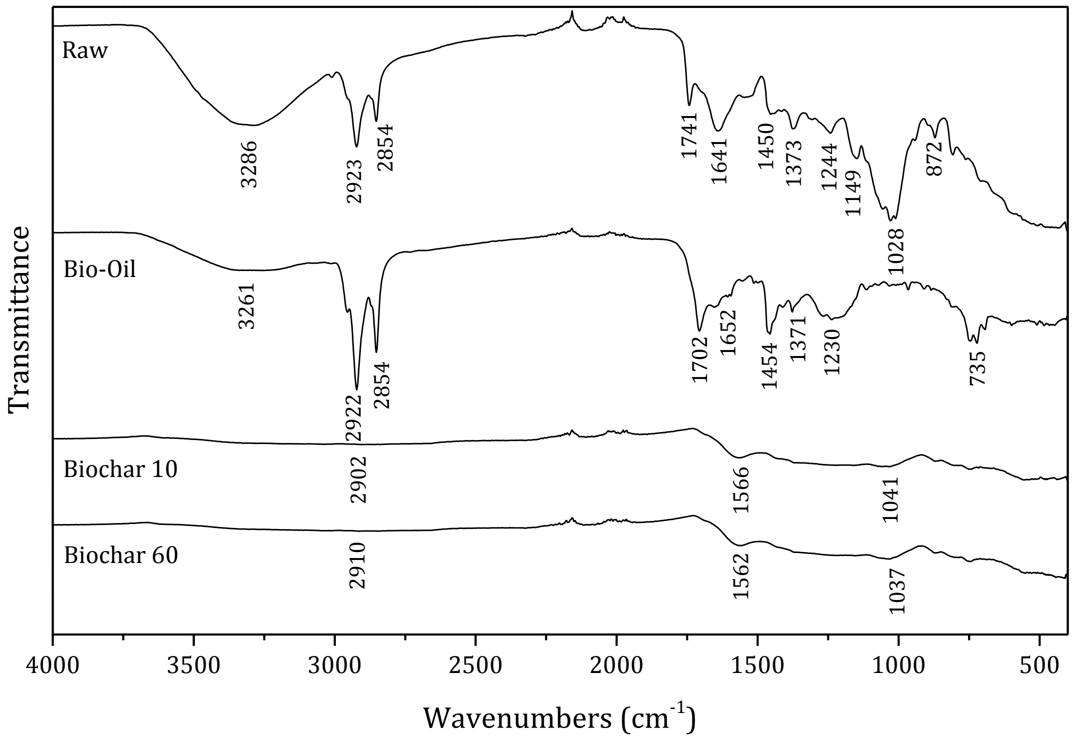


Figure 38. FTIR spectra of spent coffee grounds and its subsequent pyrolysis products.

6.3.2 TGA Results

The residual mass (TG) and rate of mass loss (DTG) superimposed to the temperatures up to 1000 ^{0}C for spent coffee grounds at heating rates of 10 and 60 ^{0}C/min are shown in Figure 39. The heating rate had a significant effect on the thermal behaviour of the coffee grounds, where the positions of the peaks in both TG and DTG curves shifted to higher temperatures as the heating rate was increased from 10 to 60 ^{0}C/min. This phenomenon is common for non-isothermal heating [283, 296], as the poor heat conduction of the biomass leads to a lower heat diffusion at a higher heating rate. At the low heating rate, the heat is able to transfer from the surface of the biomass to its centre within a sufficient time period, generating a narrow temperature gradient across the particle. At the high heating rate, the relatively steep temperature gradient causes the delay of reactions across the particle, resulting in lag of reaction occurrence shown as peak shifts [290].

Specifically, the decomposition process of the spent coffee grounds involved three discrete stages. In the first stage, a small peak summiting at about 75 ^{0}C occurred between 30-150 ^{0}C at the heating rate of 10 ^{0}C/min, followed by a similar peak centred at 105 ^{0}C in the temperature range of 50-170 ^{0}C at the 60 ^{0}C/min heating rate. The peaks in the DTG curves corresponded to the evaporation of adsorbed water in the sample. The second stage of the pyrolysis included the main complex reactions which associated with the most significant mass loss, starting at 150-170 ^{0}C and terminated at about 600 ^{0}C. During this stage, a wide variety of volatiles were decomposed and released from the biomass, contributing approximately to 75 wt % of the sample mass loss as shown in TG curves. The DTG results for the heating rate of 10 ^{0}C/min revealed the most significant peaks at 300 ^{0}C, reaching the highest mass loss rate of 0.6 wt %/^{0}C, while for the 60 ^{0}C/min heating rate, the same peak height was observed at 330 ^{0}C. These peaks can be attributed to the decomposition of hemicellulose in the spent coffee grounds, which corresponded to almost half of the sample dry weight [297]. The decomposition of the cellulose occurs at temperatures higher than hemicellulose decomposition. In the case of the studied sample, the peaks of the cellulose decomposition may be attributed to the thermal behaviour at 335 and 360 ^{0}C for the 10 and 60 ^{0}C/min, respectively, as shown in Figure 39 [298]. The last peak appeared at 390 and 425 ^{0}C according to the reaction lag due to the effect of heating rate, with a mass loss rate of 0.35 wt %/^{0}C. This mass loss is possibly related to the decomposition of the lignin structure, which will be the main contributor to the final mass of the char [299]. The third stage is the last stage of pyrolysis in the range from 600 ^{0}C to 1000 ^{0}C. During this period, the residual solid continuously decomposed at a very slow rate, with a slight loss of weight due to the char consolidation [300].

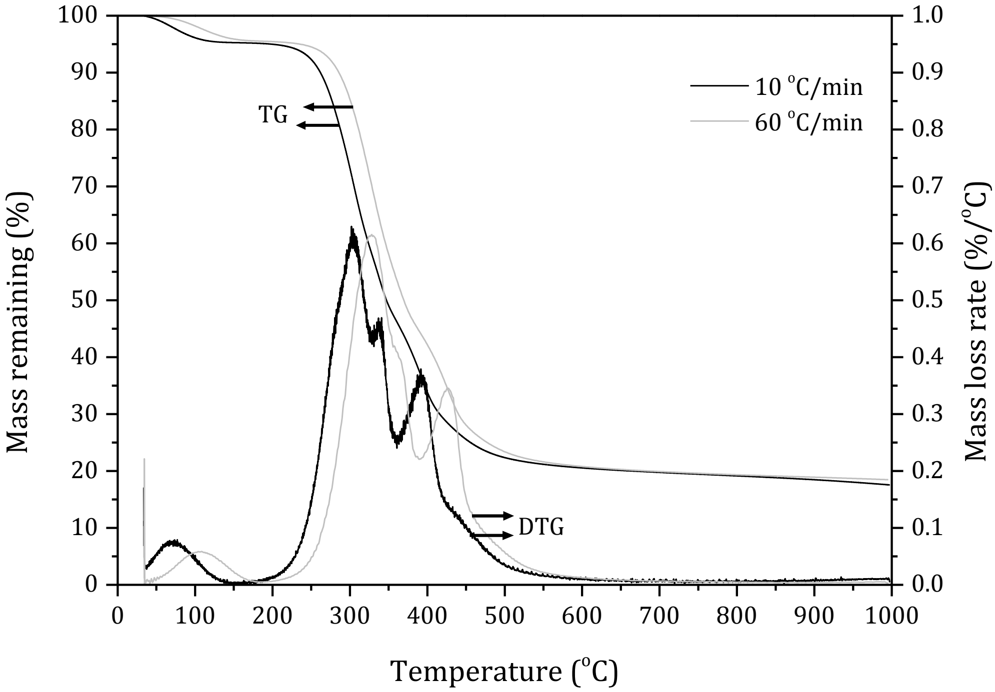


Figure 39. TGA and DTG curves for spent coffee grounds decomposition at heating rates of 10 and 60 ^{0}C/min.

6.3.3 Volatile Evolution and Heat Changes

The apparent specific heat for spent coffee grounds during heating at 10 and 60 ^{0}C/min are shown in Figure 40. The apparent specific heat is the measured specific heat as a function of temperature and includes reaction heat, which is given on a volumetric basis in the figures.

At both the heating rates of 10 and 60 ^{0}C/min, the samples displayed an initial sharp endothermic peak close to 100 ^{0}C, which was ascribed to an endothermic reaction likely to be from the evaporation of bound water. Between 250 and 450 ^{0}C, the sample heated at the 10 ^{0}C/min heating rate showed fluctuations in the specific heat, indicating combined effect of the decomposition of the individual constituents in the biomass, the hemicellulose, cellulose and lignin [301]. The exothermic reaction behaviour was observed at the same temperature range where the maximum mass loss rate occurred in the curves illustrated in Figure 39. As the temperature extended to 1000 ^{0}C, no obvious peak was found in the specific heat for both of the heating rates.

Comparing the specific heat curves in Figure 40, it is found that the slower heating rate of 10 ^{0}C/min represented greater clarity of the individual reactions than the 60 ^{0}C/min, where the peaks were larger and smoother. This is probably due to the corresponding reactions occurring in a range close to the activation temperature at the low heating rate [302].

The corresponding evolution rates of the main volatiles (i.e., CO_2, CO, H_2, CH_4, C_2H_4, and C_2H_6) for both heating rates are also shown in Figure 40. The oxides of carbon exhibited the largest evolution rates, indicating that the CO_2 and CO are the dominant volatile products during coffee grounds pyrolysis. The evolution rate peaks for these two volatile compounds coincided with the exothermic temperature range in the specific heat curves. Methane (CH_4), as a favoured gas for its high energy value, was detected as the third largest volatile product. At the heating rate of 10 ^{0}C/min, the maximum evolution rate of CH_4 occurred at 325 ^{0}C, reaching at about 0.2 wt %/min. Other combustible gases, such as hydrogen (H_2) and light hydrocarbons (including C_2H_4, and C_2H_6) were released between 300-650 ^{0}C, at much smaller concentrations compared to CO_2, CO and CH_4. The generation of H_2 and hydrocarbons are most likely the result of the secondary cracking of the oxygenated compounds [288, 290].

When comparing the evolution rates of the volatile gases at different heating rates, the positive strong effect of high heating rate was identified. As the heating rate was increased, the generation rate of CO_2, CO, H_2, CH_4, C_2H_4, and C_2H_6 increased simultaneously, especially in the temperature range between 200-700 ^{0}C. This phenomenon is in accordance with previous studies [303], and possibly due to their higher concentrations in the off-gas at the 60 ^{0}C/min heating rate [283].

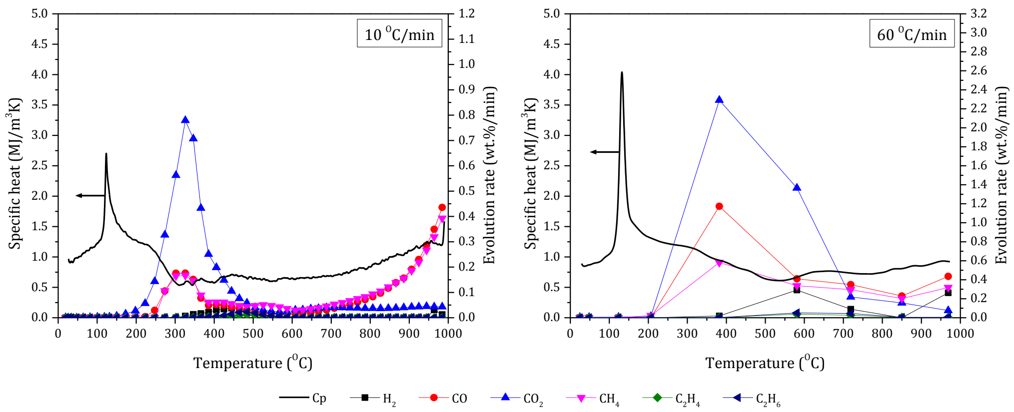


Figure 40. Specific heat and evolution rates of individual volatiles from coffee grounds pyrolysis with the temperature at heating rates of 10 and 60 ^{0}C/min.

6.3.4 Characterisation of Bio-oils

As one of the main products of biomass pyrolysis, bio-oils were collected when the coffee grounds were heated to the terminal temperature of 500 ^{0}C at varied heating rates. The pyrolytic bio-oils are one of the desirable products of pyrolysis as their utilisation potential as bio-fuels for direct combustion or for further upgrading into bio-diesel. For this purpose, the pyrolysis liquids were subjected to detailed evaluation for compound composition identification using GC-MS.

The GC-MS spectra of the bio-oils from spent coffee grounds pyrolysis at heating rates of 10 and 60 °C/min are presented in Figure 41. The major peaks were numbered sequentially and presented according to retention times with corresponding molecules identified in Table 20. The primary products in the collected bio-oil were found in the C_{16}-C_{20} bracket, which were recognised as various groups of organic acids, accounting for more than one third of the compound contents. The compounds were mainly linoleic acid (peak 14), palmitic acid (peak 13) and 1-eicosanoic acid (peak 15). The remainder of the compounds were primarily aromatic organic compounds, including catechol (peak 7), hydroquinone (peak 8) and phenol (peak 3). Caffeine (peak 11) was also detected as one of the main compounds left in the liquid pyrolytic products, correlating with the FTIR results.

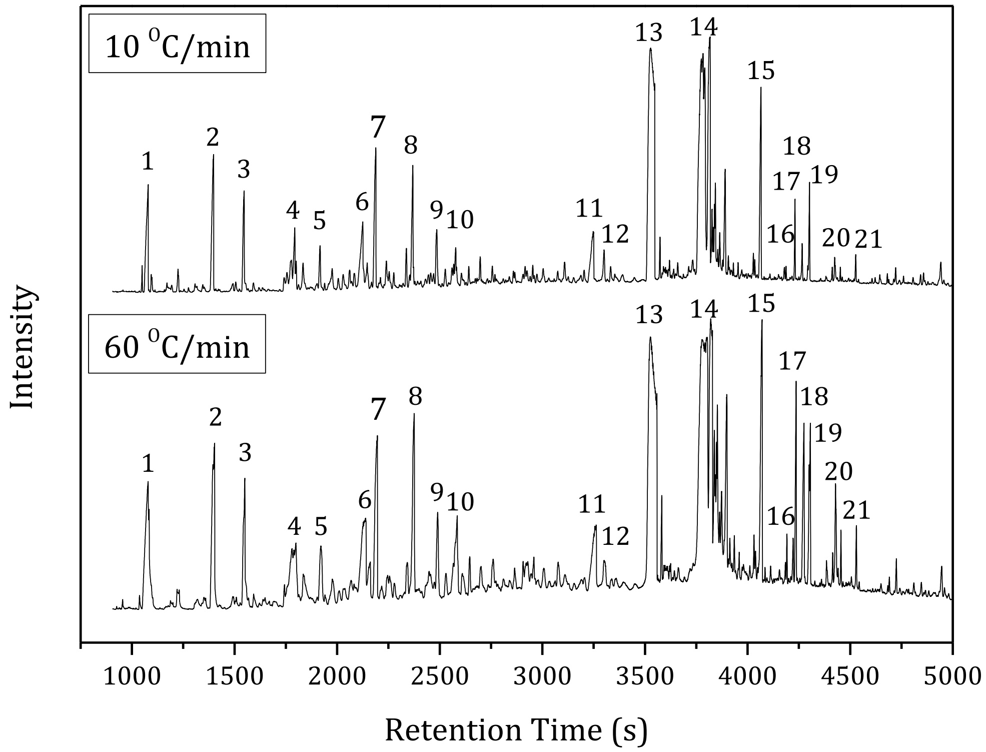


Figure 41. GC–MS spectra for bio-oils from pyrolysis of spent coffee grounds at the heating rate of 10 and 60 °C/min.

The effects of the heating rate on the bio-oil composition and compound contents were also examined in this work. From the comparisons of Figure 41 and Table 20, it showed that the oils produced at heating rates of 10 and 60 °C/min had only minor differences in the composition, while the positive effect on the compound contents was confirmed. The higher heating rate tended to slightly enhance the productions of the major compounds, which were indicated by the higher area percent of the peaks. This effect was in accordance with the previous studies confirming that higher heating rates would improve the quality of bio-oil according to the elemental composition [304].

Table 20. Identification of compounds in the 21 largest GC-MS peaks in bio-oils from pryolysis of spent coffee grounds at heating rates of 10 and 60 °C/min.

Peak No.	Compound Name	Retention Time (s)	Formula	Compound Area (%) from Two Heating Rates	
				10 °C/min	60 °C/min
1	2-ethoxyethyl acetate	1071	$C_6H_{12}O_3$	2.15	3.52
2	furan-2-ylmethanol	1398-1400	$C_5H_6O_2$	2.36	3.28
3	phenol	1500-1553	C_6H_6O	1.43	1.86
4	4-methylphenol	1744-1803	C_7H_8O	2.43	3.09
5	cycloheptanone	1926	$C_7H_{12}O$	0.63	1.14
6	Butanoic acid, di(tert-butyl)silyl ester	2123	$C_4H_8O_2$	2.00	2.61
7	catechol	2193	$C_6H_6O_2$	2.31	2.84
8	hydroquinone	2375-2377	$C_6H_6O_2$	1.72	2.57
9	2-hydroxybenzoic acid	2492-3094	$C_7H_6O_3$	1.18	1.18
10	hexacosane	2591	$C_{26}H_{54}$	1.32	1.39
11	caffeine	3257	$C_8H_{10}N_4O_2$	1.92	2.11
12	hexadecanenitrile	3308	$C_{16}H_{31}N$	0.79	0.63
13	palmitic acid	3524-3553	$C_{16}H_{32}O_2$	13.90	13.14
14	linoleic acid	3780-3895	$C_{18}H_{32}O_2$	25.59	28.67
15	1-eicosanoic acid	4069	$C_{20}H_{40}O_2$	2.53	3.36
16	1,2-benzenedicarboxylic acid, diisooctyl ester	4191	$C_{24}H_{38}O_4$	0.38	0.39
17	2,3-dihydroxypropyl hexadecanoate	4234	$C_{19}H_{38}O_4$	0.64	1.34
18	.psi.,.psi.-Carotene, 1,1',2,2'-tetrahydro-1,1'-dimethoxy-	4270	$C_{42}H_{64}O_2$	0.44	1.59
19	docosanoic acid	4305	$C_{22}H_{44}O_2$	1.03	1.67
20	1-linoleoyl glycerol	4426-4430	$C_{21}H_{38}O_4$	0.41	1.02
21	cholest-7-en-6-one, 3-(acetyloxy)-9-hydroxy-, (3á,5à)-	4529	$C_{29}H_{46}O_4$	0.28	0.40

Palmitic and linoleic acids were the dominant compounds in the bio-oils. The significant contribution to the total peak area indicates that bio-oil produced from spent coffee grounds has great potential for further biofuel production [305]. However, the high acidity property of the bio-oils is considered as a significant disadvantage for their applications as the oils can become corrosive to common construction materials [153, 285]. In order to overcome the limitations, hydrothermal processing is recommended to reduce the acidity and remove the high oxygen content of the bio-oils. Through this process bio-oils can be upgraded to favourable bio-diesel and marketable fuel chemicals [153, 306].

6.3.5 Distribution of Pyrolytic Products

The effect of pyrolysis temperature on mass yield of pyrolytic products is an important characteristic of biomass thermal treatment. The distribution of solid and gas products were obtained according to the mass balance based on the TGA and GC data, respectively. The weight fraction of the liquid product was calculated by the difference. The fraction distributions with different trends at varied heating rates are shown in Figure 42.

As the pyrolysis temperature increased gradually, the yield of bio-char decreased with a rapid increase of bio-oils and steady rise of biogas. The reduction in the char yield in the temperature range from 250 to 450 ^{0}C was consistent with the increase in the volatile matter. The liquid yield achieved maximum value of 66 wt % at 627 ^{0}C with a rapid increase rate and then decreased slowly as the temperature continued to rise. The gas yields represented a different pattern to the liquid yield. After the initial yields started at 250 ^{0}C, the gas fraction increased with a relatively steady rate before the temperature reached 627 ^{0}C, when the increase of gas yield was accompanied by a small decrease of the bio-oil yield. The distribution trends found in this work are consistent with the data illustrated in previous studies [281, 307, 308], indicating that the trend is the result of secondary reactions of bio-oil decomposition triggered by the high pyrolysis temperature. The heating rate showed minor effect on the product distributions. At the heating rate of 60 ^{0}C/min, the liquid yield and gas yield were found to be similar with those at 10 ^{0}C/min. However, the liquid yield decrease represented in the low heating rate was shifted to a lower level at the 60 ^{0}C/min heating rate. This is probably because the higher heating rate postpones the liquid decomposition to a higher temperature over 800 ^{0}C.

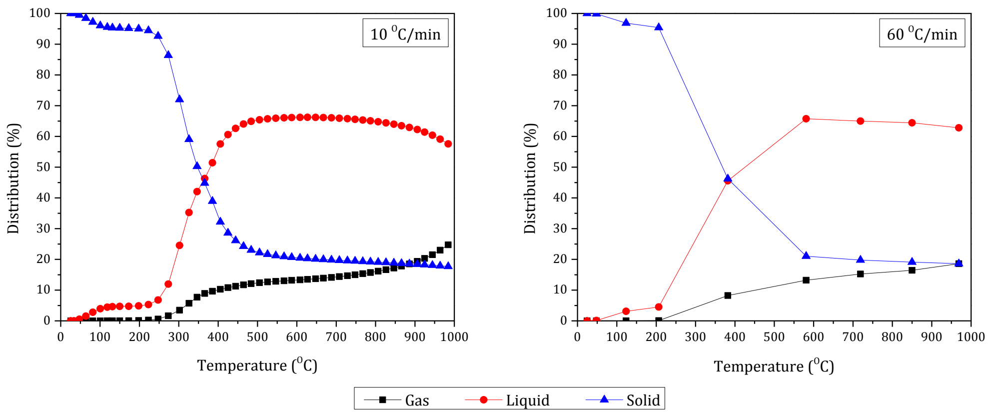


Figure 42. Distribution of gas, liquid and solid products from pyrolysis of spent coffee grounds at heating rates of 10 and 60 °C/min.

The proximate and ultimate analysis, including the HHV of the coffee grounds pyrolytic products produced at 500 °C is listed in Table 21.

Table 21. Analysis of spent coffee grounds pyrolytic products produced at 500 °C.

Products	Proximate Analysis (wt %)[a]		Ultimate Analysis (wt %)[b]					HHV
	MC	Ash	C	H	N	S	O[c]	MJ/kg
Bio-oil	68.9	<0.01	28.9	6.5	5.06	0.07	59.5	17.23
Bio-char	6.6	6.1	82.1	2.9	4.1	0.08	4.7	31.1
Biogas	-	-	38.9	5.85	-	-	55.25[d]	14.84

[a] As receive. [b] Dry basis. [c] Calculated by difference. [d] By measure.

6.3.6 Energy Conversion Efficiency of Biomass Conversion Methods and the Energy Recovery Potential

The fractions of solid, liquid and gas products of pyrolysis of spent coffee grounds at different heating rates of 10 and 60 ^{0}C/min for a maximum processing temperature of 500 ^{0}C are shown in Table 22. The energy $Q_{recovery}$, which could be potentially recovered from the biofuel products are obtained and also illustrated in Table 22, based on the estimated HHV of each of the pyrolytic products and the product distributions. The moisture content in the liquid was included in the calculation for measuring the maximum energy potential of the product. The recoverable energy was calculated using the following relationship between the product distribution and HHV:

$$Q_{recovery} = mass\%_{solid} \times HHV_{solid} + mass\%_{liquid} \times HHV_{liquid} + mass\%_{gas} \times HHV_{gas} \tag{6}$$

Theoretically, the potential energy for the low heating rate was 20.1 MJ/kg, which is in the similar range as for the high heating rate estimated at 20.5 MJ/kg.

Table 22. Distribution and energy recovery potential of pyrolytic products of spent coffee grounds at heating rates of 10 and 60 ^{0}C/min at a maximum temperature of 500 ^{0}C.

Product	10 ^{0}C/min		60 ^{0}C/min	
	Mass (%)	Energy Recovery $Q_{recovery}$ (MJ/kg)	Mass (%)	Energy Recovery $Q_{recovery}$ (MJ/kg)
Solid	22.6%	7.03	25.4%	7.91
Liquid	65.2%	11.23	62.6%	10.78
Gas	12.2%	1.81	12.0%	1.78

The total energy $Q_{pyrolysis}$ required to heat the biomass from ambient temperature to the end processing temperature of 500 ^{0}C at different heating rates were determined by integrating the specific heat (expressed as Cp) curves shown in Figure 40. The integration results revealed that heating the spent coffee grounds from room temperature to 500 ^{0}C at 10 ^{0}C/min rate requires 0.7 MJ/kg of energy, while in case of 60 ^{0}C/min it was estimated at 0.78 MJ/kg.

The energy consumed by the pyrolysis process $Q_{pyrolysis}$, the energy recovered from the pyrolytic products $Q_{recovery}$ and the energy in the spent coffee grounds $Q_{feedstock}$, were then used to calculate a theoretical efficiency of pyrolysis, indicated as η. The thermal losses in the process were ignored here.

$$\eta = \frac{Q_{recovery} - Q_{pyrolysis}}{Q_{feedstock}} \times 100\% \tag{7}$$

The overall maximum efficiency of the pyrolysis process for the pyrolysis of the spent coffee grounds to 500 ^{0}C at heating rates of 10 and 60 ^{0}C were calculated at 83.4% and 84.8%, respectively. It should be noted here that the energy consumption $Q_{pyrolysis}$, associated with the pyrolysis process, is made up of two parts. The first is the energy

$Q_{reaction}$ consumed for decomposition reactions and the energy $Q_{evaporation}$ used for moisture evaporation, which can be calculated as following [309],

$$Q_{evaporation} = (\gamma + c_w \Delta T) \times MC \tag{8}$$

Where, γ represents the enthalpy of vaporisation of water during the drying process (2.2 MJ/kg), c_w is water's specific heat capacity (4.187 kJ/kg^{0}C), ΔT is the temperature difference from ambient 25 ^{0}C to 100 ^{0}C, MC is the moisture content of the feedstock.

Considering the degree of moisture content in the feedstock, the previous calculation for pyrolysis efficiencies will be significantly influenced. For instance, an extra 10% of moisture in the spent coffee grounds will require an additional amount of 0.25 MJ/kg energy for moisture evaporation, which leads to an efficiency reduction of 1.1%. The moisture content of the coffee waste was evaluated as 60%, under as received condition. Based on previous discussions, the pyrolysis efficiency of as received coffee grounds will drop to 77%.

6.4 Conclusion

Spent coffee grounds produced by the cafeteria of an educational building was collected and studied as biomass feedstock for offsetting part of the building's heating energy consumption.

The coffee grounds were subjected to pyrolysis for the application in the synthesis of bio-products as biofuel at two different heating rates of 10 and 60 ^{0}C/min. The thermal properties of the pyrolytic products, biogas, bio-oil and bio-char were examined through a series of analysis. The strong functional group bonds indicating the existence of caffeine and lipids were identified both in the raw sample and its derived bio-oil. Along with other organic components, these identified bonds were absent in the bio-char, which was attributed to a complete decomposition. During the pyrolysis process, three discrete stages of the sample were obviously illustrated at both heating rates. These main stages represented the thermal behaviour of the sample, including the evaporation of absorbed water, complex pyrolysis reactions and the continuously decomposed residual solid. Although the sample showed similar process stages in the curves at both heating rates, the higher heating rate strongly affected the thermal behaviour of the sample by shifting the position of the peaks to higher temperatures. The gaseous products were analysed using gas chromatographic approach. The oxides of carbon, CO_2 and CO, as well as CH_4 are the three dominant volatile products during coffee grounds pyrolysis. In terms of bio-oil analysis, 21 chemical compounds with their relevant contents were identified. Palmitic and linoleic acids were the dominant compounds in the bio-oils, indicating its great potential for further biodiesel production. The positive effects of the higher heating rate on improving the quality of bio-oil regarding to the elemental composition was also confirmed through the comparison study of the bio-oils collected under different heating rate conditions. The heating rates contributed little effects on the distribution of pyrolytic products. The maximum liquid yield of 66 wt % was achieved at around 630 ^{0}C. The pyrolysis efficiency of spent coffee grounds was estimated at 77%-85%, depending on the moisture content in the feedstock.

Chapter 7 Building Energy and Greenhouse Gas Emissions Offset Potential of Renewable Energy Sources

In the previous chapters, a series of renewable energy sources were investigated individually, regarding their energy generating potential and feasibility of integrating into a case study building. In this chapter, the extent to which the alternative renewable energy sources improve the building's energy consumption profile was determined by employing the renewable energy harvesting technologies together in the case study building to model their full potential in a holistic approach to meet the building's energy consumption needs and reduce the greenhouse gas emissions. Based on the analysis of energy demand offset and greenhouse gas mitigation profile, the adaptability of the renewable energy harvesting technologies was also examined in this section.

7.1 Case Building Description and Energy Consumption Profile

The case building is an educational building located at Macquarie University Campus, Sydney, New South Wales, Australia. This educational building is a new library, represented as a flagship building and positioned at the centre of the campus and at the south side of seven existing multi-story buildings. The new library building is aiming for a Five-Star Green Building Rating referring to the benchmark of Green Building Council of Australia. The building has a footprint of 6770 m^2 and is composed of 5 stories, which accounts for a total gross floor area of 16,000 m^2. The ground level is the largest floor area in the building. Near the main entrance, there is a cafeteria providing food and drinks for the library users. Lobby meeting areas, including concourse spaces, are located after the main gates and the central cross area. They provide access to the exhibition spaces and the main collection section with open shelves. The lower ground floor and upper ground levels, 1, 2, 3 provide quiet study areas and dedicated postgraduate research spaces for 3000 undergraduate and postgraduate students. With these features, the new library becomes a new central hub, providing places for studying, and interactive communication for not only students but also university working staff. It makes the area the busiest spot on the campus.

The energy consumption profile of the building consists of varied aspects due to the size of the building as well as its multi-functional properties. The composition of the energy consumption profile, as shown in Table 23, includes heating, ventilating and air-conditioning (HVAC), lighting, domestic hot water supply (DHW) and lifts. The energy consumed by the HVAC system accounts for the majority of the building total energy demand, including the energy used for heating and cooling the building, and the energy consumed by auxiliary systems which support the operation of the HVAC system. The energy consumed by the building is monitored and recorded by the Direct Digital Control and Building Management System, from where the building's annual energy consumption is obtained. There are two types of energy supplied to the building. First, it is the electricity used for cooling the building, DHW supply, lighting and powering the lifts. The second type of energy is supplied through the natural gas consumed for heating the building. According to the energy consumption profile, solar energy and piezoelectric energy are applied to offset the building's electricity consumption, while the biomass energy is aiming to produce the heating energy, as a substitute for the natural gas.

Table 23. Annual energy consumption of the new library building.

Energy Consumption	Annual Electricity Consumption (kWh/year)	Annual Natural Gas Consumption (MJ/year)
HVAC-Heating	-	354,143
HVAC-Cooling	202,318	-
HVAC-Pumps and Fans	349,027	-
Domestic Hot Water	32,382	-
Lighting	492,752	-
Lifts	104,685	-
Total	1,181,164	354,143

7.2 Application of Renewable Energy Sources

7.2.1 Solar-Energy and Building Integrated Photovoltaics

Solar energy is initially selected as a promising renewable energy source for study, due to the abundant solar radiation throughout the year, according to the local climate conditions and its highly coordinated activity schedule with building occupants' daily routine.

The new library building has a vast flat roof area of nearly 1600 m^2, where is suitable for the installation of conventional photovoltaic arrays, which are also known as multi-crystalline (polycrystalline) silicon solar cells. The multi-crystalline silicon modules normally appear as opaque with a solid colour, ranging from blue to black. Although a wider variety of colours is available but at a cost of lower efficiency since the colour comes from reflection of some of the incident light which would otherwise be absorbed. The energy conversion efficiency of this type of module is normally around 12-20%, according to previous studies [310].

Apart from the conventional PV cells, a prototype transparent photovoltaic cell (TPC) with an ultrahigh visible transmission has been produced in the laboratory [83, 84]. By absorbing only infrared and ultraviolet light, letting visible light pass through the cells, the cell is able to reach a transmission of >55%±2% and an efficiency of 3-10%, which is sufficiently transparent for incorporation on architectural glass [83]. With these favourable features, the envelope of the building, including the windows can be used as solar electricity generators. The library building uses high performance glazing on all external façade wall areas. The glazing is shaded at arbitrary locations using angled vertical fin structures of shallow projection. The vertical building façades, including the east, north (in southern hemisphere) and west sides, with a total exposure area of 2100 m^2, can be used as extra solar collection areas. The energy generating potential of the photovoltaic cells is shown in Table 24.

Table 24. Annual energy generating potential of the new library building using varied photovoltaic cells.

Building Surfaces	PV Cell Types	Module Efficiency	Cell Installed (m^2)	Accumulative Solar Radiation (kWh/year)	Electricity Generated (kWh/year)
Roof	polycrystalline	15%	1,474	2,311,700	346,800
Facades	TPC	8%	2,061	586,000	46,900
Total	-	-	3,535	2,897,700	393,700

7.2.2 Kinetic Energy Harvesting Using Piezoelectric Tiles

Piezoelectric tiles are a type of vibration-based energy harvesters with ability to capture the vibration in the ambient environment and then directly convert the kinetic energy into usable electrical energy. Due to its working mechanism of the piezoelectric tiles, the electricity harvesting effect is greatly dependent on the mobility and density of pedestrians. Hence a public building with high occupant mobility, such as the new library of Macquarie University in this case, is the ideal place to employ this type of energy harvesters. As mentioned previously, this library building is a central hub for students and university working staff. Students come to the building for borrowing books and study, while the cafeteria inside the building is the most attractive spot for staff. For these reasons, there are estimated more than 6000 people entering and exiting the building every day, which provide the energy harvesters considerable amount of kinetic energy through the footsteps. This is especially the case for the book borrowers that walk across the central cross area, great hall and check-in/out spot to reach to the main book collection area after they enter inside of the library. After the student finish the borrowing procedures, they again have to pass through the path in sequence to leave the building. Considering the occupants mobility behaviour, three spots were selected as the tile deploying areas due to the highest pedestrian mobility density. They were the Main Entrance (central cross) area, cafeteria and check in/out spot.

In this study, Pavegen Tile, which is one of the commercialised products newly coming to the market, was selected as the kinetic energy harvester. This type of tiles is claimed to be able to generate up to 7 Watts of electricity per footstep with a dimension of 600mm × 450mm × 82mm. The pedestrian mobility statistics and the piezoelectric power generating potential are illustrated in Table 25. It should be noted that the energy harvesting efficiency of the piezoelectric tiles is still in rapid development. One of the promising upgrades is integrating secondary vibrating units to the tile, which will possibly enhance the harvesting efficiency up to nine times higher than the current efficiency.

Table 25. Electricity generating potential of the new library building using piezoelectric tiles with 3.1% total floor area covered.

Paving Area	Total Tiles	Pedestrian Flow (person/day)	Daily Electricity Generation (kWh/day)	Annual Electricity Generation (kWh/year)
Main Entrance	614	14,035	1.09	385
Cafeteria	610	1,129	0.11	39
Check-in Spot	596	11,024	1.91	671
Total	1,820	26,188	3.11	1,095

7.2.3 Bioenergy Produced from Thermal Conversion of Biomass

The spent coffee grounds generated by the cafeteria in the library building at Macquarie University Campus were evaluated as a biomass type to produce heating of the building. The most common method of biomass thermal conversion is through direct combustion. The spent coffee grounds can be subjected to a biomass boiler to generate heat energy for heating of the building during winter period. Another method is to convert the coffee grounds into varied biofuel products, such as bio-char, biogas and bio-oil, through the pyrolysis process, which was evaluated in this thesis. The bio-char and biogas can then be combusted in a biomass boiler to generate heat, although these pyrolytic products can also be used in turbines for electricity generation. The bio-oil product has great market potential for high quality fuel production due to its physico-chemical properties. As a result the bio-oil product is not considered for heat recovery in this study.

The spent coffee grounds was collected from the cafeteria and weighted daily for seven days. The average daily coffee grounds generated in the building was calculated as 21 kg. The moisture content of the coffee grounds was evaluated as 60%, under the as received conditions. Based on the previous results shown in Chapter 6, there will be 690 kg of bio-char and 375 kg of biogas that can be produced annually by pyrolysis from the coffee waste collected in the single cafeteria of the case building studied in this work. The annual heating energy recovery potential obtained by combustion and pyrolysis processes were calculated and shown in Table 26. The results reveal that the annual heat energy that can be recovered from biomass will be 57,000 MJ by direct combustion or 22,000 MJ by combustion of the pyrolysis gas and solid products.

Table 26. Annual heating energy recovery potential of combustion and pyrolysis with varied energy conversion efficiencies.

Biomass Conversion Technique	Conversion Products	Thermal Efficiency	Calorific Value (MJ/kg)	Heat Energy Recovered (MJ/year)
Combustion	-	80% [311]	23.2	56,980
Pyrolysis	Bio-char	80% [311]	31.1	17,240
	Biogas	85% [312]	14.8	4,700

7.3 Energy Demand Offset and Greenhouse Gas Mitigation

The contribution of renewable energy sources on the building's energy demand offset is further estimated. For the aspect of electricity usage, nearly 404 MWh/year electricity from the power grid of New South Wales in Australia can be replaced by building's onsite electricity generator. The electricity produced by the solar photovoltaics and piezoelectric techniques possesses the potential to meet 34% of the total electricity needs of the building. Though the energy would be mainly generated by solar cells, the piezoelectric power harvesting technology is newly emerging to the market with adequate space for further development, and has been modelled to only cover 3.1% of the floor area, due to its current high cost. This technology is expected to make more contribution for the future exploitation and with further reduction in its cost. On the other hand, the biomass processing results indicated that by bioenergy conversion processes, the energy obtained from coffee grounds collected from the library building alone would cover up to 16% of building's annual heating energy consumption if the coffee waste is used in biomass boilers for direct combustion, otherwise can cover 6% of the annual heating energy consumption, if the pyrolysis method is used. The pyrolysis method would be more useful for off-site biomass processing, rather than in-house use of the biomass for heating.

The greenhouse gas mitigation potential of the renewable energy sources that are applied to the case building is investigated based on the clean energy production and the emission factors obtained from the National Greenhouse Accounts (NGA) Factors Workbook [264] and Green Star – Industrial v1 Greenhouse Gas Emissions Calculator Guide [313]. The equation applied for the calculation is:

$$GHG_{mitigation} = Energy_{renewable} \times (EmissionFactor_{fossil} - EmissionFactor_{renewable}) \quad (9)$$

According to the calculation, a total amount of 436 tons of carbon dioxide equivalent can be offset by the application of renewable energy in the studied case building for the studied case renewable energy sources. The energy and greenhouse gas emission offset potential is summarised in Table 27.

Table 27. Building energy and greenhouse gas emissions offset potential by integrating renewable energy sources.

Conventional Energy	Grid Electricity		Natural Gas	
Annual Consumption	1,181,164	kWh/year	354,143	MJ/year
Emission Factor [a]	1.07	kgCO_2-e/kWh	0.0677	kgCO_2-e/MJ
GHG Emissions	1,263,845	kgCO_2-e/year	23,975	kgCO_2-e/year
Renewable Energy	PV and Piezoelectricity		Biomass	
Annual Production	403,555	kWh/year	56,980	MJ/year
Emission Factor [a]	0 [b]	kgCO_2-e/kWh	0.0018	kgCO_2-e/MJ
GHG Mitigation	431,804	kgCO_2-e/year	3,755	kgCO_2-e/year
Energy Replacement Rate	34.2	%	16.1	%

[a] Greenhouse Gas Emissions Factors for New South Wales in Australia from National Greenhouse Accounts (NGA) Factors Workbook (DCC, 2013).

[b] Photovoltaic and piezoelectric factors are presumed as no greenhouse gas emissions.

This research bridges the knowledge gaps between the theoretical hypothesis and practical application of the renewable alternative energy sources. The empirical findings in this study provide a solid understanding that the case building's annual energy consumption profile can be improved by integrating renewable energy sources to the building. The building's energy security is improved by increasing the energy diversity and reducing peak energy demand. Considering the rapid increase in energy price, integration of green energy sources can be useful to avoid high operational costs.

Chapter 8 Conclusion and Recommendations

8.1 Conclusions

Green building is defined as a building designed with a sustainable, integrated approach, balancing environmental, economic, and social considerations with large scale of implemented innovative renewable technologies. Green buildings have been gradually accepted by the building industry and market as an essential requirement for reducing negative environmental footprints caused by the buildings. The statistical results reveal a stable growth in the number of green buildings approved in Australia since 2004. The increasing tendency is particularly evident in the educational building sector.

The motivations that drive the fast-growth of green projects in universities and higher institutions were identified through a qualitative approach, indicating that the factors that enhance universities' reputation and meet the specific needs for research, were the major influencing parameters responsible for the decision-makers and managers to invest in green buildings. The factors that deal with enhancing university's financial condition and the environmental protection were found to be minor influencing factors.

Essentially, the powerful drivers for the decision-makers to adopt green construction procedures and practices are the benefits the university can achieve from the green buildings. More specifically, the green projects offer direct benefits to the universities. The green identity of the well planned building and its favourable impression to both the academic area and beyond, directly boosts the university's reputation and publicity. The well-designed building which meets the specific needs for education or research purposes also enhances university's teaching and research capacity. On the other hand, green buildings provide the universities additional indirect benefits. The environmentally sustainable property of the green project reveals the great efforts that the university makes to fulfil its responsibility, as well as supply a technical verification opportunity for education and research. Moreover, the environmental protection consideration guarantees a higher possibility for the university to compete for the government funding which can be used for its expansion.

Having considered the greening of buildings in Australian educational institutions, this work carried out a holistic investigation on renewable energy sources and emerging renewable energy technologies that could be potentially integrated into an educational green building to optimise the building's energy consumption and greenhouse gas emission profiles. The aim of the study was to investigate if the green educational building can be partially or fully energy self-sustainable using the indoor and outdoor renewable energy sources.

As one of the most abundant outdoor renewable energy sources, the solar energy that could be used by the building and its relevant utilisation technique, hybrid solar air conditioning system were investigated in this thesis. The simulation results indicated that the building integrated photovoltaic technology would significantly contribute to offset building's energy consumption. The PV panels installed on the investigated building would entirely cover the annual cooling electricity consumption of the building. Additionally, the greenhouse gas emissions caused by cooling the building could be completely offset by the production of renewable energy. The surplus electricity could be also used by other electronic appliances in the building to mitigate the greenhouse gas emissions further when the solar based PV technology is integrated in the building.

Apart from the outdoor energy sources, utilisation of an indoor kinetic energy source generated from the pedestrian footsteps was considered. The results revealed that locating high traffic areas is critical for optimisation of the piezoelectric energy harvesting efficiency. Pedestrian mobility analysis should be applied when determining the optimised tile deployment districts. This analysis can be simply conducted by employing the density flow evaluation indicator which was proposed in this work. With regard to the electricity generating potential of the piezoelectric harvesters, newly commercialised piezoelectric tiles were applied to the case building for adaptation tests. Paving of a total number of 1820 tiles was modelled for the busiest areas of the case building, where the daily pedestrian traffic reaches over 26,000 pedestrians. By covering 3.1% of the total floor area of the case building, the piezoelectric energy harvester was estimated to generate 1.1 MWh per year. Furthermore, if the piezoelectric tile can be upgraded with integration of the plucked method, the total energy potential of the tile arrangement considered in this study can potentially increase to almost 10 MWh/year, which will be approximately 0.5 % of the total energy usage of the building.

Spent coffee grounds produced by the cafeteria of the case building was collected and studied as biomass feedstock for offsetting part of the building's heating energy consumption. The coffee grounds were subjected to pyrolysis for the application in the synthesis of biofuel products at two different heating rates of 10 and 60 ^{0}C/min. The thermal properties of the pyrolytic products, biogas, bio-oil and bio-char were examined through a series of analytical tests. The strong functional group bonds indicating the existence of caffeine and lipids were identified both in the raw sample and its derived bio-oil. Along with other organic components, these identified bonds were absent in the bio-char, which was attributed to a complete decomposition. During the pyrolysis process, three discrete stages of the sample were obviously illustrated at both heating rates. These main stages represented the thermal behaviour of the sample, including the evaporation of absorbed water, complex pyrolysis reactions and the continuously decomposed residual solid. Although the sample showed similar process stages in the curves at both heating rates, the higher heating rate strongly affected the thermal behaviour of the sample by shifting the position of the peaks to higher temperatures. The gaseous products were analysed using a gas chromatographic approach. The oxides of carbon, CO_2 and CO, as well as CH_4 were the three dominant volatile products during coffee grounds pyrolysis. In terms of bio-oil analysis, 21 chemical compounds with their relevant contents were identified. Palmitic and linoleic acids were the dominant compounds in the bio-oils, indicating its great potential for further upgrading to biodiesel. The positive effects of the higher heating rate on improving the quality of bio-oil regarding the elemental composition was also confirmed through the comparison study of the bio-oils collected under different heating rate conditions. The heating rates contributed little to the distribution of pyrolytic products. The maximum liquid yield of 66 wt % was achieved at around 630 ^{0}C. The pyrolysis efficiency of spent coffee grounds was estimated at 77-85%, depending on the moisture content in the feedstock.

All of the renewable energy candidates were integrated into the case building to estimate the contribution of the renewable energy sources on offsetting the building's energy demand. For the aspect of electricity use, nearly 404 MWh/year electricity from the power grid can be replaced by building's onsite electricity generator. The electricity that can potentially be produced by the solar photovoltaics and piezoelectric techniques possesses the potential to meet 34% of the total electricity needs of the building. Though the energy would be mainly generated by solar cells, the piezoelectric power harvesting technology is newly emerging to the market with adequate space for further development, and has been modelled to only cover 3.1% of the floor area, due to its current high cost. This technology is expected to make more contributions for the future exploitation and with further reduction in its cost. On the other hand, the biomass processing results indicated that by bioenergy conversion processes, the energy obtained from coffee grounds collected from the library building would cover up to 16% of the building's annual heating energy consumption if the coffee waste is used in biomass boilers for direct combustion, otherwise can cover 6% of the annual heating energy consumption, if the pyrolysis method is used. The pyrolysis method would be more useful for off-site biomass processing, rather than in-house use of the biomass for heating.

Furthermore, the greenhouse gas mitigation potential of the renewable energy sources that were considered for the case building was investigated. A total amount of 436 tons of carbon dioxide equivalent can be offset every year by the energy diversification approach.

The integration of renewable energy sources from outdoor and indoor environment would significantly improve the building's annual energy consumption profile, although there is still a long match ahead to achieve the goal of building's full self-sustainability even when the most advanced renewable energy harvesting technology is applied. This work contributes to the existing knowledge in solar energy harvesting by providing numerical analysis of power generating potential. Moreover, this is the first study to report the main factors that would significantly affect the energy harvesting efficiency of the macro-scale piezoelectric energy harvesters. Furthermore, the study has also confirmed the feasibility of using spent coffee grounds generated on-site as biomass feedstock for bioenergy generation.

Overall, the building's energy security can be enhanced by increasing the energy diversity and reducing peak energy demand. The conclusion of this study is that it may be possible to achieve a low carbon building footprint through the application of renewable energy sources. Further research would be needed to explore other opportunities in order to reach the rudiment of zero energy buildings (ZEB).

8.2 Recommendations

In this study, the energy diversification approach was carried out on an educational building. The renewable energy sources that could be potentially integrated into the building were selected and discussed based on the local climate conditions, the function of the building itself and the behaviour of the building occupants. However, due to the complexity and uniqueness of buildings, the outcomes of this research should not be applied mechanically to other building sectors, such as commercial, industrial and residential buildings. For better understanding of the adaptabilities of the renewable energy sources and the relevant techniques for building integration, further investigation may be needed.

More specifically, the utilisation of solar energy was considered with priority in this study due to the abundant solar radiation and high transmittance in Australia. For those buildings located at high density urban areas surrounded by tall buildings or areas with polluted air, where insufficient solar insolation is provided, the solar energy harvesting efficiency will be significantly affected. Although the exterior surface of the studied building was modelled at 90% glazed, the area that effectively receives solar radiation is limited since the glazing area is shaded at arbitrary locations using angled vertical fin structures of shallow projection. Theoretically, these shading structures could be considered as another ideal place for solar energy harvesting, but the irregular interval space and varied angle of shading structure deployment make the analysis a difficult task at this stage and is recommended as a future study.

In terms of the piezoelectric energy harvesting, a broad application prospect can be expected since the manufacturing technique and the relevant material science are developing rapidly. The concern on increasing its energy converting efficiency and reducing its application costs will be a challenging topic in the long term.

The biomass offers great opportunity for production of in-house heat in the buildings. This study considered the calorific value and the pyrolysis of the coffee grounds, which is the main biomass produced in the case study building. Anaerobic digestion is another promising technique that recovers bioenergy from feedstock. The initial tests performed in this study with digestion of coffee grounds revealed significantly lower biogas production rates than what was reported in the literature, despite that the methodological approach applied in this thesis simulated the literature experimental methods. The factors that could be responsible for the difference are the unoptimised substrate to inoculum ratio and the pH of the digestate. The experimental results are presented in the Appendix C section of the thesis. Further research will be required to optimise the biogas yields using the digestion technology, as another option that can be integrated into the green buildings. Moreover, the biomass feedstock which can be collected in the building should not be limited to the coffee waste, but can be extended into a variety of organic wastes. Kitchen waste or a mixture of food waste, containing spent tea leaves, fruits, vegetables and crops may also be used as a feed material for renewable energy production. The operating parameters of bioenergy generation for different mixture ratios need to be evaluated for the specific conditions in order to determine the full bioenergy potential of processing these organic wastes.

This work investigated the possibility and energy generating potential of integrated renewable energy sources into the educational building to offset its energy consumption and greenhouse gas emissions, regardless of the initial costs, energy and carbon embodied in the energy harvesters. It is necessary to evaluate the renewable energy harvesting techniques from a cost-benefit aspect, as well as a holistic life-cycle aspect across all stages of production, installation, processing and end-use decommissioning phases.

References

[1] S. Gendebien, S. Bertagnolio, V. Lemort. Investigation on a ventilation heat recovery exchanger: Modeling and experimental validation in dry and partially wet conditions. Energy and Buildings. 62 (2013) 176-89.

[2] P. Wargocki, D.P. Wyon, J. Sundell, G. Clausen, P.O. Fanger. The effects of outdoor air supply rate in an office on perceived air quality, Sick Building Syndrome (SBS) symptoms and productivity. Indoor Air-International Journal of Indoor Air Quality and Climate. 10 (2000) 222-36.

[3] J. Sundell. On the history of indoor air quality and health. Indoor Air. 14 (2004) 51-8.

[4] K. Engvall, P. Wickman, D. Norback. Sick building syndrome and perceived indoor environment in relation to energy saving by reduced ventilation flow during heating season: a 1 year intervention study in dwellings. Indoor Air. 15 (2005) 120-6.

[5] J.D. Spengler, Q.Y. Chen. Indoor air quality factors in designing a healthy building. Annual Review of Energy and the Environment. 25 (2000) 567-600.

[6] N.H. Wong, B. Huang. Comparative study of the indoor air quality of naturally ventilated and air-conditioned bedrooms of residential buildings in Singapore. Building and Environment. 39 (2004) 1115-23.

[7] D. Chwieduk. Towards sustainable-energy buildings. Applied Energy. 76 (2003) 211-7.

[8] UN. Report of the World Commission on Environment and Development: Our Common Future. http://www.un-documents.net/our-common-future.pdf. [Accessed 20/01/2014]

[9] P. Tymkow. Building services design for energy efficient buildings2013.

[10] A. E2114-04. Standard terminology for sustainability relative to the performance of buildings. http://www.astm.org/DATABASE.CART/HISTORICAL/E2114-04.htm. [Accessed 20/01/2014]

[11] J. Bumett. City buildings - Eco-labels and shades of green! Landscape and Urban Planning. 83 (2007) 29-38.

[12] I.Z. Bribian, A.V. Capilla, A.A. Uson. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Building and Environment. 46 (2011) 1133-40.

[13] N. Lin, F. Liu. Green Low Carbon Design in the Application of Energy-Saving Building. Renewable and Sustainable Energy Ii, Pts 1-4. 512-515 (2012) 2878-81.

[14] M. Liu, B.Z. Li, R.M. Yao. A generic model of Exergy Assessment for the Environmental Impact of Building Lifecycle. Energy and Buildings. 42 (2010) 1482-90.

[15] M. Medineckiene, Z. Turskis, E.K. Zavadskas. Sustainable Construction Taking into Account the Building Impact on the Environment. Journal of Environmental Engineering and Landscape Management. 18 (2010) 118-27.

[16] P. Eichholtz, N. Kok, J.M. Quigley. The Economics of Green Building. Review of Economics and Statistics. 95 (2013) 50-63.

[17] Y.H. Mao, G.H. Yang. Sustainable Development Drivers for Green Buildings: Incremental Costs-Benefits Analysis of green buildings. Sustainable Development of Urban Environment and Building Material, Pts 1-4. 374-377 (2012) 76-81.

[18] A. Sev. A comparative analysis of building environmental assessment tools and suggestions for regional adaptations. Civil Engineering and Environmental Systems. 28 (2011) 231-45.

[19] W.L. Lee, J. Burnett. Benchmarking energy use assessment of HK-BEAM, BREEAM and LEED. Building and Environment. 43 (2008) 1882-91.

[20] R. Reed, A. Bilos, S. Wilkinson, K.-W. Schulte. International comparison of sustainable rating tools. The Journal of Sustainable Real Estate. 1 (2009) 1-22.

[21] Y. Roderick, D. McEwan, C. Wheatley, C. Alonso. Comparison of energy performance assessment between LEED, BREEAM and Green Star. Eleventh International IBPSA Conference, Glasgow, Scotland, 27-30 July 2009. Integrated Environmental Solutions Limited2009. pp. 1167-76.

[22] P.E.D. Love, M. Niedzweicki, P.A. Bullen, D.J. Edwards. Achieving the Green Building Council of Australia's World Leadership Rating in an Office Building in Perth. Journal of Construction Engineering and Management-Asce. 138 (2012) 652-60.

[23] BREEAM. BREEAM International New Construction (NC). http://www.breeam.org/. [Accessed 22/01/2014]

[24] LEED. Projects earn points to satisfy green building requirements. http://www.usgbc.org/leed/rating-systems/credit-categories. [Accessed 22/01/2014]

[25] GBCA. The dollars and sense of green buildings: building the business case for green commercial buildings in Australia. Green Building Council of Australia (GBCA)2008.

[26] A. Haapio, P. Viitaniemi. A critical review of building environmental assessment tools. Environmental Impact Assessment Review. 28 (2008) 469-82.

[27] L. Perez-Lombard, J. Ortiz, R. Gonzalez, I.R. Maestre. A review of benchmarking, rating and labelling concepts within the framework of building energy certification schemes. Energy and Buildings. 41 (2009) 272-8.

[28] T. Saunders. A discussion document comparing international environmental assessment methods for buildings. BRE, March. (2008).

[29] EPU. EU Directive on the Energy Performance of Buildings. http://www.dfpni.gov.uk/content - energy performance of buildings-pubs-directive. [Accessed 14/08/2014]

[30] Q.K. Cao, L.J. Li, B. Yu. Decision-making research of green purchasing based on Set-pair Analysis. Proceedings of 2007 International Conference on Management Science & Engineering (14th) Vols 1-3. (2007) 555-60.

[31] A.J. Hoffman, R. Henn. Overcoming the Social and Psychological Barriers to Green Building. Organization & Environment. 21 (2008) 390-419.

[32] C.T. Griffin, C. Knowles, C. Theodoropoulos, J.H. Allen. Barriers to the implementation of sustainable structural materials in green buildings. Structures and Architecture. (2010) 1349-57.

[33] A.P. McCoy, Y.H. Ahn, A.R. Pearce. Towards Establishing Diffusion Barriers for Innovative Green Building Products: A Survey of Sips Builders. Journal of Green Building. 7 (2012) 153-76.

[34] X.L. Zhang, L.Y. Shen, V.W.Y. Tam, W.W.Y. Lee. Barriers to implement extensive green roof systems: A Hong Kong study. Renewable & Sustainable Energy Reviews. 16 (2012) 314-9.

[35] T.H. Hakkinen, T., K. Belloni. Barriers and drivers for sustainable building. Building Research and Information. 39 (2011) 239-55.

[36] J. Mair, L. Jago. The development of a conceptual model of greening in the business events tourism sector. Journal of Sustainable Tourism. 18 (2010) 77-94.

[37] S. Boo, E. Park. An examination of green intention: the effect of environmental knowledge and educational experiences on meeting planners' implementation of green meeting practices. Journal of Sustainable Tourism. 21 (2013) 1129-47.

[38] K.Y.H. Connell. Internal and external barriers to eco-conscious apparel acquisition. International Journal of Consumer Studies. 34 (2010) 279-86.

[39] C.J. Kibert. Sustainable construction : green building design and delivery. Third edition ed. John Wiley & Sons, Hoboken, N.J., 2013.

[40] B.G. Hwang, J.S. Tan. Green building project management: obstacles and solutions for sustainable development. Sustainable Development. 20 (2012) 335-49.

[41] J. Yudelson. The green building revolution. Island Press, Washington ; London, 2008.

[42] S. Lee, B. Lee, J. Kim, J. Kim. A Financing Model to Solve Financial Barriers for Implementing Green Building Projects. Scientific World Journal. (2013).

[43] C. Nelms, A.D. Russell, B.J. Lence. Assessing the performance of sustainable technologies for building projects. Canadian Journal of Civil Engineering. 32 (2005) 114-28.

[44] T. Lutzkendorf, D. Lorenz. Integrating sustainability into property risk assessments for market transformation. Building Research and Information. 35 (2007) 644-61.

[45] S.E. Sayce, L. Parnell, P. Understanding investment drivers for UK sustainable property. Building Research and Information. 35 (2007) 629-43.

[46] G. Kats, E. Capital. Green building costs and financial benefits. Massachusetts Technology Collaborative Boston, MA2003.

[47] P. Eichholtz, N. Kok, J.M. Quigley. Doing well by doing good? Green office buildings. The American Economic Review. 100 (2010) 2492-509.

[48] H.F. Castleton, V. Stovin, S.B.M. Beck, J.B. Davison. Green roofs; building energy savings and the potential for retrofit. Energy and Buildings. 42 (2010) 1582-91.

[49] D.H.W. Li, T.N.T. Lam, W.W.H. Chan, A.H.L. Mak. Energy and cost analysis of semi-transparent photovoltaic in office buildings. Applied Energy. 86 (2009) 722-9.

[50] J. Heerwagen. Green buildings, organizational success and occupant productivity. Building Research and Information. 28 (2000) 353-67.

[51] W.J. Fisk. Health and productivity gains from better indoor environments and their relationship with building energy efficiency. Annual Review of Energy and the Environment. 25 (2000) 537-66.

[52] A. Feige, H. Wallbaum, M. Janser, L. Windlinger. Impact of sustainable office buildings on occupant's comfort and productivity. Journal of Corporate Real Estate. 15 (2013) 7-34.

[53] R. Ries, M.M. Bilec, N.M. Gokhan, K.L. Needy. The economic benefits of green buildings: a comprehensive case study. The Engineering Economist. 51 (2006) 259-95.

[54] P. Gluch, A.C. Stenberg. How do trademedia influence green building practice? Building Research and Information. 34 (2006) 104-17.

[55] B. Klein, K.B. Leffler. The Role of Market Forces in Assuring Contractual Performance. Journal of Political Economy. 89 (1981) 615-41.

[56] D.B. Turban, D.W. Greening. Corporate social performance and organizational attractiveness to prospective employees. Academy of Management Journal. 40 (1997) 658-72.

[57] P.R. Rosenbaum, D.B. Rubin. The Central Role of the Propensity Score in Observational Studies for Causal Effects. Matched Sampling for Causal Effects. (2006) 170-84.

[58] I. Dincer. Renewable energy and sustainable development: a crucial review. Renewable & Sustainable Energy Reviews. 4 (2000) 157-75.

[59] J. Ferreira, M.D. Pinheiro, J. de Brito. Portuguese sustainable construction assessment tools benchmarked with BREEAM and LEED: An energy analysis. Energy and Buildings. 69 (2014) 451-63.

[60] Y. Schwartz, R. Raslan. Variations in results of building energy simulation tools, and their impact on BREEAM and LEED ratings: A case study. Energy and Buildings. 62 (2013) 350-9.

[61] D.K. Prasad, M. Snow. Designing with solar power : a source book for building integrated photovoltaics (BiPV)2005.

[62] F. Dincer. The analysis on photovoltaic electricity generation status, potential and policies of the leading countries in solar energy. Renewable & Sustainable Energy Reviews. 15 (2011) 713-20.

[63] IEA. World Energy Outlook 2013 International Energy Agency. http://www.iea.org/media/executivesummaries/WEO_2013_ES_English_WEB.pdf. [Accessed 12/11/2013]

[64] S. Suwin, J. Lynton, B. Marita, C. Leesa, H. Michael, H. David, et al. Australian Energy Resource Assessment. (2010).

[65] T.T. Chow. A review on photovoltaic/thermal hybrid solar technology. Applied Energy. 87 (2010) 365-79.

[66] P. Bajpai, V. Dash. Hybrid renewable energy systems for power generation in stand-alone applications: A review. Renewable & Sustainable Energy Reviews. 16 (2012) 2926-39.

[67] J. Urbanetz, C.D. Zomer, R. Ruther. Compromises between form and function in grid-connected, building-integrated photovoltaics (BIPV) at low-latitude sites. Building and Environment. 46 (2011) 2107-13.

[68] I.P. dos Santos, R. Ruther. The potential of building-integrated (BIPV) and building-applied photovoltaics (BAPV) in single-family, urban residences at low latitudes in Brazil. Energy and Buildings. 50 (2012) 290-7.

[69] S. Barkaszi, J. Dunlop. Discussion of strategies for mounting photovoltaic arrays on rooftops. Solar Engineering. (2001) 333-8.

[70] B.-a.m. (BAPV). PV Mounting Systems & Tracking Devices. http://www.greenrhinoenergy.com/solar/technologies/pv_tracking.php. [Accessed 05/03/2014]

[71] C.H. Peng, Y. Huang, Z.S. Wu. Building-integrated photovoltaics (BIPV) in architectural design in China. Energy and Buildings. 43 (2011) 3592-8.

[72] T.Y.Y. Fung, H. Yang. Study on thermal performance of semi-transparent building-integrated photovoltaic glazings. Energy and Buildings. 40 (2008) 341-50.

[73] M.E. Meral, F. Dincer. A review of the factors affecting operation and efficiency of photovoltaic based electricity generation systems. Renewable & Sustainable Energy Reviews. 15 (2011) 2176-84.

[74] S. Rustemli, F. Dincer, E. Unal, M. Karaaslan, C. Sabah. The analysis on sun tracking and cooling systems for photovoltaic panels. Renewable & Sustainable Energy Reviews. 22 (2013) 598-603.

[75] W. Tian, Y.P. Wang, J.B. Ren, L. Zhu. Effect of urban climate on building integrated photovoltaics performance. Energy Conversion and Management. 48 (2007) 1-8.

[76] P. Heinstein, C. Ballif, L.-E. Perret-Aebi. Building Integrated Photovoltaics (BIPV): Review, Potentials, Barriers and Myths. Green. 3 (2013) 125-56.

[77] S. Hegedus. Thin film solar modules: The low cost, high throughput and versatile alternative to Si wafers. Progress in Photovoltaics. 14 (2006) 393-411.

[78] K.L. Chopra, P.D. Paulson, V. Dutta. Thin-film solar cells: An overview. Progress in Photovoltaics. 12 (2004) 69-92.

[79] F.C. Krebs, J. Fyenbo, M. Jorgensen. Product integration of compact roll-to-roll processed polymer solar cell modules: methods and manufacture using flexographic printing, slot-die coating and rotary screen printing. Journal of Materials Chemistry. 20 (2010) 8994-9001.

[80] A. Hinsch, H. Brandt, W. Veurman, S. Hemming, M. Nittel, U. Wurfel, et al. Dye solar modules for facade applications: Recent results from project ColorSol. Solar Energy Materials and Solar Cells. 93 (2009) 820-4.

[81] M.R. Travino. Dye-sensitized solar cells and solar cell performance. Nova Science Publisher, New York, 2012.

[82] ScienceDaily. Flexible Solar Panels. http://www.solaripedia.com/13/11/flexible_solar_panels.html. [Accessed 27/02/2014]

[83] R.R. Lunt, V. Bulovic. Transparent, near-infrared organic photovoltaic solar cells for window and energy-scavenging applications. Applied Physics Letters. 98 (2011).

[84] R.R. Lunt, T.P. Osedach, P.R. Brown, J.A. Rowehl, V. Bulovic. Practical Roadmap and Limits to Nanostructured Photovoltaics. Advanced Materials. 23 (2011) 5712-27.

[85] B.P. Jelle, C. Breivik, H.D. Rokenes. Building integrated photovoltaic products: A state-of-the-art review and future research opportunities. Solar Energy Materials and Solar Cells. 100 (2012) 69-96.

[86] K.E. Park, G.H. Kang, H.I. Kim, G.J. Yu, J.T. Kim. Analysis of thermal and electrical performance of semi-transparent photovoltaic (PV) module. Energy. 35 (2010) 2681-7.

[87] S.A. Kalogirou. Solar thermal collectors and applications. Progress in Energy and Combustion Science. 30 (2004) 231-95.

[88] D. Tchernev. Solar energy application of natural zeolites. Natural Zeolites—Occurrence, Properties, Use. (1978).

[89] Y.H. Bi, T.W. Guo, L. Zhang, L.G. Chen. Solar and ground source heat-pump system. Applied Energy. 78 (2004) 231-45.

[90] D. Schmidt. Low exergy systems for high-performance buildings and communities. Energy and Buildings. 41 (2009) 331-6.

[91] D. Tennyson. Solar Thermal Collectors. http://irishenergynews.com/home/index.php/2010/09/08/solar-thermal-collectors/. [Accessed 15/01/2014]

[92] L. Perez-Lombard, J. Ortiz, C. Pout. A review on buildings energy consumption information. Energy and Buildings. 40 (2008) 394-8.

[93] A.M. Papadopoulos, S. Oxizidis, N. Kyriakis. Perspectives of solar cooling in view of the developments in the air-conditioning sector. Renewable & Sustainable Energy Reviews. 7 (2003) 419-38.

[94] G. Grossman. Solar-powered systems for cooling, dehumidification and air-conditioning. Solar Energy. 72 (2002) 53-62.

[95] Z.F. Li, K. Sumathy. Technology development in the solar absorption air-conditioning systems. Renewable & Sustainable Energy Reviews. 4 (2000) 267-93.

[96] A.V. Doroshenko, Y.P. Kvurt, L.P. Kholpanov. Solar Absorption Systems as the Foundation for the New Generation of Heat-Pumping, Refrigerating and Air Conditioning Technologies. Engineering Physics and Mechanics: Analysis, Prediction and Applications. (2010) 1-146.

[97] R.Z. Wang, Z.S. Lu. Solar Air Conditioning by the Match of Solar Collector and Sorption Systems. 23rd Iir International Congress of Refrigeration. 23 (2011) 4003-10.

[98] D.N. Nkwetta, M. Smyth. The potential applications and advantages of powering solar air-conditioning systems using concentrator augmented solar collectors. Applied Energy. 89 (2012) 380-6.

[99] P. Lamp, F. Ziegler. European research on solar-assisted air conditioning. International Journal of Refrigeration-Revue Internationale Du Froid. 21 (1998) 89-99.

[100] Y.T. Li, L. Lu, H.X. Yang. Energy and economic performance analysis of an open cycle solar desiccant dehumidification air-conditioning system for application in Hong Kong. Solar Energy. 84 (2010) 2085-95.

[101] W. Concina, S. Sadineni, R. Boehm. Solar Assisted Desiccant Cooling Simulations for Different Climate Zones. Proceedings of the Asme 5th International Conference on Energy Sustainability 2011, Pts a-C. (2012) 127-36.

[102] S. Rosiek, F.J. Batlles. Integration of the solar thermal energy in the construction: Analysis of the solar-assisted air-conditioning system installed in CIESOL building. Renewable Energy. 34 (2009) 1423-31.

[103] H.Y. Chan, S.B. Riffat, J. Zhu. Review of passive solar heating and cooling technologies. Renewable & Sustainable Energy Reviews. 14 (2010) 781-9.

[104] Y.H. Hwang, R. Radermacher, A. Al Alili, I. Kubo. Review of solar cooling technologies. Hvac&R Research. 14 (2008) 507-28.

[105] C.A. Balaras, G. Grossman, H.M. Henning, C.A.I. Ferreira, E. Podesser, L. Wang, et al. Solar air conditioning in Europe - an overview. Renewable & Sustainable Energy Reviews. 11 (2007) 299-314.

[106] A.M. Baniyounes, Y.Y. Ghadi, M.G. Rasul, M.M.K. Khan. An overview of solar assisted air conditioning in Queensland's subtropical regions, Australia. Renewable & Sustainable Energy Reviews. 26 (2013) 781-804.

[107] I. Sarbu, C. Sebarchievici. Review of solar refrigeration and cooling systems. Energy and Buildings. 67 (2013) 286-97.

[108] H.M. Henning. Solar assisted air conditioning of buildings - an overview. Applied Thermal Engineering. 27 (2007) 1734-49.

[109] L.A. Chidambaram, A.S. Ramana, G. Kamaraj, R. Velraj. Review of solar cooling methods and thermal storage options. Renewable & Sustainable Energy Reviews. 15 (2011) 3220-8.

[110] J. Tichy. Fundamentals of piezoelectric sensorics : mechanical, dielectric, and thermodynamical properties of piezoelectric materials. 1st ed. Springer, New York, 2010.

[111] J. Erhart. Experiments to demonstrate piezoelectric and pyroelectric effects. Physics Education. 48 (2013) 438.

[112] B. Jaffe, W.R. Cook, H.L. Jaffe. Piezoelectric ceramics. Academic Press, London, New York,, 1971.

[113] H. Tomohiro, N. Fujii. Method of polarization-treating piezoelectric material. Google Patents2002.

[114] T.J. Lewis. The piezoelectric effect. Electrical Insulation and Dielectric Phenomena, 2005 CEIDP '05 2005 Annual Report Conference on2005. pp. 717-20.

[115] S. Tasaka, S. Miyata. The Origin of Piezoelectricity in Poly(Vinylidene Fluoride). Ferroelectrics. 32 (1981) 17-23.

[116] T.o. Ikeda. Fundamentals of piezoelectricity. Corrected pbk. ed. Oxford University Press, Oxford ; New York, 1996.

[117] E. Bischur, N. Schwesinger. Organic piezoelectric energy harvesters in floor. Materials Science and Information Technology, Pts 1-8. 433-440 (2012) 5848-53.

[118] K.A. Cook-Chennault, N. Thambi, A.M. Sastry. Powering MEMS portable devices - a review of non-regenerative and regenerative power supply systems with special emphasis on piezoelectric energy harvesting systems. Smart Materials and Structures. 17 (2008).

[119] A. Reinders, J.C. Diehl, H. Brezet. The power of design : product innovation in sustainable energy technologies. Wiley, Chichester, West Sussex, 2013.

[120] H.S. Kim, J.H. Kim, J. Kim. A Review of Piezoelectric Energy Harvesting Based on Vibration. International Journal of Precision Engineering and Manufacturing. 12 (2011) 1129-41.

[121] R.A. Steven, A.S. Henry. A review of power harvesting using piezoelectric materials (2003–2006). Smart Materials and Structures. 16 (2007).

[122] K.H. Mak, S. McWilliam, A.A. Popov, C.H.J. Fox. Performance of a cantilever piezoelectric energy harvester impacting a bump stop. Journal of Sound and Vibration. 330 (2011) 6184-202.

[123] S. Roundy, P.K. Wright. A piezoelectric vibration based generator for wireless electronics. Smart Materials & Structures. 13 (2004) 1131-42.

[124] H.A. Sodano, D.J. Inman, G. Park. Comparison of piezoelectric energy harvesting devices for recharging batteries. Journal of Intelligent Material Systems and Structures. 16 (2005) 799-807.

[125] G. Tang, J.Q. Liu, H.S. Liu, Y.G. Li, C.S. Yang, D.N. He, et al. Piezoelectric MEMS generator based on the bulk PZT/silicon wafer bonding technique. Physica Status Solidi a-Applications and Materials Science. 208 (2011) 2913-9.

[126] A.M. Flynn, S.R. Sanders. Fundamental limits on energy transfer and circuit considerations for piezoelectric transformers. Ieee Transactions on Power Electronics. 17 (2002) 8-14.

[127] Piezo-University. Basic Designs of Piezoelectric Positioning Drives/Systems. http://www.physikinstrumente.com/en/products/primages.php?sortnr=400800.00&picview=2. [Accessed 24/02/2014]

[128] H. Abramovich, C. Milgrom, E. Harash, L. Edery-Azulay, U. Amit. PIEZOELECTRIC STACK COMPRESSION GENERATOR. Google Patents2010.

[129] Innowattech. Innowattech IPEG PAD Harvests Energy From Passing Trains. http://www.innowattech.co.il/technology.aspx. [Accessed 03/01/2014]

[130] Pavegen. Pavegen System. http://www.pavegen.com/. [Accessed 20/10/2013]

[131] F. Duarte, F. Casimiro, D. Correia, R. Mendes, A. Ferreira. Waynergy people: a new pavement energy harvest system. (2013).

[132] PowerLeap. http://www.powerleap.net/. [Accessed 05/01/2014]

[133] O.D. Authority. Pedestrians to power walkway to London 2012 Olympic park. http://www.energyharvestingjournal.com/articles/pedestrians-to-power-walkway-to-london-2012-olympic-park-00004578.asp?sessionid=1. [Accessed 05/01/2014]

[134] P.M. Mortensen, J.D. Grunwaldt, P.A. Jensen, K.G. Knudsen, A.D. Jensen. A review of catalytic upgrading of bio-oil to engine fuels. Applied Catalysis a-General. 407 (2011) 1-19.

[135] A. Demirbas. Biofuels sources, biofuel policy, biofuel economy and global biofuel projections. Energy Conversion and Management. 49 (2008) 2106-16.

[136] M. Balat. Production of bioethanol from lignocellulosic materials via the biochemical pathway: A review. Energy Conversion and Management. 52 (2011) 858-75.

[137] A. Downie, D. Lau, A. Cowie, P. Munroe. Approaches to greenhouse gas accounting methods for biomass carbon. Biomass and Bioenergy. 60 (2014) 18-31.

[138] M.F. Demirbas, M. Balat, H. Balat. Potential contribution of biomass to the sustainable energy development. Energy Conversion and Management. 50 (2009) 1746-60.

[139] H.C. Ong, T.M.I. Mahlia, H.H. Masjuki. A review on energy scenario and sustainable energy in Malaysia. Renewable & Sustainable Energy Reviews. 15 (2011) 639-47.

[140] H. Kopetz. Build a biomass energy market. Nature. 494 (2013) 29-31.

[141] E.G. Pereira, J.N. da Silva, J.L. de Oliveira, C.S. Machado. Sustainable energy: A review of gasification technologies. Renewable & Sustainable Energy Reviews. 16 (2012) 4753-62.

[142] E.S. Lora, R.V. Andrade. Biomass as energy source in Brazil. Renewable & Sustainable Energy Reviews. 13 (2009) 777-88.

[143] T. Olivier, C.C. Capital, D.N. Veritas. Scoping Study on Financial Risk Management Instruments for Renewable Energy Projects United Nations Environment Programme. Citeseer.

[144] A. Demirbas. Biomass resource facilities and biomass conversion processing for fuels and chemicals. Energy Conversion and Management. 42 (2001) 1357-78.

[145] R.H. Zhang, H.M. El-Mashad, K. Hartman, F.Y. Wang, G.Q. Liu, C. Choate, et al. Characterization of food waste as feedstock for anaerobic digestion. Bioresource Technology. 98 (2007) 929-35.

[146] J. Gustavsson, C. Cederberg, U. Sonesson. Global food losses and food waste : extent, causes and prevention : study conducted for the International Congress "Save Food!" at Interpack 2011 Du\0308sseldorf, Germany. Food and Agriculture Organization of the United Nations, Rome, 2011.

[147] R. Mazen, M. Radwan, M. Abdel-Samiea. Utilization of biomass energy in high-rise buildings. Energy (IYCE), 2013 4th International Youth Conference on2013. pp. 1-3.

[148] M. Carpio, M. Zamorano, M. Costa. Impact of using biomass boilers on the energy rating and CO2 emissions of Iberian Peninsula residential buildings. Energy and Buildings. 66 (2013) 732-44.

[149] M. Carlini, S. Castellucci, S. Cocchi, E. Allegrini, M. Li. Italian Residential Buildings: Economic Assessments for Biomass Boilers Plants. Mathematical Problems in Engineering. (2013).

[150] Y. Huang, D.R. Mcllveen-Wright, S. Rezvani, M.J. Huang, Y.D. Wang, A.P. Roskilly, et al. Comparative techno-economic analysis of biomass fuelled combined heat and power for commercial buildings. Applied Energy. 112 (2013) 518-25.

[151] J. Harrod, P.J. Mago, R. Luck. Sizing analysis of a combined cooling, heating, and power system for a small office building using a wood waste biomass-fired Stirling engine. International Journal of Energy Research. 36 (2012) 64-74.

[152] A. Demirbas. Thermochemical conversion of hazelnut shell to gaseous products for production of hydrogen. Energy Sources. 27 (2005) 339-47.

[153] V. Strezov, T.J. Evans, C. Hayman. Thermal conversion of elephant grass (Pennisetum Purpureum Schum) to bio-gas, bio-oil and charcoal. Bioresource Technology. 99 (2008) 8394-9.

[154] A. Demirbas. Yields of oil products from thermochemical biomass conversion processes. Energy Conversion and Management. 39 (1998) 685-90.

[155] M.J. Antal, M. Gronli. The art, science, and technology of charcoal production. Industrial & Engineering Chemistry Research. 42 (2003) 1619-40.

[156] J. Lehmann. A handful of carbon. Nature. 447 (2007) 143-4.

[157] D. Day, R.J. Evans, J.W. Lee, D. Reicosky. Economical CO(2), SO(x), and NO(x) capture from fossil-fuel utilization with combined renewable hydrogen production and large-scale carbon sequestration. Energy. 30 (2005) 2558-79.

[158] Y.J. Lin, H.T. Lin. Thermal performance of different planting substrates and irrigation frequencies in extensive tropical rooftop greeneries. Building and Environment. 46 (2011) 345-55.

[159] S.N. Naik, V.V. Goud, P.K. Rout, A.K. Dalai. Production of first and second generation biofuels: A comprehensive review. Renewable & Sustainable Energy Reviews. 14 (2010) 578-97.

[160] S. Czernik, A.V. Bridgwater. Overview of applications of biomass fast pyrolysis oil. Energy & Fuels. 18 (2004) 590-8.

[161] A. Demirbas. Competitive liquid biofuels from biomass. Applied Energy. 88 (2011) 17-28.

[162] D. Iribarren, J.F. Peters, J. Dufour. Life cycle assessment of transportation fuels from biomass pyrolysis. Fuel. 97 (2012) 812-21.

[163] J.Q. Fan, T.N. Kalnes, M. Alward, J. Klinger, A. Sadehvandi, D.R. Shonnard. Life cycle assessment of electricity generation using fast pyrolysis bio-oil. Renewable Energy. 36 (2011) 632-41.

[164] J.L. Figueiredo, C. Valenzuela, A. Bernalte, J.M. Encinar. Pyrolysis of Holm-Oak Wood - Influence of Temperature and Particle-Size. Fuel. 68 (1989) 1012-6.

[165] M. Becidan, O. Skreiberg, J.E. Hustad. Products distribution and gas release in pyrolysis of thermally thick biomass residues samples. Journal of Analytical and Applied Pyrolysis. 78 (2007) 207-13.

[166] K. Raveendran, A. Ganesh. Heating value of biomass and biomass pyrolysis products. Fuel. 75 (1996) 1715-20.

[167] S. Yilmaz, H. Selim. A review on the methods for biomass to energy conversion systems design. Renewable & Sustainable Energy Reviews. 25 (2013) 420-30.

[168] A. Donoso-Bravo, J. Mailier, C. Martin, J. Rodriguez, C.A. Aceves-Lara, A. Vande Wouwer. Model selection, identification and validation in anaerobic digestion: A review. Water Research. 45 (2011) 5347-64.

[169] P. McKendry. Energy production from biomass (part 2): conversion technologies. Bioresource Technology. 83 (2002) 47-54.

[170] J.W. Lee. Advanced biofuels and bioproducts. Springer, New York ; London, 2013.

[171] D. Shi. Analysis of China's Renewable Energy Development under the Current Economic and Technical Circumstances. China & World Economy. 17 (2009) 94-109.

[172] H.B. Qin, H.H. Lang, H.J. Yang. Characterization of the methanogen community in a household anaerobic digester fed with swine manure in China. Applied Microbiology and Biotechnology. 97 (2013) 8163-71.

[173] S.K. Cheng, Z.F. Li, H.P. Mang, E.M. Huba. A review of prefabricated biogas digesters in China. Renewable & Sustainable Energy Reviews. 28 (2013) 738-48.

[174] N. Curry, P. Pillay. Biogas prediction and design of a food waste to energy system for the urban environment. Renewable Energy. 41 (2012) 200-9.

[175] G. He, B. Bluemling, A.P. Mol, L. Zhang, Y. Lu. Comparing centralized and decentralized bio-energy systems in rural China. Energy Policy. 63 (2013) 34-43.

[176] S. De Meester, J. Demeyer, F. Velghe, A. Peene, H. Van Langenhove, J. Dewulf. The environmental sustainability of anaerobic digestion as a biomass valorization technology. Bioresource Technology. 121 (2012) 396-403.

[177] K. Komatsu, H. Yasui, R. Goel, Y.Y. Li, T. Noike. Feasible Power Production from Municipal Sludge Using an Improved Anaerobic Digestion System. Ozone-Science & Engineering. 33 (2011) 164-70.

[178] M. Esen, T. Yuksel. Experimental evaluation of using various renewable energy sources for heating a greenhouse. Energy and Buildings. 65 (2013) 340-51.

[179] T. Woolley. Green building handbook : a guide to building products and their impact on the environment. E & FN Spon, London, 1997.

[180] WGBC. GBC Directory. World Green Building Council (WGBC). http://www.worldgbc.org/green-building-councils/GBC-Directory. [Accessed 11/10/2011]

[181] M. Ala-Juusela, Huovila, P., Jahn, J., Nystedt, A. and Vesanen, T. Energy Use and Greenhouse Gas Emissions from Construction and Buildings. Buildings and Climate Change Status, Challenges and Opportunities, Paris, UNEP. (2006).

[182] J. Yudelson. Marketing Green Building Services: Strategies for Success. (2008).

[183] T. Lutzkendorf, D. Lorenz. Sustainable property investment: valuing sustainable buildings through property performance assessment. Building Research and Information. 33 (2005) 212-34.

[184] H. Priemus. How to make housing sustainable? The Dutch experience. Environment and Planning B-Planning & Design. 32 (2005) 5-19.

[185] L. Oerlemans, K. Arkesteijn. The early adoption of green power by Dutch households - An empirical exploration of factors influencing the early adoption of green electricity for domestic purposes. Energy Policy. 33 (2005) 183-96.

[186] R. Ozaki. Adopting Sustainable Innovation: What Makes Consumers Sign up to Green Electricity? Business Strategy and the Environment. 20 (2011) 1-17.

[187] J. Skopek. Sustainable and Smart University Campuses; Strategic Approach to Sustainability and Building Intelligence for University Campuses. Cesb 10: Central Europe Towards Sustainable Building - from Theory to Practice. (2010) 185-8.

[188] J. Galayda, J. Yudelson. Green building trends in higher education: white paper. (2010).

[189] A. Nicolaides. The implementation of environmental management towards sustainable universities and education for sustainable development as an ethical imperative. International Journal of Sustainability in Higher Education. 7 (2006) 414 - 24.

[190] G.R.A. Richardson, J.K. Lynes. Institutional motivations and barriers to the construction of green buildings on campus: A case study of the University of Waterloo, Ontario. International Journal of Sustainability in Higher Education. 8 (2007) 339 - 54.

[191] A.F. Cupido, Baetz, Brian W., Pujari, Ashish and Chidiac, Samir. Evaluating Institutional Green Building Policies: A Mixed-Methods Approach. Journal of Green Building. 5 (2010) 115-31.

[192] A. Beringer, T. Wright, L. Malone. Sustainability in higher education in Atlantic Canada. International Journal of Sustainability in Higher Education. 9 (2008) 48 - 67.

[193] ABS. 8731.0 Building Approvals, Australia. Australian Bureau of Statistics (ABS). http://www.abs.gov.au/ausstats/abs@.nsf/mf/8731.0. [Accessed 31/08/2011]

[194] GBCA. Green Star Project Directory. Green Building Council of Australia (GBCA). http://www.gbca.org.au/project-directory.asp. [Accessed 13/08/2011]

[195] W.C. Booth, G.G. Colomb, J.M. Williams. The craft of research. 3rd ed. University of Chicago Press, Chicago ; London, 2008.

[196] M. Sandelowski. Sample-Size in Qualitative Research. Research in Nursing & Health. 18 (1995) 179-83.

[197] A. Strauss, J. Corbin. Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory. (1998).

[198] C. Sallfors, A. Fasth, L.R.M. Hallberg. Oscillating between hope and despair - a qualitative study. Child Care Health and Development. 28 (2002) 495-505.

[199] D. Douglas. Inductive theory generation: A grounded approach to business inquiry. Electronic journal of business research methods. 2 (2003) 47.

[200] B. Glaser, A. Strauss. The Discovery of Grounded Theory: strategies for qualitative research. (1967).

[201] C. Karkanias, S.N. Boemi, A.M. Papadopoulos, T.D. Tsoutsos, A. Karagiannidis. Energy efficiency in the Hellenic building sector: An assessment of the restrictions and perspectives of the market. Energy Policy. 38 (2010) 2776-84.

[202] B. Glaser. Theoretical Sensitivity: Advances in the Methodology of Grounded Theory. (1978).

[203] D. Douglas. Grounded theories of management: a methodological review. Management Research News. 26 (2003) 44-60.

[204] J. Corbin, A. Strauss. Grounded Theory Research: Procedures,Canons and Evaluative Criteria. Zeitschrift fur Soziologie. 19 (1990).

[205] R. Martin. The local geographies of the financial crisis: from the housing bubble to economic recession and beyond. Journal of Economic Geography. 11 (2011) 587-618.

[206] D. Guellec, S. Wunsch-Vincent. Policy Responses to the Economic Crisis: Investing in Innovation for Long-Term Growth. OECD, Directorate for Science, Technology and Industry. (2009).

[207] DEEWR. Joint Media Release $580 million fast-tracked into Australian universities. Department of Education Employment and Work Relations (DEEWR). http://mediacentre.dewr.gov.au/mediacentre/Gillard/Releases/580millionfasttrackedintoAustralianuniversities.htm. [Accessed 13/05/2011]

[208] C. Schneller, S. Golden. The Impact of the Financial Crisis to Higher Education. The 1st Asia-Europe Education Workshop. (2010).

[209] C.J. Kibert. Sustainable construction : green building design and delivery. 2nd ed. John Wiley & Sons, Hoboken, N.J., 2008.

[210] L. Heschong, R.L. Wright, S. Okura. Daylighting impacts on human performance in school. Journal of the Illuminating Engineering Society. 31 (2002) 101-+.

[211] L. Edwards, P. Torcellini. A literature review of the effects of natural light on building occupants. National Renewable Energy Laboratory, Golden, Colorado, USA, 2002.

[212] V. Anna-Maria. Evaluation of a sustainable Greek vernacular settlement and its landscape: Architectural typology and building physics. Building and Environment. 44 (2009) 1095-106.

[213] R. Mora, G. Bitsuamlak, M. Horvat. Integrated life-cycle design of building enclosures. Building and Environment. 46 (2011) 1469-79.

[214] G. Kim, J.T. Kim. Healthy-daylighting design for the living environment in apartments in Korea. Building and Environment. 45 (2010) 287-94.

[215] DEEWR. Education Investment Fund (EIF) Evaluation Criteria No. 2 of 2009. Department of Education Employment and Work Relations (DEEWR). http://www.comlaw.gov.au/Details/F2009L03016. [Accessed 20/10/2011]

[216] N. Sadafi, E. Salleh, L.C. Haw, Z. Jaafar. Evaluating thermal effects of internal courtyard in a tropical terrace house by computational simulation. Energy and Buildings. 43 (2011) 887-93.

[217] D. Marini. Optimization of HVAC systems for distributed generation as a function of different types of heat sources and climatic conditions. Applied Energy. 102 (2013) 813-26.

[218] X. Li, V. Strezov, M. Amati. A qualitative study of motivation and influences for academic green building developments in Australian universities. Journal of Green Buildings. 8 (2013).

[219] G.A.a. ABARE. Australian Energy Resource Assessment. in: G. Australia, (Ed.).2010. pp. 261-2.

[220] R.J. Davy, A. Troccoli. Interannual variability of solar energy generation in Australia. Solar Energy. 86 (2012) 3554-60.

[221] T. Miyazaki, A. Akisawa, T. Kashiwagi. Energy savings of office buildings by the use of semi-transparent solar cells for windows. Renewable Energy. 30 (2005) 281-304.

[222] P.W. Wong, Y. Shimoda, M. Nonaka, M. Inoue, M. Mizuno. Semi-transparent PV: Thermal performance, power generation, daylight modelling and energy saving potential in a residential application. Renewable Energy. 33 (2008) 1024-36.

[223] A. Chel, G.N. Tiwari, A. Chandra. Simplified method of sizing and life cycle cost assessment of building integrated photovoltaic system. Energy and Buildings. 41 (2009) 1172-80.

[224] X.Q. Zhai, M. Qu, Y. Li, R.Z. Wang. A review for research and new design options of solar absorption cooling systems. Renewable & Sustainable Energy Reviews. 15 (2011) 4416-23.

[225] D. Chemisana, J. Lopez-Villada, A. Coronas, J.I. Rosell, C. Lodi. Building integration of concentrating systems for solar cooling applications. Applied Thermal Engineering. 50 (2013) 1472-9.

[226] Q.P. Ha, V. Vakiloroaya. A novel solar-assisted air-conditioner system for energy savings with performance enhancement. Procedia Engineering. 49 (2012) 116-23.

[227] D. Ibarra., C.F. Reinhart. Solar availability: a comparison study of six irradiation distribution methods. 12th Conference of International Building Performance Simulation Association. Proceedings of Building Simulation, Sydney, 2011. pp. 2627-34.

[228] D.B. Crawley, J.W. Hand, M. Kurnmert, B.T. Griffith. Contrasting the capabilities of building energy performance simulation programs. Building and Environment. 43 (2008) 661-73.

[229] J. Stromann-Andersen, P.A. Sattrup. The urban canyon and building energy use: Urban density versus daylight and passive solar gains. Energy and Buildings. 43 (2011) 2011-20.

[230] DOE. About EnergyPlus. U.S. Department of Energy. http://apps1.eere.energy.gov/buildings/energyplus/energyplus_about.cfm. [Accessed 30/04/2013]

[231] X.F. Pang, M. Wetter, P. Bhattacharya, P. Haves. A framework for simulation-based real-time whole building performance assessment. Building and Environment. 54 (2012) 100-8.

[232] A. Evans, V. Strezov, T.J. Evans. Assessment of sustainability indicators for renewable energy technologies. Renewable & Sustainable Energy Reviews. 13 (2009) 1082-8.

[233] DOCCEE. National greenhouse accounts (NGA) factors. Department of Climate Change and Energy Efficiency, Canberra, 2010.

[234] S. Sharples, H. Radhi. Assessing the technical and economic performance of building integrated photovoltaics and their value to the GCC society. Renewable Energy. 55 (2013) 150-9.

[235] M.J. Adinoyi, S.A.M. Said. Effect of dust accumulation on the power outputs of solar photovoltaic modules. Renewable Energy. 60 (2013) 633-6.

[236] M. Mani, R. Pillai. Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations. Renewable & Sustainable Energy Reviews. 14 (2010) 3124-31.

[237] S. Ghazi, A. Sayigh, K. Ip. Dust effect on flat surfaces - A review paper. Renewable & Sustainable Energy Reviews. 33 (2014) 742-51.

[238] S. Mekhilef, R. Saidur, M. Kamalisarvestani. Effect of dust, humidity and air velocity on efficiency of photovoltaic cells. Renewable & Sustainable Energy Reviews. 16 (2012) 2920-5.

[239] W.C. Whitman. Refrigeration & air conditioning technology. 6th ed. Delmar Cengage Learning, Clifton Park, N.Y., 2009.

[240] H. Lund. Renewable energy strategies for sustainable development. Energy. 32 (2007) 912-9.

[241] H. Okamoto, T. Suzuki, K. Mori, Z. Cao, T. Onuki, H. Kuwano. The advantages and potential of electret-based vibration-driven micro energy harvesters. International Journal of Energy Research. 33 (2009) 1180-90.

[242] Y. Uzun, E. Kurt. Performance exploration of an energy harvester near the varying magnetic field of an operating induction motor. Energy Conversion and Management. 72 (2013) 156-62.

[243] T.o. Ikeda. Fundamentals of piezoelectricity. Oxford University Press, Oxford ; New York, 1990.

[244] S. Saadon, O. Sidek. A review of vibration-based MEMS piezoelectric energy harvesters. Energy Conversion and Management. 52 (2011) 500-4.

[245] A. Erturk, D.J. Inman. Introduction to Piezoelectric Energy Harvesting. Piezoelectric Energy Harvesting. John Wiley & Sons, Ltd2011. pp. 1-18.

[246] G.E. Niell, A.E. Alex. Vibrational Energy Harvesting From Human Gait. IEEE/ASME Transactions on Mechatronics. 18 (2013).

[247] J. Nunes-Pereira, V. Sencadas, V. Correia, J.G. Rocha, S. Lanceros-Méndez. Energy harvesting performance of piezoelectric electrospun polymer fibers and polymer/ceramic composites. Sensors and Actuators A: Physical. 196 (2013).

[248] C.A. Howells. Piezoelectric energy harvesting. Energy Conversion and Management. 50 (2009) 1847-50.

[249] M.J. Guan, W.H. Liao. On the efficiencies of piezoelectric energy harvesting circuits towards storage device voltages. Smart Materials & Structures. 16 (2007) 498-505.

[250] A. Badel, D. Guyomar, E. Lefeuvre, C. Richard. Efficiency enhancement of a piezoelectric energy harvesting device in pulsed operation by synchronous charge inversion. Journal of Intelligent Material Systems and Structures. 16 (2005) 889-901.

[251] E. Lefeuvre, A. Badel, C. Richard, L. Petit, D. Guyomar. A comparison between several vibration-powered piezoelectric generators for standalone systems. Sensors and Actuators a-Physical. 126 (2006) 405-16.

[252] N. Elvin, A. Elvin, D.H. Choi. A self-powered damage detection sensor. Journal of Strain Analysis for Engineering Design. 38 (2003) 115-24.

[253] Y.J. Yoon, W.T. Park, K.H.H. Li, Y.Q. Ng, Y. Song. A Study of Piezoelectric Harvesters for Low-Level Vibrations in Wireless Sensor Networks. International Journal of Precision Engineering and Manufacturing. 14 (2013) 1257-62.

[254] H. Vocca, I. Neri, F. Travasso, L. Gammaitoni. Kinetic energy harvesting with bistable oscillators. Applied Energy. 97 (2012) 771-6.

[255] F. Duarte, F. Casimiro, D. Correia, R. Mendes, A. Ferreira. A new pavement energy harvest system. Renewable and Sustainable Energy Conference (IRSEC), 2013 International2013. pp. 408-13.

[256] C.-h. Sun, Y.-k. Zhang, J.-h. Du, G. Shang. Electromechanical Analysis of Piezoelectric Harvesting Unit from Road Vibration with FEA. Advanced Materials Research. 726 - 731 (2013) 3144-7.

[257] S. Cafiso, M. Cuomo, A. Di Graziano, C. Vecchio. Experimental Analysis for Piezoelectric Transducers Applications into Roads Pavements. Advances in Applied Materials and Electronics Engineering Ii. 684 (2013) 253-7.

[258] A. Arjun, A. Sampath, S. Thiyagarajan, V. Arvind. A novel approach to recycle energy using Piezoelectric Crystals. Int J Environ Sci Devel. 2 (2011) 488-92.

[259] J. Rastegar, C. Pereira, H.L. Nguyen. Piezoelectric-based power sources for harvesting energy from platforms with low frequency vibration - art. no. 617101. Smart Structures and Materials 2006: Industrial and Commercial Applications of Smart Structures Technologies. 6171 (2006) 17101-.

[260] T.-T. Wu, S.-H. Wang, W.-S. Yao, M.-C. Tsai. Analysis of high efficiency piezoelectric floor on intelligent buildings. IEEE. (2010) 1777-80.

[261] X. Li, V. Strezov, M. Amati. A Qualitative Study of Motivation and Influences for Academic Green Building Developments in Australian Universities. Journal of Green Building. 8 (2013) 166-83.

[262] J. Ryall. Japan harnesses energy from footsteps. The Telegraph. http://www.telegraph.co.uk/earth/energy/3721841/Japan-harnesses-energy-from-footsteps.html. [Accessed 04/05/2014]

[263] A. Office. New South Wales Auditor-General's Report. https://www.opengov.nsw.gov.au/desktop/13710. [Accessed 04/05/2014]

[264] DCC. National Greenhouse Accounts Factors—July 2013. Department of Climate Change and Energy Efficiency.

http://www.climatechange.gov.au/sites/climatechange/files/documents/07_2013/national-greenhouse-accounts-factors-july-2013.pdf. [Accessed 07/04/2014]

[265] E. Kiriyama, Y. Kajikawa. A multilayered analysis of energy security research and the energy supply process. Applied Energy.

[266] S.K. Mandotra, P. Kumar, M.R. Suseela, P.W. Ramteke. Fresh water green microalga Scenedesmus abundans: A potential feedstock for high quality biodiesel production. Bioresource Technology. 156 (2014) 42-7.

[267] P.V. Abdelnur, B.G. Vaz, J.D. Rocha, M.B.B. de Almeida, M.A.G. Teixeira, R.C.L. Pereira. Characterization of Bio-oils from Different Pyrolysis Process Steps and Biomass Using High-Resolution Mass Spectrometry. Energy & Fuels. 27 (2013) 6646-54.

[268] M. Auta, L.M. Ern, B.H. Hameed. Fixed-bed catalytic and non-catalytic empty fruit bunch biomass pyrolysis. Journal of Analytical and Applied Pyrolysis. (2014).

[269] M. Balat, M. Balat, E. Kirtay, H. Balat. Main routes for the thermo-conversion of biomass into fuels and chemicals. Part 1: Pyrolysis systems. Energy Conversion and Management. 50 (2009) 3147-57.

[270] M. Kılıç, A.E. Pütün, B.B. Uzun, E. Pütün. Converting of oil shale and biomass into liquid hydrocarbons via pyrolysis. Energy Conversion and Management. 78 (2014) 461-7.

[271] G.-G. Choi, S.-H. Jung, S.-J. Oh, J.-S. Kim. Total utilization of waste tire rubber through pyrolysis to obtain oils and CO2 activation of pyrolysis char. Fuel Processing Technology. 123 (2014) 57-64.

[272] G. Pourhashem, S. Spatari, A.A. Boateng, A.J. McAloon, C.A. Mullen. Life Cycle Environmental and Economic Tradeoffs of Using Fast Pyrolysis Products for Power Generation. Energy & Fuels. 27 (2013) 2578-87.

[273] C.A. Mullen, A.A. Boateng, N.M. Goldberg. Production of Deoxygenated Biomass Fast Pyrolysis Oils via Product Gas Recycling. Energy & Fuels. 27 (2013) 3867-74.

[274] C.H. Biradar, K.A. Subramanian, M.G. Dastidar. Production and fuel quality upgradation of pyrolytic bio-oil from Jatropha Curcas de-oiled seed cake. Fuel. 119 (2014) 81-9.

[275] T.M.T. Pham, K.H. Kurisu, K. Hanaki. Greenhouse gas emission mitigation potential of rice husks for An Giang province, Vietnam. Biomass & Bioenergy. 35 (2011) 3656-66.

[276] H. Viana, W.B. Cohen, D. Lopes, J. Aranha. Assessment of forest biomass for use as energy. GIS-based analysis of geographical availability and locations of wood-fired power plants in Portugal. Applied Energy. 87 (2010) 2551-60.

[277] A. Yesil, Y. Yilmaz. Review article: coffee consumption, the metabolic syndrome and non-alcoholic fatty liver disease. Alimentary Pharmacology & Therapeutics. 38 (2013) 1038-44.

[278] B. Bean. 18,000 cups of coffee per week. http://www.staffnews.mq.edu.au/past_issues/past_stories/2010/18,000_cups_of_coffee_per_week. [Accessed 21/03/2014]

[279] D. Pujol, C. Liu, J. Gominho, M.A. Olivella, N. Fiol, I. Villaescusa, et al. The chemical composition of exhausted coffee waste. Industrial Crops and Products. 50 (2013) 423-9.

[280] E.E. Kwon, H. Yi, Y.J. Jeon. Sequential co-production of biodiesel and bioethanol with spent coffee grounds. Bioresource Technology. 136 (2013) 475-80.

[281] R. Bedmutha, C.J. Booker, L. Ferrante, C. Briens, F. Berruti, K.K.C. Yeung, et al. Insecticidal and bactericidal characteristics of the bio-oil from the fast pyrolysis of coffee grounds. Journal of Analytical and Applied Pyrolysis. 90 (2011) 224-31.

[282] D.R. Vardon, B.R. Moser, W. Zheng, K. Witkin, R.L. Evangelista, T.J. Strathmann, et al. Complete Utilization of Spent Coffee Grounds To Produce Biodiesel, Bio-Oil, and Biochar. Acs Sustainable Chemistry & Engineering. 1 (2013) 1286-94.

[283] T. Kan, V. Strezov, T. Evans. Catalytic Pyrolysis of Coffee Grounds Using NiCu-Impregnated Catalysts. Energy & Fuels. 28 (2014) 228-35.

[284] E. Zanella, M. Della Zassa, L. Navarini, P. Canu. Low-Temperature Co-pyrolysis of Polypropylene and Coffee Wastes to Fuels. Energy & Fuels. 27 (2013) 1357-64.

[285] V. Strezov, T.J. Evans. Thermal processing of paper sludge and characterisation of its pyrolysis products. Waste Management. 29 (2009) 1644-8.

[286] V. Strezov, B. Moghtaderi, J.A. Lucas. Computational calorimetric investigation of the reactions during thermal conversion of wood biomass. Biomass & Bioenergy. 27 (2004) 459-65.

[287] V. Strezov, B. Moghtaderi, J.A. Lucas. Thermal study of decomposition of selected biomass samples. Journal of Thermal Analysis and Calorimetry. 72 (2003) 1041-8.

[288] V. Strezov, M. Patterson, V. Zymla, K. Fisher, T.J. Evans, P.F. Nelson. Fundamental aspects of biomass carbonisation. Journal of Analytical and Applied Pyrolysis. 79 (2007) 91-100.

[289] S. Grierson, V. Strezov, G. Ellem, R. Mcgregor, J. Herbertson. Thermal characterisation of microalgae under slow pyrolysis conditions. Journal of Analytical and Applied Pyrolysis. 85 (2009) 118-23.

[290] T. Kan, S. Grierson, R. de Nys, V. Strezov. Comparative Assessment of the Thermochemical Conversion of Freshwater and Marine Micro- and Macroalgae. Energy & Fuels. 28 (2014) 104-14.

[291] C. Torri, I.G. Lesci, D. Fabbri. Analytical study on the pyrolytic behaviour of cellulose in the presence of MCM-41 mesoporous materials. Journal of Analytical and Applied Pyrolysis. 85 (2009) 192-6.

[292] A.P. Craig, A.S. Franca, L.S. Oliveira. Discrimination between defective and non-defective roasted coffees by diffuse reflectance infrared Fourier transform spectroscopy. Lwt-Food Science and Technology. 47 (2012) 505-11.

[293] J. Wang, S. Jun, H.C. Bittenbender, L. Gautz, Q.X. Li. Fourier Transform Infrared Spectroscopy for Kona Coffee Authentication. Journal of Food Science. 74 (2009) C385-C91.

[294] B.R. Singh, M.A. Wechter, Y.H. Hu, C. Lafontaine. Determination of caffeine content in coffee using Fourier transform infra-red spectroscopy in combination with attenuated total reflectance technique: a bioanalytical chemistry experiment for biochemists. Biochemical Education. 26 (1998) 243-7.

[295] A. Farah, T. De Paulis, L.C. Trugo, P.R. Martin. Effect of roasting on the formation of chlorogenic acid lactones in coffee. Journal of Agricultural and Food Chemistry. 53 (2005) 1505-13.

[296] L. Lin, R. Yan, Y. Liu, W. Jiang. In-depth investigation of enzymatic hydrolysis of biomass wastes based on three major components: Cellulose, hemicellulose and lignin. Bioresource Technology. 101 (2010) 8217-23.

[297] S.I. Mussatto, L.M. Carneiro, J.P.A. Silva, I.C. Roberto, J.A. Teixeira. A study on chemical constituents and sugars extraction from spent coffee grounds. Carbohydrate Polymers. 83 (2011) 368-74.

[298] C. Djilani, R. Zaghdoudi, A. Modarressi, M. Rogalski, F. Djazi, A. Lallam. Elimination of organic micropollutants by adsorption on activated carbon prepared from agricultural waste. Chemical Engineering Journal. 189 (2012) 203-12.

[299] M.G. Plaza, A.S. Gonzalez, C. Pevida, J.J. Pis, F. Rubiera. Valorisation of spent coffee grounds as CO2 adsorbents for postcombustion capture applications. Applied Energy. 99 (2012) 272-9.

[300] C. Rodriguez, G. Gordillo. Adiabatic gasification and pyrolysis of coffee husk using air-steam for partial oxidation. Journal of Combustion. 2011 (2011).

[301] H.P. Yang, R. Yan, H.P. Chen, C.G. Zheng, D.H. Lee, D.T. Liang. In-depth investigation of biomass pyrolysis based on three major components: Hemicellulose, cellulose and lignin. Energy & Fuels. 20 (2006) 388-93.

[302] C.J. Mulligan, L. Strezov, V. Strezov. Thermal Decomposition of Wheat Straw and Mallee Residue Under Pyrolysis Conditions. Energy & Fuels. 24 (2010) 46-52.

[303] P.T. Williams, S. Besler. The influence of temperature and heating rate on the pyrolysis of biomass. Renewable Energy. 7 (1996) 233-50.

[304] Q.H. Lin, G.Y. Chen, Y.K. Liu. Scale-up of microwave heating process for the production of bio-oil from sewage sludge. Journal of Analytical and Applied Pyrolysis. 94 (2012) 114-9.

[305] J. Becker, L.L. Toft, D.F. Aarup, S.R. Villadsen, M. Glasius, S.B. Iversen, et al. A High Temperature, High Pressure Facility for Controlled Studies of Catalytic Activity under Hydrothermal Conditions. Energy & Fuels. 24 (2010) 2737-46.

[306] J.D. Martinez, A. Veses, A.M. Mastral, R. Murillo, M.V. Navarro, N. Puy, et al. Co-pyrolysis of biomass with waste tyres: Upgrading of liquid bio-fuel. Fuel Processing Technology. 119 (2014) 263-71.

[307] T.N. Trinh, P.A. Jensen, K. Dam-Johansen, N.O. Knudsen, H.R. Sorensen. Influence of the Pyrolysis Temperature on Sewage Sludge Product Distribution, Bio-Oil, and Char Properties. Energy & Fuels. 27 (2013) 1419-27.

[308] R.R. Xiao, W. Yang. Influence of temperature on organic structure of biomass pyrolysis products. Renewable Energy. 50 (2013) 136-41.

[309] Z.H. Wang, D.Z. Chen, X.D. Song, L. Zhao. Study on the combined sewage sludge pyrolysis and gasification process: mass and energy balance. Environmental Technology. 33 (2012) 2481-8.

[310] M.A. Green, K. Emery, Y. Hishikawa, W. Warta, E.D. Dunlop. Solar cell efficiency tables (version 39). Progress in photovoltaics: research and applications. 20 (2012) 12-20.

[311] B. Hebenstreit, R. Schnetzinger, R. Ohnmacht, E. Höftberger, J. Lundgren, W. Haslinger, et al. Techno-economic study of a heat pump enhanced flue gas heat recovery for biomass boilers. Biomass and Bioenergy.

[312] S. Evangelisti, P. Lettieri, R. Clift, D. Borello. Distributed Generation By Energy From Waste Technology: A Life Cycle Perspective. Process Safety and Environmental Protection.

[313] GBCA. Green Star – Ene-1 Greenhouse Gas Emissions. Green Building Council of Australia. http://www.gbca.org.au/green-star/queries-and-rulings/ene-1-greenhouse-gas-emissions/35198.htm. [Accessed 07/04/2014]

Appendix A: Declaration of Authorship Contributions

A Qualitative Study of Motivation and Influences for Academic Green Building Developments in Australian Universities

Contributions to the paper were as follows:

(85%) Xiaofeng Li undertook the data collection, including survey and interviews in the new library of Macquarie University and then conducted the analytical work, with the supervision and assistance of Vladimir Strezov and Marco Amati. Xiaofeng was the primary author and correspondent for the manuscript.

(10%) Vladimir Strezov acted in his capacity as Principal Supervisor in supporting the analytical work and was a major reviewer of the manuscript.

(5%) Marco Amati supported this work as Co-Supervisor in setting up contact with the Green Building Council of Australia for building data and interviewee candidates. Marco also reviewed the manuscript.

Energy, CO_2 Emission Assessment of Conventional and Solar Assisted Air Conditioning Systems

Contributions to the paper were as follows:

(90%) Xiaofeng Li undertook the data collection, modelling and analytical work in this work. Xiaofeng was the primary author and correspondent for the manuscript.

(10%) Vladimir Strezov acted in his capacity as Principal Supervisor in supporting the analytical work and was a major reviewer of the manuscript.

Modelling Piezoelectric Energy Harvesting Potential in an Educational Building

Contributions to the paper were as follows:

(90%) Xiaofeng Li undertook the data collection, modelling and analytical work in this work. Xiaofeng was the primary author and correspondent for the manuscript.

(10%) Vladimir Strezov acted in his capacity as Principal Supervisor in supporting the analytical work and was a major reviewer of the manuscript.

Energy Recovery Potential Analysis of Spent Coffee Grounds Pyrolysis Products

Contributions to the paper were as follows:

(85%) Xiaofeng Li undertook the sample collection in the cafeteria of the new library at Macquarie University. Xiaofeng then conducted the thermal conversion and analytical tests in the laboratory at Macquarie University, with the supervision and assistance of Vladimir Strezov. Xiaofeng was the primary author and correspondent for the manuscript.

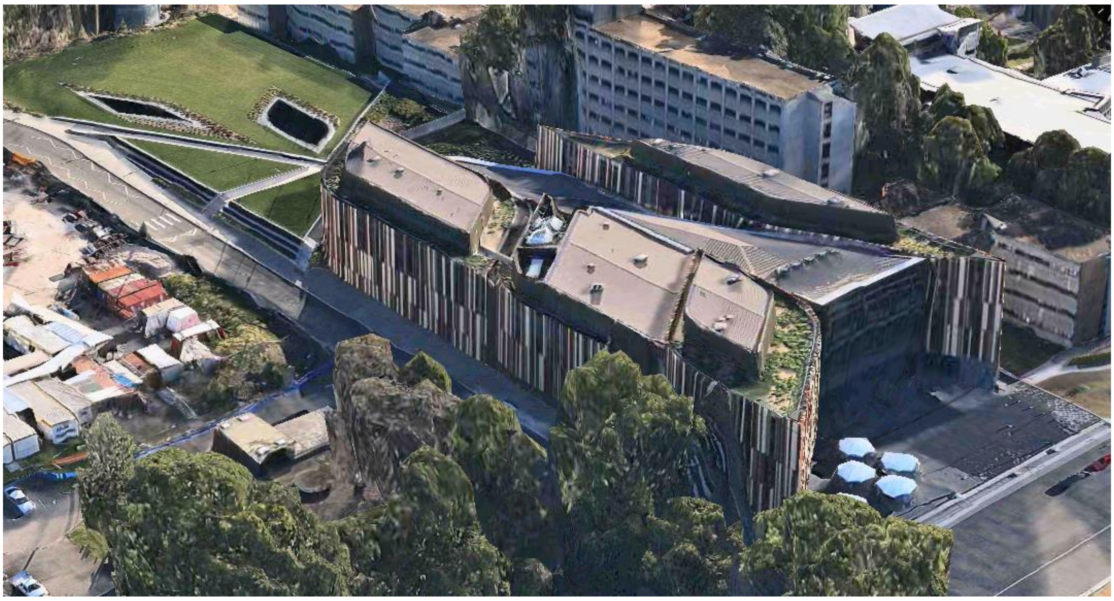
(10%) Vladimir Strezov acted in his capacity as Principal Supervisor in supporting the analytical work and was a major reviewer of the manuscript.

(5%) Tao Kan acted in his capacity as a Post-Doctoral Researcher by providing assistance in operation of the GC and GC-MS work.

Appendix B: Supplementary Information

The following represents supplementary information relevant to the case study building.

B1. Architectural Appearance of the Library Building with the Adjacent Buildings

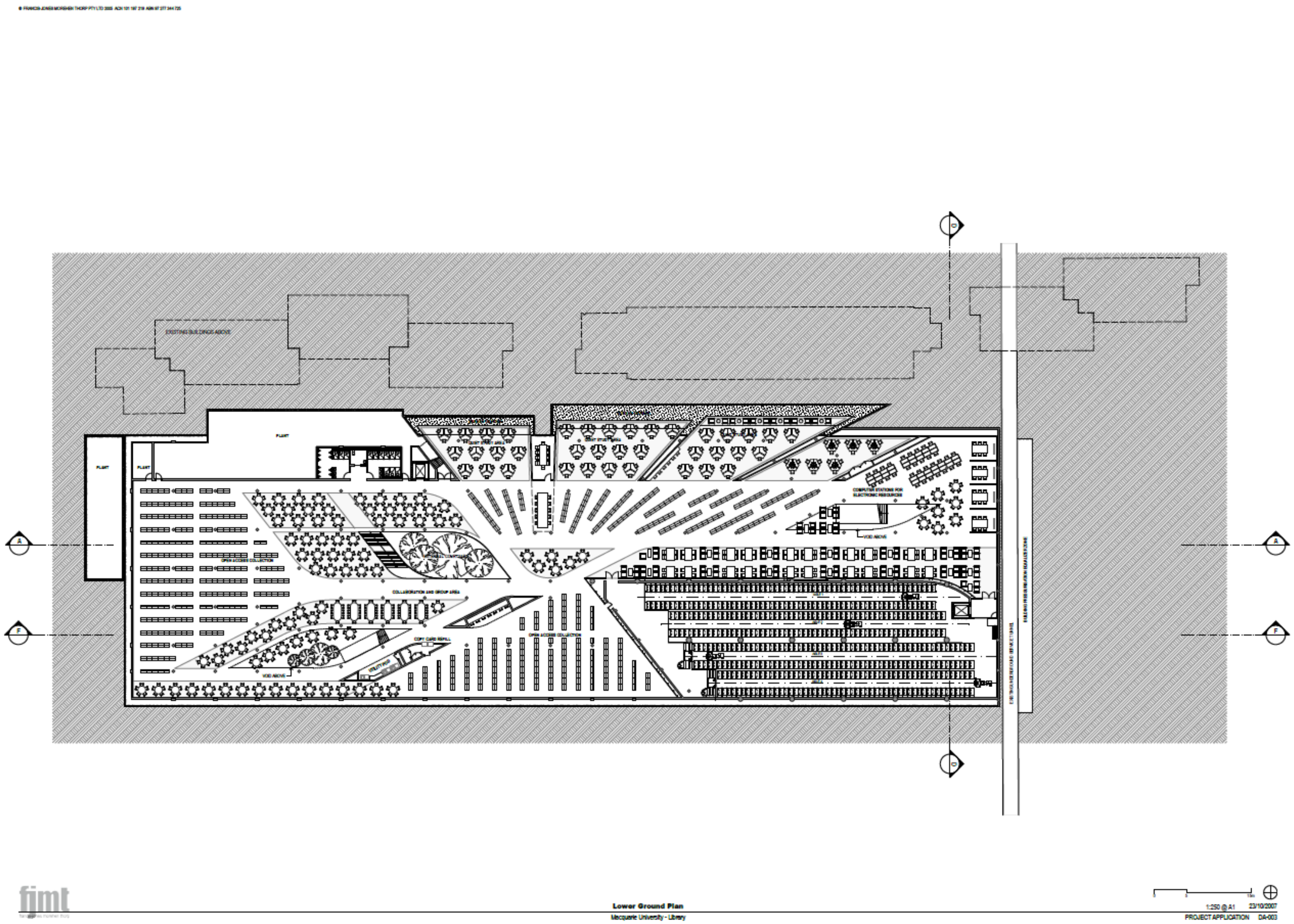


B2. Building Drawing Plans

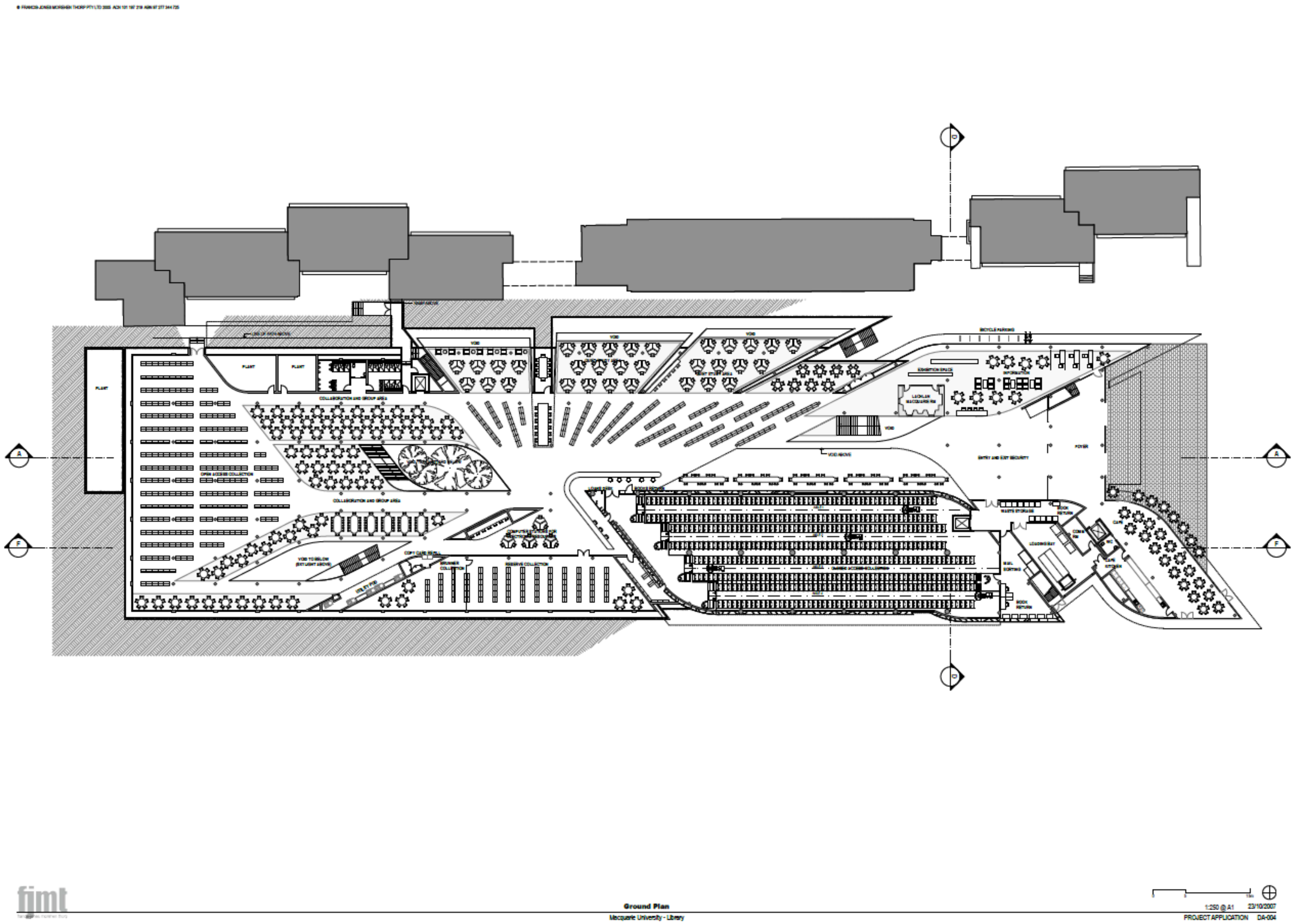
The building drawing plans were obtained from Macquarie University Library webpage:

http://library.mq.edu.au/newlibrary/keydocs.html

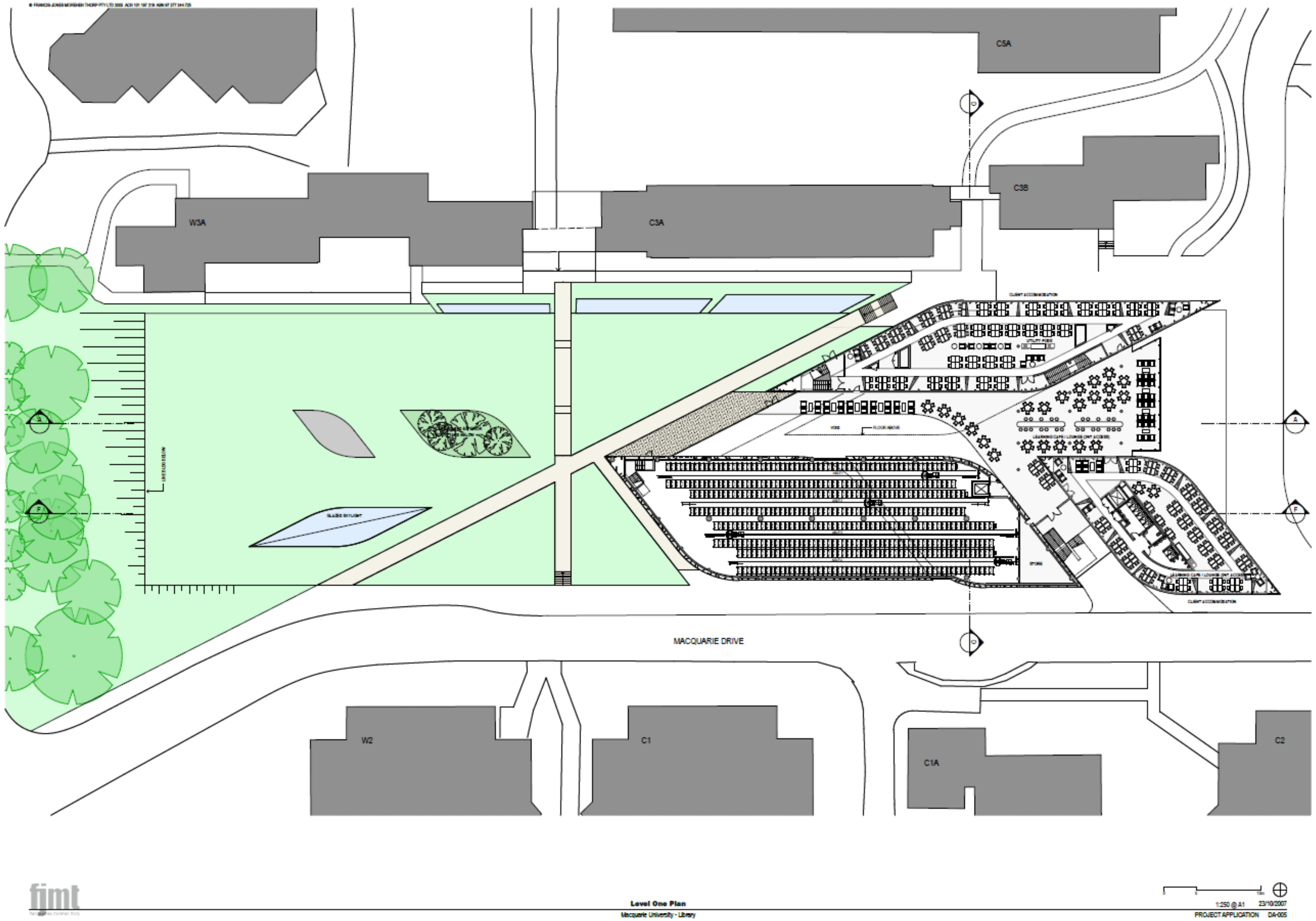
B2.1 Lower Ground Level Plan



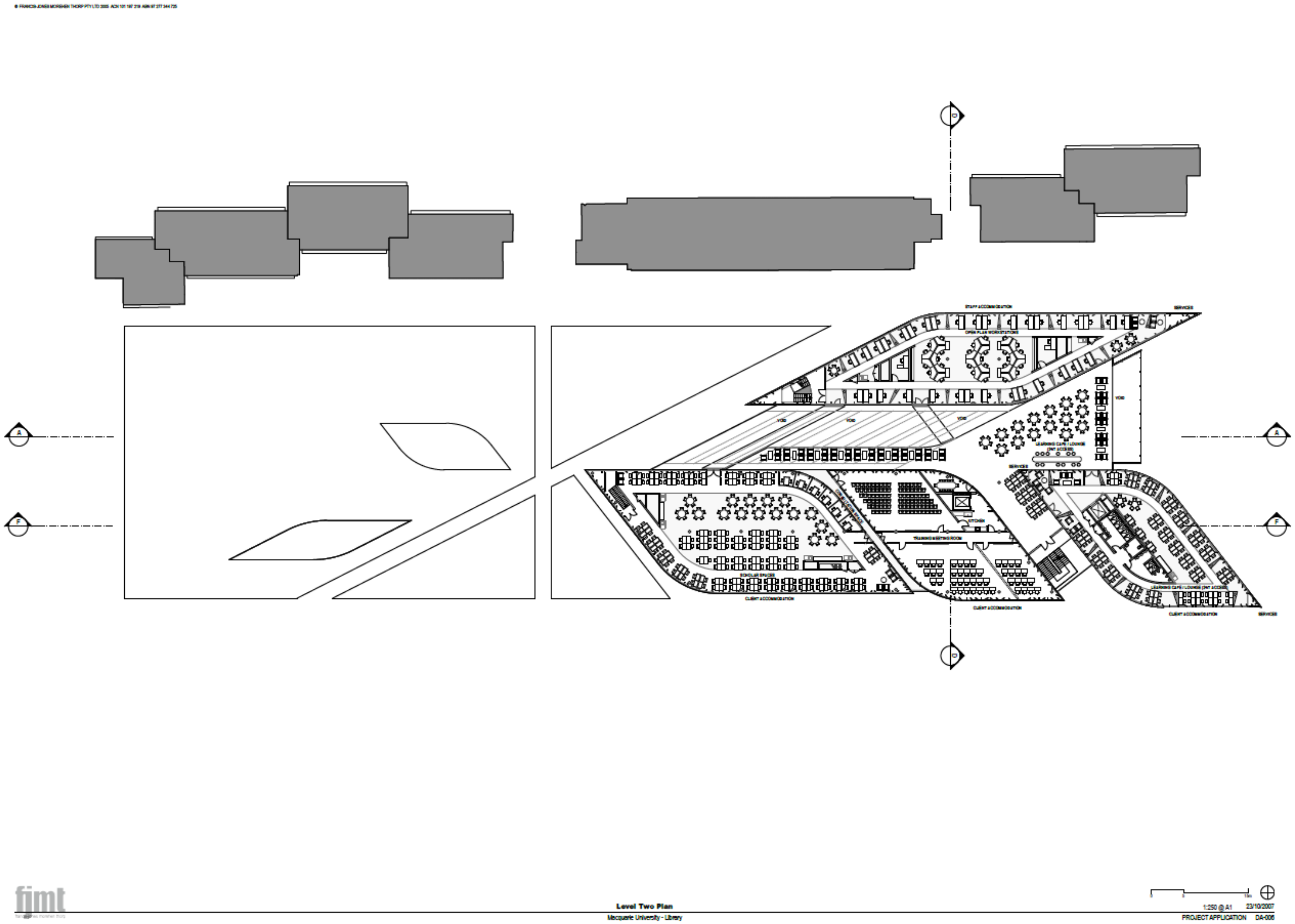
B2.2 Ground Level Plan



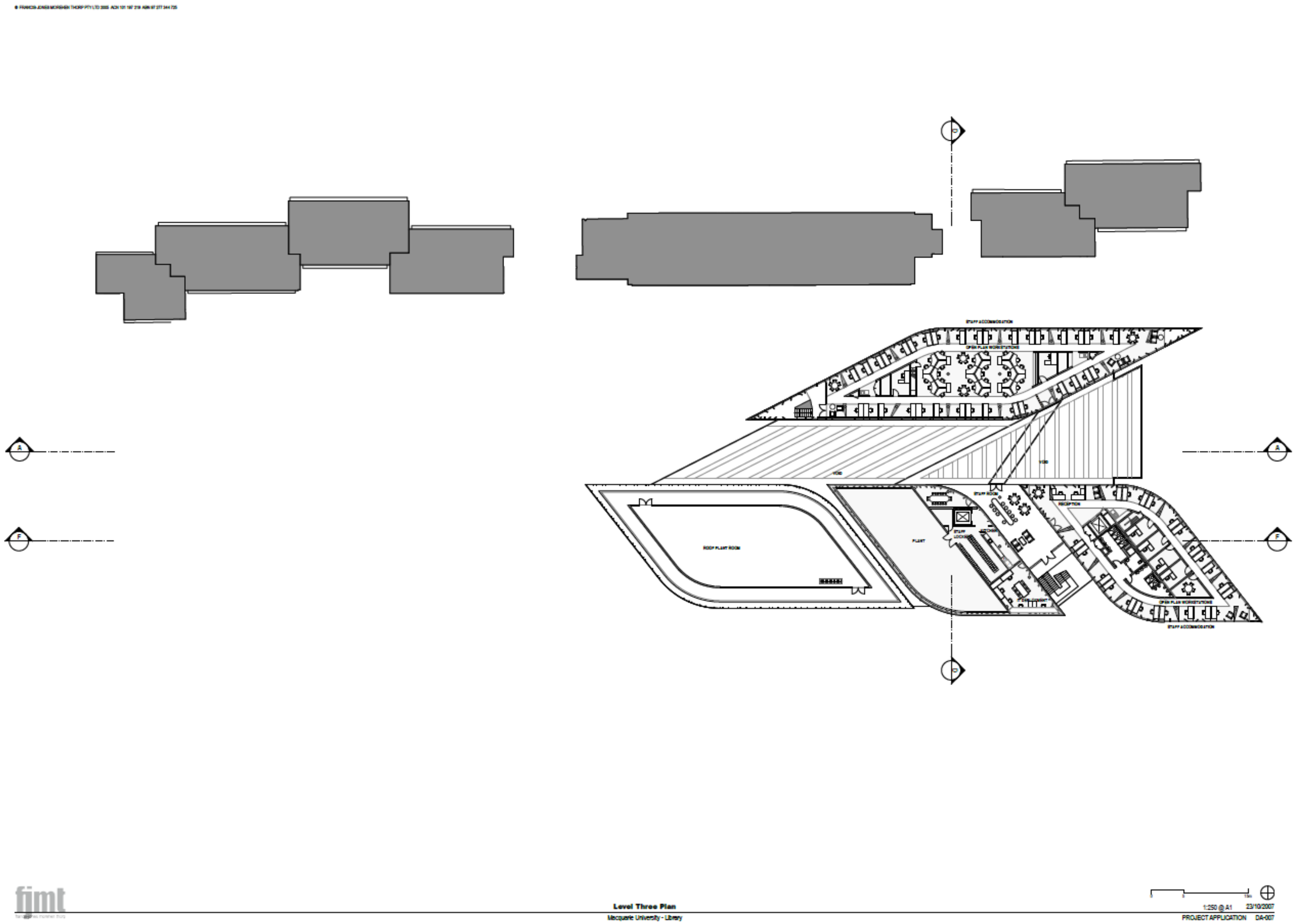
B2.3 Level One Plan



B2.4 Level Two Plan



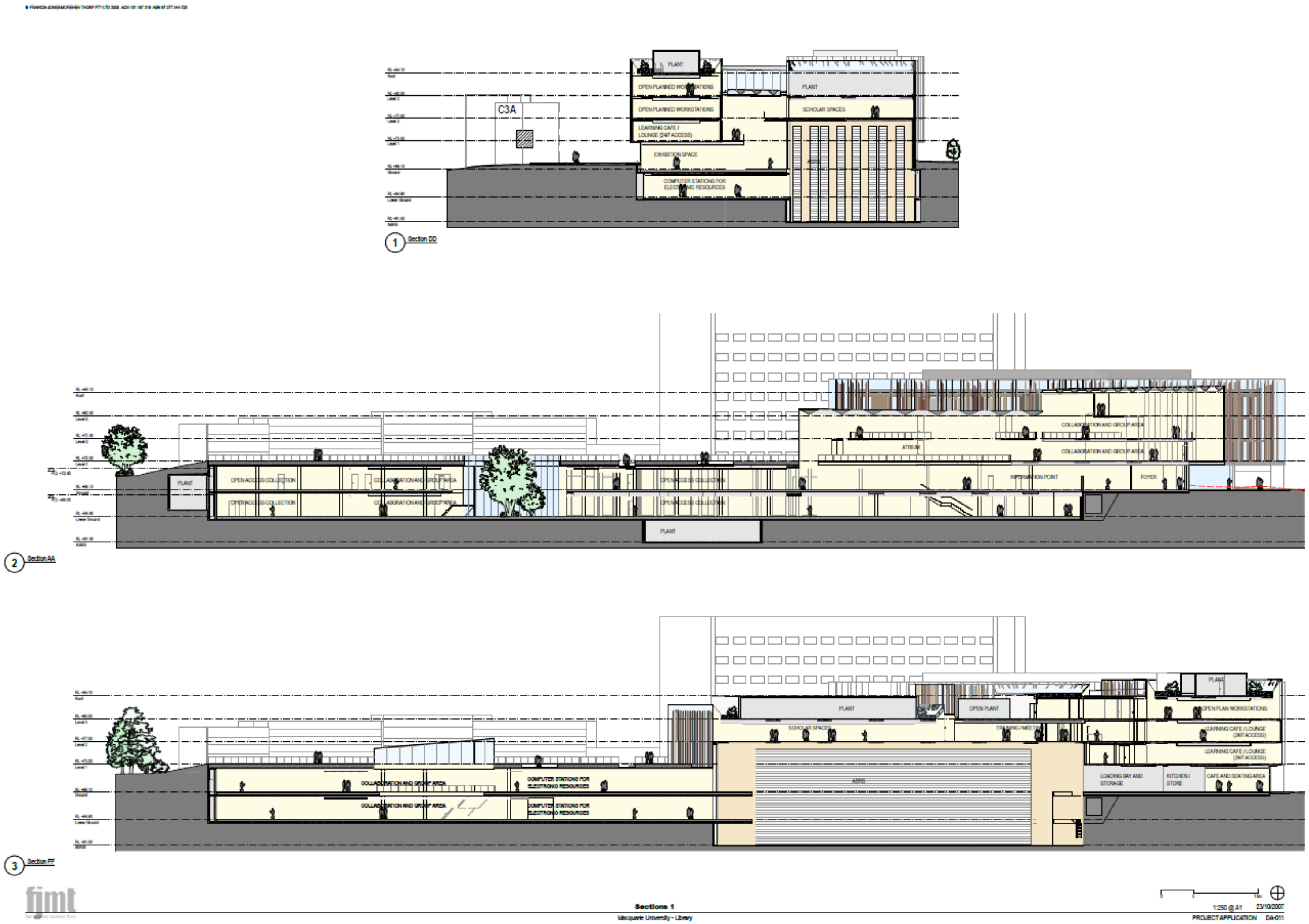
B2.5 Level Three Plan



B2.6 Elevation 1

B2.7 Elevation 2

B2.8 Section



Appendix C: Bioenergy Recovery Using Anaerobic Digestion

C1. Method

The biogas yield potential of spent coffee grounds was determined using batch anaerobic digestion tests. The sample was digested using a 500 mL glass digester at an initial loading of 25.7 g in an incubator which provided the digester a static thermophilic temperature of 50±2 ^{0}C. At the beginning of the digestion tests, 25.4 g inoculum was mixed with the sample substrate. The inoculum was dewatered sludge collected directly from the centrifuge exit of a municipal wastewater treatment plant in Sydney, Australia. The sludge had average TS and VS/TS values of 84.7% (dry basis) and 48.5%, respectively.

In order to correct the biogas produced from the inoculum, a blank digester, which contained only the inoculum at the same amount of 25 g, was incubated under the same thermal conditions. The pH value of the sample with inoculum batch was 6.9, while for the inoculum only batch was 8.5. After the sample substrate and inoculum were added, each digester was filled up to 250 mL with tap water. The effective volume of each digester was 250 mL. The digesters were tightly closed with a rubber stopper and airtight tapes. To assure the anaerobic conditions, the head space was purged with nitrogen gas for five minutes. During the experiment, each digester was manually mixed once a day.

The biogas produced was collected and measured using water displacement technique, as illustrated in Figure C1 and its methane content was measured by a gas chromatograph (GC).

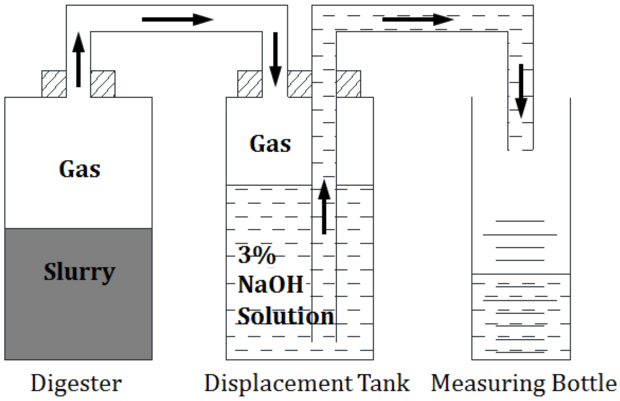


Figure C1. Schematic description of anaerobic digestion with water displacement set up.

C2. Results

The methane yield and methane production rate during the digestion of spent coffee grounds are shown in Figure C2 a) and b), respectively. The digestion process of spent coffee grounds lasted for 14 days and an amount of 310 mL methane was produced during the process, while the digestion in the blank digester was fully completed on the 9th day with a total amount of 85 mL methane yield. The pH value of the sample slurry after digestion was 5.84, and the slurry in the blank digester was pH of 7.78. Comparing the sample and blank digesters, it is obvious that the majority of methane was obtained during the first two days. A dramatic drop in the methane production rate was observed after the second day. For the sample curve, the production rate presented a continuous decrease trend and reached the bottom at the 9th day. The digestion process formally ceased on the 13th day after a second small yield increase during the day 10 to 12.

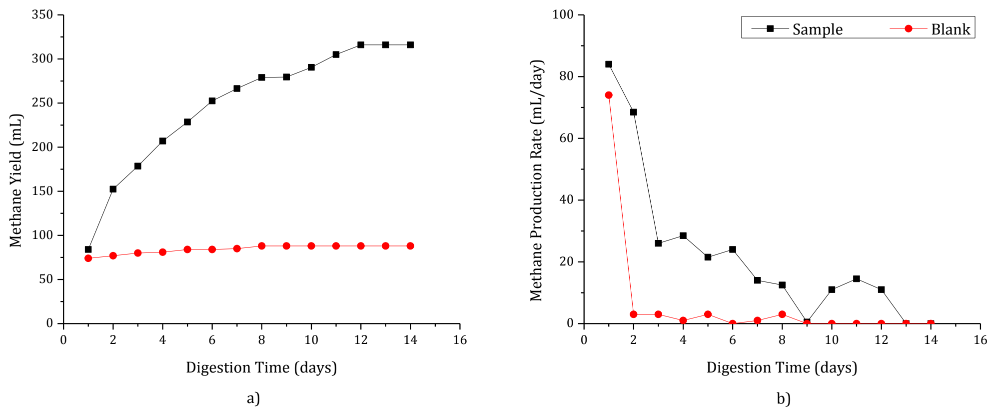


Figure C2. Methane yield of spend coffee grounds during anaerobic digestion at 50 ^{0}C a) methane yield, b) methane production rate.

Appendix D: Final Ethics Approval Letter

MACQUARIE UNIVERSITY

XIAOFENG LI <xiaofeng.li2@students.mq.edu.au>

Final Approval - Issues Addressed

1 message

Faculty of Science Research Office <sci.ethics@mq.edu.au> Thu, Nov 29, 2012 at 1:44 PM

To: Dr Vladimir Strezov <vladimir.strezov@mq.edu.au>, Dr Marco Amati <marco.amati@mq.edu.au>, Mr Xiaofeng Li <xiaofeng.li2@students.mq.edu.au>
Cc: Prof Richie Howitt <richie.howitt@mq.edu.au>, Ms Katherine Wilson <katherine.wilson@mq.edu.au>

Dear Dr Strezov,

RE: Ethics project entitled:"A qualitative study of motivation and influences for Academic Green building development in Australian Universities"
Ref number: 5201200830.

Thank you for your recent correspondence. Your response has addressed the issues raised by the Faculty of Science Human Research Ethics Sub-Committee and you may now commence your research.

This research meets the requirements of the National Statement on Ethical Conduct in Human Research (2007). The National Statement is available at the following web site:

http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/e72.pdf.

The following personnel are authorised to conduct this research:
Assoc Prof Vlad Strezov
Dr Marco Amati
Mr Xiaofeng Li

NB. STUDENTS: IT IS YOUR RESPONSIBILITY TO KEEP A COPY OF THIS APPROVAL EMAIL TO SUBMIT WITH YOUR THESIS.

Please note the following standard requirements of approval:

1. The approval of this project is conditional upon your continuing compliance with the National Statement on Ethical Conduct in Human Research (2007).

2. Approval will be for a period of five (5) years subject to the provision of annual reports.

Progress Report 1 Due: 28 November 2013
Progress Report 2 Due: 28 November 2014
Progress Report 3 Due: 28 November 2015
Progress Report 4 Due: 28 November 2016
Final Report Due: 28 November 2017

NB. If you complete the work earlier than you had planned you must submit a Final Report as soon as the work is completed. If the project has been discontinued or not commenced for any reason, you are also required to submit a Final Report for the project.

Progress reports and Final Reports are available at the following website:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/forms

3. If the project has run for more than five (5) years you cannot renew approval for the project. You will need to complete and submit a Final Report and submit a new application for the project. (The five year limit on renewal of approvals allows the Committee to fully re-review research in an environment where legislation, guidelines and requirements are continually changing, for example, new child protection and privacy laws).

4. All amendments to the project must be reviewed and approved by the Committee before implementation. Please complete and submit a Request for Amendment Form available at the following website:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/forms

5. Please notify the Committee immediately in the event of any adverse effects on participants or of any unforeseen events that affect the continued ethical acceptability of the project.

6. At all times you are responsible for the ethical conduct of your research in accordance with the guidelines established by the University. This information is available at the following websites:
http://www.mq.edu.au/policy/

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/policy

If you will be applying for or have applied for internal or external funding for the above project it is your responsibility to provide the Macquarie University's Research Grants Management Assistant with a copy of this email as soon as possible. Internal and External funding agencies will not be informed that you have final approval for your project and funds will not be released until the Research Grants Management Assistant has received a copy of this email.

If you need to provide a hard copy letter of Final Approval to an external organisation as evidence that you have Final Approval, please do not hesitate to contact the Ethics Secretariat at the address below.

Please retain a copy of this email as this is your official notification of final ethics approval.

Yours sincerely,
Richie Howitt, Chair
Faculty of Science Human Research Ethics Sub-Committee
Macquarie University
NSW 2109

Appendix E: Endnote

---

[i] Innova 21 SA - GBCA Green Star Case Study

http://www.gbca.org.au/greenstar-projects/project-profile.asp?projectID=791;

[accessed 13.05.11]

[ii] Major medical science precinct taking shape

http://www.brandtasmania.com/newsletter.php?ACT=story&issue=103&story=0;

[accessed 12.08.11]

[iii] New cancer research centre for Sydney

http://www.smh.com.au/news/National/New-cancer-research-centre-for-Sydney/2007/06/25/1182623779331.html; [accessed 12.05.11]

[iv] NaLSH Newsletter October 2010

http://www.csu.edu.au/division/facilitiesm/projects/nalsh-additional-info; [accessed 16.05.11]

[v] Bond University Mirvac School of Sustainable Development - GBCA Green Star Case Study

http://www.gbca.org.au/greenstar-projects/project-profile.asp?projectID=146;

[accessed 17.05.11]

[vi] $205M science & technology hub for QUT

http://www.projectlink.com.au/IndustryNews/$205m-science--technology-hub-for-qut.html; [accessed 14.05.11]

[vii] Bond University's new building dazzles under 6 green stars

http://www.arup.com/News/2008-08%20August/11-08-08-Bond_Universitys_new_building_dazzles_under_6_green_stars.aspx; [accessed 17.05.11]

[viii] Academic Accommodation 3 - GBCA Green Star Case Study

http://www.gbca.org.au/greenstar-projects/project-profile.asp?projectID=491;

[accessed 17.05.11]

[ix] Australian Hearing Hub

http://www.mq.edu.au/omp/projects/projects_hearing_hub.html; [accessed 14.05.11]

[x] Parkville Centre for Neuroscience and Austin Neuroscience Facility

http://www.umowlai.com.au/projects.asp?PageID=137; [accessed 12.05.11]

[xi] Sneak preview of new research centre

http://www.acrf.com.au/2010/sneak-preview-of-new-research-centre/; [accessed 12.05.11]

[xii] Construction of new Shepparton campus to begin

http://www.latrobe.edu.au/news/articles/2009/article/construction-of-new-shepparton-campus-to-begin; [accessed 16.05.11]

xiii La Trobe Institute of Molecular Science, Victoria, Australia

http://www.e-architect.co.uk/melbourne/la_trobe_institute.htm; [accessed 15.05.11]

[xiv] Design Hub vision

http://rmit.net.au/browse;ID=vk2dipqcc5t71; [accessed 13.05.11]

xv University's new Peter Doherty Institute receives $90m in funding

http://blogs.unimelb.edu.au/musse/?p=491; [accessed 12.05.11]

[xvi] Engineering Pavilion to become green centrepiece for Curtin

http://www.sciencewa.net.au/index.php?/energy/technology-and-innovation/engineering-pavilion-to-become-greencentrepiece-for-curtin.html;

[accessed 16.05.11]

[xvii] Bond University Mirvac School of Sustainable Development

http://www.mirvac.com/Mirvac-School-of-Sustainable-Development; [accessed 17.05.11]

[xviii] New business hub

http://www.fbe.unimelb.edu.au/about/berkeley_st.html; [accessed 12.05.11]

[xix] $75m Australian Catholic University Health and Wellbeing Centre by Woods Bagot Approved

http://www.e-architect.co.uk/melbourne/acu_centre_health_wellbeing.htm; [accessed 17.05.11]

[xx] Medical Science Precinct

http://www.menzies.utas.edu.au/article.php?Doo=ContentView&id=1273; [accessed 20.06.11]