Spring 2010

Energy From the Sun: A Solar Feasibility Study for Macquarie University

JJ Augenbraun
SIT Study Abroad

Energy from the Sun:
A Solar Feasibility Study for Macquarie University

Augenbraun, JJ
Academic Director: Brennan, Peter
Project Advisor: Davies, Carol
Williams College
Psychology
Australia, Sydney
Submitted in partial fulfillment of the requirements for Australia: Sustainability and Environmental Action, SIT Study Abroad, Spring 2010

Abstract

Macquarie University uses over 30,000,000 kilowatt hours (kWh) of electricity per year. As one of the largest energy consumers in its area, the University is looking for ways to reduce the cost and environmental impact associated with its operations. One possible option is the use of solar energy to generate electricity on campus. However, solar energy is a complicated issue, especially for a large scale project. By taking the time to evaluate options prior to beginning a project of this scale, money and effort can be saved in the future. The purpose of this study is to examine the feasibility and associated benefits of installing solar electricity generation capacity on campus.

This report begins by looking at the various options for solar systems at Macquarie University. Solar insolation data from NASA were used to calculate the estimated amount of electricity that each system would produce annually. Cost data were used to estimate the cost of each system and the cost per kWh of electricity from each system. In addition, space and energy use data from the University were used to determine the size and capacity of the systems required and the availability of space on campus. Furthermore, interviews with nine people were used to evaluate the non-financial benefits of using solar at the University.

A large scale one axis tracking photovoltaic system proved to be the cheapest option with a 16 year payback period and a cost of $0.26 per kWh. With the currently available 71,000 square meters of usable space, up to 12,850,000 kWh or 42% of the University's 2010 electricity use could be generated with solar energy. By 2020, with the addition of another 26,700 square meters of usable space, up to17,680,000 kWh of electricity could be generated per year. However, this would only provide 32% of the University's 2020 projected electricity demand. By 2030, another 10,000 square meters of space will be available, increasing annual generation to 19,500,000 kWh or 31% of the University's 2030 electricity use. Non-financial benefits included: reduced environmental impact, learning and teaching opportunities, a symbol of commitment to sustainability, energy security, and publicity.

The University cannot generate 100% of its electricity from on campus solar installations. In addition, solar electricity is relatively expensive compared to current electricity prices. However, given the long time horizon for the University and the non-financial benefits, the University should consider installing at least one of the smaller systems identified in the discussion section.

ISP Topic Codes:
Environmental Studies (527), Sustainable Technologies (803), Higher Education (213)
Keywords:
Solar Energy, Feasibility Study

Table of Contents

Acknowledgements

Firstly, I would like to thank Hilary Bekmann at Macquarie University's Sustainability Office. Hilary is the Manager of Operational Sustainability at Macquarie University and helped make this project possible. From organizing interviews to providing me with information about Macquarie University's operations to reading over drafts of this paper, Hilary's help was invaluable. I would also like to thank the rest of the staff at Macquarie University's Sustainability Office and Office of Facilities Management. Thank you for letting me work in your office and providing me with help throughout my project. To Leanne Denby (Director of Sustainability), John Macris (Biodiversity Director), Adrian Emilsen (Sustainable Transport Officer), Belinda Bean (Sustainable Support Officer), Michelle Shackleton (Sustainable Research Assistant), and Iain Brew (Sustainability Multimedia Administrator): thank you for taking the time to offer your insights into sustainability at Macquarie University and giving me information for my report. I would also like to thank Eden Ottignon, a student at the University, for making time for me to interview him.

In addition, I would like to thank everyone associated with the SIT: Sustainability and Environmental Action program. I would especially like to thank Carol Davies, my ISP advisor and Sustainability Officer at Armidale City Council and the University of New England, for all her help on organizing this project. Thank you for dealing with all my questions and reading over a draft of my paper. Also, I would like to thank Peter Brennan, the Academic Director, for organizing a great semester. I would like to thank Laura Brennan, the Program Director, for teaching me how to effectively use field research techniques. In addition, I would like to thank David Brown, the Program Assistant, for helping with all the program logistics and making sure we stay safe during ISP.

Finally, I would like to thank Daniel, Katherine, Maryanne, and Ellie Trees for letting me stay at their house in Denistone during ISP. They were wonderful hosts, and I really enjoyed spending five weeks staying with them.

Thank you again to all who have helped me with this project.

List of Figures and Tables

1. Introduction

1.1. World and Australian Energy Consumption

According to the U.S. Department of Energy, the world population consumed approximately 472 quadrillion British Thermal Units (Btu) of energy in 2006. In 2010, the Department of Energy estimates that this number will grow to 508 quadrillion Btu and will reach 678 quadrillion Btu by 2030 (U.S. Department of Energy 2009b). Of this amount, Australia consumes approximately 5.6 quadrillion Btu, which is one of the highest per capita rates of consumption in the world. This Btu measurement encompasses all energy used in Australia and includes all energy generated from any source of fuel (U.S. Department of Energy 2009a).

In 2006, liquid fuels were the largest single source of energy in the world and provided 40% of world energy. This category includes fuels derived from both petroleum and biological sources. Coal is the second largest source of energy, providing approximately 25% of world energy in 2006. Coal is followed by natural gas at approximately 23% and then renewable sources at 7% and finally nuclear energy at 5% (Figure 1.1). Renewable sources are the fastest growing source of energy, increasing at a rate of 3% per year. However, the vast majority of renewable energy comes from hydroelectricity, leaving solar, wind, and geothermal energy largely untapped (Figure 1.2, U.S. Department of Energy 2009b).

Figure 1.1. World energy use by fuel type, 1980-2030. Source: U.S. Department of Energy 2009b.

Figure 1.2. World renewable electricity generation by source, 2006-2030. Source: U.S. Department of Energy 2009b.

While the Btu is a convenient unit to use for analyzing aggregated energy use of a wide range of fuel sources, the kilowatt hour (kWh) is the traditional unit used for quantifying the use of electricity (1 kWh = 3,412 Btu) and is more useful for the purposes of this study. In 2006, world electricity consumption totaled 18 trillion kWh. This was generated from a variety of energy sources totaling 184 quadrillion Btu. Of this amount, approximately 66% was lost in production and transmission. This 184 quadrillion represents approximately 39% of world energy consumption in 2006. The remaining 61% of world energy is used in a variety of non-electricity generation purposes including transportation, agriculture, and industrial processes (U.S. Department of Energy 2009b). Of the 18 trillion kWh of electricity used in the world each year, Australia uses approximately 220 billion kWh or 1.2% of the total (U.S. Department of Energy 2009a).

Of this 220 billion kWh, only 6.5% comes from renewable sources. Of the electricity generated from renewable sources in Australia, hydroelectricity currently produces 94% of it, and solar and wind combined produce the other 6% (Department of Resources, Energy and Tourism 2009, p. 33). This small amount of renewable energy use is not due to a lack of renewable sources. Australia has sufficient wind, solar, biomass, geothermal, wave, and tidal sources available to drastically increase the amount of electricity generated from renewable sources (Australian Academy of Science 2009, pp. 6-7). To address the lack of use of renewable energy in electricity production and to address the threat of climate change due to greenhouse gas emissions, the Australian Federal Government has set a target of deriving 20% of Australia's electricity from renewable energy sources by 2020 (Department of Resources, Energy and Tourism 2009, p. 35).

To achieve this goal, vast expansions in renewable energy production will be necessary. One of the greatest opportunities for increasing the use of solar energy in Australia comes in the form of increasing solar electricity generation capacity at Australian institutions that use large amounts of energy (Department of Energy, Utilities and Sustainability 2005, p. 2). An added benefit of these sorts of distributed generation projects is to reduce the two-thirds of energy that is lost during the production and transmission of electricity. By constructing a power source close to the end user of the electricity, much of this loss can be avoided. As a result, the power generation needs of close-to-source generation are lower than that required under traditional generation arrangements where energy is generated hundreds of kilometers from where it is used (U.S. Department of Energy 2007, p. 40).

1.2. Solar Energy

1.2.1. Background Information

Solar electricity is energy generated from the sun. The generation of solar electricity produces no greenhouse gases and releases no carbon into the air. However, there are some greenhouse gases emitted during the production and transportation of the equipment used to generate solar electricity. On a per kilowatt hour basis, this release of greenhouse gases is very small compared to the greenhouse gas emissions associated with the production of a kilowatt hour of electricity from a non-renewable energy source such as coal or natural gas. On average, after four years of operation, solar installations have offset the amount of greenhouse gas emitted by their production and transportation (Bankier & Gale 2006). Given that the lifespan of the average solar installation is longer than four years, solar electricity production provides an opportunity to reduce greenhouse gas emissions associated with the production of electricity. As a result, solar energy can help reduce the impact of electricity production on the climate.

The idea of capturing the sun's energy is not a new concept. The first solar collector to produce heat was built in 1767 by a Swiss scientist named Horace de Saussure. In 1891, Clarence Kemp patented the first commercial solar water heater in the United States. These first inventions used solar energy to provide hot water to houses. In 1893, Edmund Becquerel, a French physicist, discovered the photovoltaic effect. This discovery led to the development of early photovoltaic cells. However, the early solar cells were not very efficient and not commercially viable. Finally, in 1954, Bell Telephone Laboratories developed a cell that was 4% efficient. In the years since, scientists have developed photovoltaic cells that are upward of 13% efficient. In addition, with a technology known as solar thermal electricity, which uses mirrors to concentrate solar energy, efficiencies can reach more than 30% (Jones 2003, pp. 21-24).

Prior to the examination of the technical details of using sunlight to generate electricity, it is important to define two units used in this report: watts (W) and watt hours (Wh). A watt is a measure of power while a watt hour is a measure of energy equivalent to using one watt for one hour. Power stations are given a capacity rating in units of power (based on W), but their output is measured in units of energy (based on Wh). Prefixes can be added before watts or watt hours to specify larger amounts of power and energy, respectively (Table 1.1). For example, a 100 W light bulb that is left on for an hour uses 100 Wh. If that

Table 1.1. Common prefixes and units of power and energy.

Power			Energy		
Value	Name	Symbol	Value	Name	Symbol
10^0 W	Watt	W	10^0 W	Watt hour	Wh
10^3 W	Kilowatt	kW	10^3 W	Kilowatt hour	kWh
10^6 W	Megawatt	MW	10^6 W	Megawatt hour	MWh
10^9 W	Gigawatt	GW	10^9 W	Gigawatt hour	GWh
10^{12} W	Terawatt	TW	10^{12} W	Terawatt hour	TWh
10^{15} W	Petawatt	PW	10^{15} W	Petawatt hour	PWh

same light bulb is left on for 10 hours, it uses 1000 Wh or 1 kWh. A 100 MW power plant running 24 hours a day for a year would produce 876,000 MWh or 876 GWh (Rozenblat 2009). For reference, Australia uses 220 billion kWh per year which is equivalent to 220 TWh per year (U.S. Department of Energy 2009a).

In terms of the amount of solar energy available, enough solar energy reaches the surface of the earth[1] in one hour to provide energy for the entire human population for a year (Nature Education 2010). This fact translates to the earth receiving approximately 8.2 sextillion Btu or 8.2 million quadrillion Btu per year. Based on our current estimated annual consumption of approximately 500 quadrillion Btu, the sun provides in excess of 16,000 times the amount of energy society uses in a year (Ecoworld 2010). As a result, solar energy has the potential to meet our current and future energy needs for years to come. However, society needs to vastly expand the world's current solar energy generation capacity to take advantage of this near limitless resource. The world's current solar electricity generation capacity is only 16 GW which accounts for only 6% of the world's renewable power capacity of 280 GW (REN21 2009, p. 13). For perspective, the world's total power capacity is approximately 4 TW or 4,000 GW which means solar accounts for only 0.4% of the world's total power capacity (U.S. Department of Energy 2008).

1.2.2. Solar Thermal Electricity

As solar technology has developed, two main ways to generate electricity from solar energy have emerged. The first type, solar thermal electricity (STE), uses specially shaped mirrors to capture and focus the sun. The beams of focused sunlight are used to create a thermal differential that can be used to produce steam. This steam can then be used to turn a turbine to produce electricity (Diesendorf 2007, pp. 158-160). There are three main types of designs used in the generation of solar thermal electricity.

The first type is known as a parabolic dish system (Figure 1.3). In this setup, a receiver is positioned at the focal point of the mirrors mounted on the parabolic dish (Reid 1999, p. 3). The concentrated solar energy at the receiver heats a transfer fluid (usually synthetic oil or molten salt) to approximately 750 °C. This fluid is then used either in a Stirling

Figure 1.3. Schematic of a parabolic dish collector. Source: Reid 1999, p. 3.

[1] Including the ocean surfaces.

Figure 1.4. Linked parabolic dishes in Northern Territory. Source: Research Institute for Sustainable Energy 2009.

engine[2] positioned in the receiver or combined with the fluid from several linked parabolic dishes to turn a turbine connected to a generator (Figure 1.4). The parabolic dish system is the most efficient type of solar technology at 25-30% efficiency. The Australian National University is working in conjunction with Wizard Information Systems to construct a demonstration plant in Whyalla, South Australia (Research Institute for Sustainable Energy 2009). The largest dishes under development by this team have a collector area of 400 square meters and can generate 50 kW of power at peak production (Diesendorf 2007, p. 160). In addition, the Solar Systems Company has constructed four systems using parabolic dish technology in the Northern Territory with a capacity of over 900 kW (Solar Systems 2009).

The second type of design is known as a central receiver system. This system consists of thousands of mirrors arranged in circles around a central tower. These mirrors, or heliostats, focus the incoming solar energy on a point at the top of the tower. This focused energy heats a transfer fluid in the tower which is then used to generate steam to turn a turbine connected to a generator. Each heliostat can track the sun independently to ensure the light it reflects is properly focused on the central tower's receiver (Figure 1.5, Reid 1993, p. 3). This system heats the transfer fluid to approximately 550 °C. This technology has not been widely deployed with only a few demonstration projects around the world. One such project near Seville, Spain has the capacity to generate 11 MW of power using an array of 624 mirrors focused on a 40 story tower (Figure 1.6, Research Institute for Sustainable Energy 2009).

Figure 1.5. Schematic of central receiver system. Source: Reid 1999, p. 3.

Figure 1.6. 11 MW central receiver tower in Spain. Source: Research Institute for Sustainable Energy 2009.

[2] A Stirling engine is a heat engine that is driven by an external heat source such as solar. The engine is driven by the alternating heating and cooling of gas inside its cylinders (Nice 2010, p. 2).

While central receiver technology is a highly efficient way to convert sunlight into electricity, it can only currently be effectively employed on the large scale of multi-megawatt projects. These generation plants can produce vast amounts of energy when sufficient space is available. For example, the world's largest central receiver tower in California has been designed to produce 500 megawatts (MW) of electricity at peak production when completed in 2010 (Thomas 2007, p. 17). However, the larger scale projects require tremendous amounts of space to accommodate all the heliostats. For example, the planned 500 MW plant in California will require over 6,000 acres or over 24,000,000 square meters (Parry 2007).

The third type of design for generating solar thermal electricity is known as the parabolic trough system. In this design, parabolic troughs are covered with mirrors that focus solar energy on a receiver tube positioned along the focal point of the trough. This receiver tube contains transfer fluid that collects the concentrated heat and allows the generation of steam to turn a turbine. The troughs pivot throughout the day to track the sun and maximize heat production (Figure 1.7, Reid 1999, pp. 3-4). Since these systems are parabolic along only one axis (versus the multi-axis parabolic shape of the dish collectors), they are simpler to design, install, and operate. However, the concentrating factor of the design is lower than

Figure 1.7. Schematic of parabolic trough collector. Source: Reid 1999, p. 4.

Figure 1.8. 64 MW parabolic trough system in Nevada. Source: Research Institute for Sustainable Energy 2009.

the other two types of solar thermal electricity resulting in less possible power generated per square meter of space used. Trough systems can range in size from tens of kilowatts up to many megawatts, such as the 64 MW station in Nevada that covers 400 acres of land (Figure 1.8, Diesendorf 2007, p. 159). These systems are usually oriented horizontally in long lines along an east-west axis to minimize the amount of movement needed to track the sun (Research Institute for Sustainable Energy 2009).

1.2.3. Photovoltaics

The other main way to generate electricity from the sun is through the use of photovoltaics. Photovoltaic panels are commonly made on wafers of pure crystalline silicon. The average size of a cell is 15 centimeters in diameter and three-tenths of a millimeter in thickness. Approximately 40 of these cells are joined together and covered by glass to form a solar panel of half a square meter. By installing different numbers of these panels, engineers can design systems that range in generation capacity from a few hundred watts up to many kilowatts (Diesendorf 2007, p. 161). For reference, approximately 9 square meters is required for a 1 kW capacity system (National Renewable Energy Laboratory 2010a).

Photovoltaics work by directly converting the energy of the sun into DC electricity which can then be converted by inverters into AC electricity for use in a normal electricity grid. Sunlight consists of a stream of photons that contain various amount of energy. This energy can be used to produce electricity through a process using semiconductors embedded in a solar panel. A semiconductor consists of two energy bands of electrons created by using materials with slightly different compositions. The upper level is known as the conduction band or n-type layer, and the lower level is known as the valence band or the p-type layer. The conjunction between the two layers is known as the p-n junction, and the energy difference at the p-n junction is known as the bandgap. When the semiconductor absorbs a photon of equal or greater energy than the bandgap, electrons will move from the p-type to the n-type layer through a connecting conductor (Harvey 2006, p. 435). This removal of electrons from the p-type layer creates space in that layer which electrons from the n-type layer will fill by flowing through another connecting conductor. This flow of electrons creates an electrical charge difference between the two layers which in turn creates a voltage potential. This voltage potential can be used to produce DC electricity which can then be converted to AC electricity (Figure 1.9, U.S. Department of Energy 2010).

Figure 1.9. Diagram of how a photovoltaic cell works. Source: U.S. Department of Energy 2010.

Photons of lower energy than the bandgap do not produce any electricity, and photons of higher energy than the bandgap will produce electricity, but their remaining energy is converted to wasted heat. As a result, engineers must carefully pick the materials used in creating the semiconductor to ensure maximum possible efficiency. For a single bandgap, the maximum possible efficiency for capturing the energy of photons is 40% because many photons will either be of too low energy to move any electrons or will be of higher energy than the bandgap, resulting in some wasted heat energy. Theoretically, if photovoltaic cells of different bandgaps were stacked, maximum efficiency could reach 85-90%. As of now, the majority of photovoltaic cells are made with silicon crystals. These cells can reach up to 25% efficiency in laboratory settings but usually only achieve 14-16% in commercial applications. Other materials, including cadmium, indium, telluride, selenium, gallium, and arsenic, have been used in the creation of higher efficiency cells that can reach up to 32% efficiency in laboratory settings. However, many of these materials are toxic and/or rare which means they are unlikely to gain widespread commercial use. Total production can also be improved by using systems that track the sun on either one or two axes (Harvey 2006, pp. 435-437).

1.2.4. Solar Shortcomings

While solar energy has the potential for generating a vast amount of electricity, there are currently several disadvantages slowing its wide scale deployment. The major current downside is the cost associated with solar energy. For example, the current average capital expenditure for a solar power station is $6.20[3] per watt including all associated construction and material costs. Compared to the average capital expenditure of $1.60 per watt for a coal-fired power plant, solar power stations cost significantly more. This higher construction cost results in a higher lifetime cost per kWh of electricity generated despite the relatively low operational expenditures associated with a solar installation. While there are some subsidies available in certain countries, on average, solar electricity costs more per kWh than does a kWh of electricity produced from conventional forms of energy (Green 2010).

In addition, there is the obvious disadvantage that most solar power stations can only produce electricity while the sun is shining. While in a residential setting there is the possibility for storing electricity in batteries, this is not a viable option for large scale solar power stations. As an alternative, engineers and scientists are working on systems that would involve using other forms of energy storage to allow solar power stations to provide electricity throughout the night. For example, some solar thermal electricity power stations are being designed to store thermal energy in molten salt. One such power station in Spain will incorporate the storage of thermal energy in molten salt to allow the station to operate at

[3] All prices are given in Australian dollars.

an annual capacity factor of 65%[4] (Diesendorf 2007, p. 159). For comparison, the average capacity factor for photovoltaics is approximately 14% and 18-26% for solar thermal (Doty Energy 2010). For conventional power stations, capacity factors are usually between 65% and 85% (Diesendorf 2007, p. 74). Another option, compressed air energy storage, is currently being explored for storing solar energy for nighttime use in the United States. In this scheme, solar power stations are oversized by at least 50%, and the excess electricity generated during the day is used to pump compressed air into underground caverns. When energy is needed when the sun is not shining, the compressed air can be used to turn a turbine and produce electricity. In the United States, this has been presented as a viable option for supplying consistent electricity from a solar power station to the national grid (Fthenakis, Mason & Zweibel 2009, pp. 389, 397).

Furthermore, in addition to photovoltaic cells already having a relatively low efficiency rating, they are hampered by two other significant sources of inefficiencies. First, the conversion from DC to AC electricity is on average only 77% efficient. This is caused by a combination of factors including the efficiency of the inverters, wiring, transformer, and connections. As a result, a system with a rated capacity of 100 kW will only actually produce 77 kW of AC electricity when operating at full capacity (National Renewable Energy Laboratory 2010a). The other significant source of inefficiency is the effect of heat on photovoltaic cells. As cells are heated by the sun, they tend to lose efficiency at a rate of approximately 0.5% per degree Celsius above 25 °C. On a sunny day, panels can reach temperatures up to 80 °C, resulting in significant decreases in efficiency. As a result, photovoltaic cells currently capture only a small amount of the total energy striking them (Harvey 2006, pp. 438-439).

1.2.5. Benefits of Solar Energy in Institutional Settings

As previously mentioned, one of the greatest opportunities for increasing the use of solar energy in Australia comes from increasing the solar electricity generation capacity at various large institutions throughout the country. Institutions of higher education often have many buildings with large roofs as well as expanses of unused land that would be suitable for solar installations. Some institutions, both in Australia and abroad, have already begun to generate solar electricity on campus. For example, Monash University in Victoria, Australia

[4] Capacity factor refers the ratio of the actual output of a power station and the output of the power station if it had operated at its full nameplate capacity the entire time (Diesendorf 2007, p.73). In this case, the nameplate capacity is 15 MW, which means that at a 65% capacity factor, it will produce: 65% x (15 MW x 24 hours x 365 days) = 85.4 GWh/year compared to a possible total of 131.4 GWh/year.

has recently installed a 416 panel array expected to generate 100,000 kWh of electricity per year. This array is currently the largest at any Australian university (O'Loughlin 2010). However, this array will soon be eclipsed by the 1.2 MW photovoltaic array planned by the University of Queensland which will generate up to 1750 MWh per year (Dunne 2010). In the United States, Harvard University has recently completed a 500 kW array that will generate over 630,000 kWh per year (Ailworth 2009). Numerous other schools have smaller arrays such as the two arrays at Williams College totaling over 30 kW in capacity that generate 30,000 kWh per year (Johns 2010).

In many cases, these projects have been supported by substantial grants and rebates to make them economically feasible. For example, the University of Queensland's array is partially funded by a $1.5 million grant from the Queensland government (Dunne 2010). However, in addition to the possibility of financial benefits from operating a solar array, there are many non-financial benefits for a university associated with such a project. One such benefit is a boost in institutional ranking for universities pursuing an agenda of sustainability and low environmental impact. Over the past few years, many leading educational institutions have made commitments to reducing their environmental impact and to pursuing alternative energy. Based on colleges and universities in the United States, there is a strong correlation between institutional ranking and sustainability. For example, the number one liberal arts college in the United States, Williams College, is also the number one college in the United States in terms of sustainability[5]. In addition, the number two ranked college in the United States, Amherst College, is ranked number three in terms of sustainability (U.S. News and World Report 2010; Roberts Environmental Center 2010, p. 3). As sustainability becomes a more important part of rankings, the institutions that already have a strong tradition of minimizing their environmental impact through such measures as using solar energy will have an advantage.

In addition, using solar electricity generated on campus serves as a symbol of a university's commitment to the environment. This symbol encourages students, faculty, and staff to take pro-environmental actions in their everyday lives (Australian Research Institute in Education for Sustainability 2009, p. 3). Moreover, using solar energy produced on campus gives universities a public relations boost as evidenced by the media coverage of institutions that install solar arrays. There is often extensive media coverage throughout the

[5] In the Roberts Environmental Center Report, sustainability is evaluated based on performance in several categories including: environmental education, environmental policy statement, green building, transportation, green purchasing, energy use, greenhouse gas emissions, and a variety of other factors.

design, installation, and commissioning stages of any alternative energy project (Narrative Network 2009, p. 4). This further helps a university become a more widely known and respected institution both nationally and internationally.

Finally, a solar installation on campus provides valuable teaching and learning opportunities. A university with solar technology can allow students hands-on education with solar energy. Furthermore, courses and curricula can be designed to take advantage of the opportunity provided by having direct access to a solar installation and its associated data. In some cases collaboration between students and professors can lead to the commercial development of solar technology as was the case with projects from the University of Sydney, University of New South Wales, and the Australian National University (Taylor 2008, p. 14). Moreover, in the Talloires Declaration, over 350 university leaders have committed to a ten-point plan of action for integrating sustainability and environmental literacy into curriculum and practice. Seventeen Australian universities have signed this declaration, but only a fraction of these have followed through in practice with actual renewable energy installations (University Leaders for a Sustainable Future 1990). A solar installation will serve as a great starting point for meeting this call for raising awareness of environmental issues and implementing sustainable practices. Based on this wide range of possible benefits, Macquarie University has decided to explore the possibility of using solar energy to provide for a significant portion of its electricity consumption.

1.3. Macquarie University

1.3.1. Solar, Sustainability, and Macquarie University

Macquarie University was founded in 1964 as Sydney's third university. Located in North Ryde, a suburb of Sydney, New South Wales, the University's campus encompasses 311 acres of land. On this property are approximately seventy buildings ranging in use from administrative offices to research labs to classrooms to a library and a student center. The University has an enrollment of 32,782 students and employs 2,221 faculty and staff members. Macquarie University is currently expanding rapidly to accommodate increasing demand for higher education (Macquarie University 2009).

With the population of an average town, Macquarie University consumes a large amount of natural resources. In particular, Macquarie University uses a huge amount of electricity each year. As a whole, the campus draws approximately 30,000,000 kWh of electricity per year from the state electrical grid. This amount translates to approximately 27,000 tonnes of carbon dioxide emissions per year. With the exception of four buildings on campus which are powered by a cogeneration plant, all electricity is produced off campus

(Macquarie University Sustainability Office 2008, pp. 2-5). Of the electricity purchased by Macquarie, only 6% comes from a renewable energy source (Macquarie University Sustainability Office 2009).

In an effort to minimize its environmental footprint and set an example for other universities, Macquarie University established the Sustainability Office in 2007. The Sustainability Office is working to make Macquarie University a more sustainable university through a variety of projects, initiatives, and campaigns. The Sustainability Office has set targets related to sustainability in the areas of people, planet, and participation. In terms of people, the University will strive to increase the understanding of sustainability among students, staff, and faculty. With regard to the planet target, the University will try to use resources efficiently while becoming a model of sustainable community. In the area of participation, the University will attempt to foster a sense of environmentally responsible living (Macquarie University Sustainability Office 2009). The decision to pursue these targets was made in line with the University's commitment to serve as a leader in the effort to reduce human impact on the environment set forth in its Strategic Plan (Macquarie University Sustainability Office 2008, p. 6). This commitment is further reinforced by the Macquarie University Greenhouse Gas Reduction Master Plan which seeks to limit "the impact of University activities on the concentration of greenhouse gases in the atmosphere" (Bekmann 2010, p. 2). In addition, the University hopes to instill environmental responsibility into its students in both social and academic contexts (Macquarie University Sustainability Office 2009).

1.3.2. Sustainability Measures Already Taken

To achieve these goals, the Sustainability Office has already undertaken a wide range of projects. In 2008, the Sustainability Office started an energy saving campaign designed to get people to turn off lights in classrooms, offices, and other common spaces. In addition, the Sustainability Office commissioned an Energy Savings Action Plan in compliance with New South Wales regulations for high energy users. This plan helped identify areas of potential energy savings and future projects for the Sustainability Office. In 2009, the University began purchasing 5% of its electricity from a green source certified by the state government. The University will aim to increase the amount of green power it purchases each year by 1%. Furthermore, air-conditioning set points are currently being implemented across campus resulting in up to 20% reductions in carbon dioxide emissions. The Sustainability Office has also implemented recycling, carpooling, and biking campaigns to reduce the environmental impact of the campus.

Recently, the Sustainability Office had four solar-powered street lights installed as a pilot to explore the feasibility of adding more of these street lights across campus (Macquarie University Sustainability Office 2009). Moreover, the University has committed to a minimum Five Star Green Star, Green Building Accreditation for all new building projects on campus (Bekmann[6] 2010, personal communication, 15 April). In addition, the University has already been generating some of its own electricity through a cogeneration plant on campus since 2001. This cogeneration plant produces approximately 4,000,000 kWh of electricity per year by burning natural gas. The excess heat is used to heat the University's two swimming pools, to run an absorption chiller in the summer, and to heat the surrounding buildings in the winter. This system results in a 44% reduction in greenhouse gas emissions compared to purchasing the additional electricity from the grid. In addition, three thermal storage tanks of 1 million liters each have been constructed on campus. These storage tanks allow the University to use off-peak electricity to chill water for use in the campus air conditioning systems. By using off-peak electricity, Macquarie is able to decrease its peak demand and help prevent the construction of additional coal-fired baseload[7] power plants (Macquarie University Sustainability Office 2008, pp. 14-16). Overall, the steps taken by Macquarie University have begun to reduce the University's impact on the environment by lowering its carbon dioxide emissions and promoting sustainable lifestyles for its students, faculty, and staff.

1.3.3. Solar Energy at Macquarie University

The University currently does not have any renewable energy generation capability on campus. However, in line with the University's Greenhouse Gas Reduction Master Plan and its Strategic Plan, the University has recently decided to explore the possibility of installing a large scale solar energy project on campus. As the University continues to grow, it will need to begin generating more of its own electricity due to the general lack of generation capacity in the Sydney area and particularly within the Macquarie Park corridor in which it sits. Rather than limiting investigation to increasing its natural gas use through expanding its cogeneration capacity, the Sustainability Office has decided to explore the possibility of

[6] Hilary Bekmann is the Manager of Operational Sustainability at Macquarie University and my supervisor at the University.

[7] A baseload power plant is used to meet the continuous electricity need of its service region. It typical produces energy at a constant rate and cannot easily adjust its energy output on short notice (Association of Energy Engineers 2010).

using solar energy (Bekmann 2010, personal communication, 15 April). The first step in this process is to conduct a solar energy feasibility study.

1.4. Study Goal and Justification

The goal of this study is to research and report on the feasibility and associated benefits of Macquarie University installing solar electricity generation capacity on campus. In particular, this study is intended to inform University staff about possible locations for such an installation and about costs associated with a solar project ranging in scale from providing 1% to 100% of the University's electricity needs. In addition, this report will investigate which of the available solar system options is the most practical for Macquarie University. Furthermore, this study will explore the benefits to Macquarie University associated with pursuing such a project including the environmental, financial, learning, teaching, and publicity benefits.

As evidenced from the variety of solar systems and possible benefits already discussed, solar energy is a complex topic. Despite all the benefits of constructing solar arrays at institutions, not every location or building is suited for the installation of solar systems. For example, buildings in climates far from the equator are not particularly well-suited for solar systems because there are less sun hours per year the further the location is from the equator. In addition, some buildings do not have roofs oriented toward the sun, making mounting solar systems difficult. Moreover, the roofs of some buildings may be shaded by either trees or the roofs of other buildings (Schlager & Weisblatt 2006, pp. 219-220). As such, it is important to conduct a feasibility study examining a wide range of issues before committing to a solar project. By taking some time to plan and evaluate options prior to beginning a project of this scale, money and effort can be saved in the future.

2. Methodology

2.1. Campus Description

This feasibility study was conducted on Macquarie University's campus in the Sydney suburb of North Ryde in New South Wales, Australia. The campus consists of 311 acres or 1.26 million square meters of land, of which 121 acres or 490,000 square meters (39%) is currently undeveloped open space. However, the University has a Master Plan for development to 2030 that will see the amount of open space decrease to roughly 84 acres or 340,000 square meters (27%). While this is still a large amount of land, the open spaces are not necessarily contiguous to one another and some plots are smaller than 1 acre in size. In addition, the University owns 42 acres of sports fields, but these fields are located approximately 1 kilometer from the main campus and are on the opposite side of the M2 Motorway (Macris[8] 2010, personal communication, 16 April). The northern portion of the campus abuts bush land which requires a 20 meter buffer zone. There are also several streams running through campus that require 20 meter buffer zones on either side of their banks (Bekmann 2010, personal communication, 15 April).

The campus consists of closely clustered large buildings in the center with smaller buildings on the outskirts of campus (Figure 2.1). Most of the larger sections of open space

Figure 2.1. Map of Macquarie University campus as of 2009. Source: Macquarie University 2009.

are located on the perimeter of campus. However, much of the undeveloped land is either slated for development in the next twenty years or is covered with bush land or other vegetation. The campus is roughly a square bounded by Talavera Road to the northeast, Culloden Road to the northwest, Epping Road to the southwest, and Herring Road to the southeast. The main axis of campus is located on an east-west line. The terrain is mostly flat with a few gently sloping hills.

2.2. Solar Data

2.2.1. Overview of NASA Data

To calculate the amount of electricity that can be generated from a solar installation requires the use of solar insolation data. Average solar insolation is the amount of solar radiation reaching the surface of the earth in any given area. Average solar insolation is also known as total solar insolation and is measured in kWh/m^2/day. By knowing the average daily solar insolation and the peak power rating of a solar installation, the amount of electricity generated per day can be calculated (Stapleton & Milne 2008).

There were two potential sources of daily solar insolation data to inform the analysis of solar electricity production. One source of data is the National Aeronautics and Space Administration (NASA) based in the United States. The other source of data is the observatory at Macquarie University. The NASA data source was chosen over the observatory at Macquarie University due to significant gaps in the solar insolation data collected at the observatory. NASA provides satellite derived values for average solar insolation for any specific latitude and longitude through its Surface Meteorology and Solar Energy website. The NASA satellite method for calculating average solar insolation has been validated to be within 1% of ground stations that use pyranometers to measure solar insolation at a specific ground location (Stackhouse & Whitlock 2010).

For this study, NASA average daily solar insolation data for a horizontal surface were used for the time span of July 1983 to June 2006. Data are for the latitude of 33.77° S and the longitude of 151.11° E. This set of coordinates represents the geographical center of the Macquarie University campus. The data set used in calculations for this report consisted of 8,401 average daily solar insolation readings spanning 23 years of data collection.

2.2.2. Solar Data Analysis

Since the NASA data were provided in two columns of 8,401 rows each, the first step of the data analysis was to group the data by year. Thus, the modified data were arranged in

[8] John Macris is Biodiversity Planner at Macquarie University and works with the Sustainability Office.

46 columns of 365 rows each. Solar insolation data from February 29 were eliminated for the six leap years in the data set. This step was taken to ensure that when grouped by year, the data from each day of the year lined up across all the columns. For example, the 23 years of January 1 data were now all in the same row.

The next step in the analysis was to delete all but one of the columns containing dates. This left 23 columns of daily data plus one column containing the dates of each row of insolation data. The data were then averaged across each row to give an average daily solar insolation value for each day of the year. From this value, the expected daily electricity production can be calculated according to the following general equation:

$$E = i * s * d \quad (1)$$

Where E represents electricity production in kWh, i represents the daily solar insolation in $kWh/m^2/day$, s represents the capacity of the system, and d represents the adjustment for inefficiencies associated with inverting the electricity from DC to AC, temperature, cleanliness of panels, downtime for maintenance, and other sources of inefficiency (National Renewable Energy Laboratory 2010a).

If the inefficiencies variable is excluded, this is a relatively straightforward calculation. However, since the inefficiencies can result in a significant loss of electricity production, it is important to account for them in the calculations. There are several publicly available programs of varying levels of sophistication that will perform these calculations. One such program, the Solar Advisor Model (SAM), allows the user to account for the inefficiencies associated with a solar installation. The program allows the user to select the type of solar system from a wide selection listed in the program's library, specify a system capacity, and input the appropriate solar insolation data. From this information, the program will generate an estimate of each month's electricity production in kWh that accounts for the average inefficiencies associated with a solar system. The program will also give space requirement estimates for certain types of solar systems (National Renewable Energy Laboratory 2010b). This program was used to calculate monthly and yearly energy production figures of the solar systems evaluated in this report. For the calculations, all default settings were used except for adjustments to the system size and azimuth[9]. Once a yearly production figure was calculated, long term production estimates for 25 years[10] of

[9] By default, the azimuth is set to face south, but for a project in the southern hemisphere it should be set to face north.
[10] The accepted average lifespan of a solar project. However, there is a high likelihood that a system would continue to operate well beyond 25 years with proper maintenance (Diesendorf 2007, p. 165).

operation were made based on a 1% decrease in system performance each year (National Renewable Energy Laboratory 2010a).

2.3. Cost Data

2.3.1. Overview

Cost data were initially requested from several companies that manufacture and install solar systems both in Australia and internationally. Data were solicited first via email request and then by follow-up phone calls for companies that did not respond to the initial emails. In both cases, the purpose of the feasibility study was explained and an overview of Macquarie University's needs was provided to the company. Most companies were reluctant to provide firm estimates, so the cost data used in the calculations for this report were based on average costs calculated by the U.S. Department of Energy based on reported costs from a large range of systems (Sutula 2006, pp. 42-46, 63-65). However, due to the differences in solar industries in Australia and the United States, these average costs needed to be increased to more accurately reflect the costs of solar systems in Australia. For Australia, only reliable price information on small residential systems could be found. On average, a 1 kW system will cost approximately $12,500 AUD in Australia (New South Wales Government 2010). In the United States, a similar sized system will cost approximately $10,000 AUD[11] (Sutula 2006, p. 42). Based on this comparison, 25% was added to the prices in the Department of Energy report to estimate the cost of similar systems in Australia. In addition, any incentives, rebates, and grants for large scale solar projects were identified and evaluated.

2.3.2. Cost Data Analysis

Cost data were used to calculate a total cost for various types and sizes of systems. This total cost included the cost of the solar modules, construction, infrastructure improvements, and operation and maintenance. Prior to further calculations, any available rebates, incentives, and grants were subtracted from the total cost of the system as appropriate. An average cost for each type of system on a per kW of capacity basis was then made according to Equation 2:

$$\text{Cost per kW of capacity} = (\text{total cost of project}) / (\text{kW capacity of system}) \qquad (2)$$

In addition, from the long term electricity production estimates of the arrays, a cost per kWh of electricity produced was calculated in 2010 dollars according to Equation 3:

[11] Adjusted for inflation and converted to Australian dollars.

Cost per kWh = (total cost of project) / (25 year projected electricity production) (3)

Furthermore, the simple payback period of the different options was calculated by dividing the total project cost by the value of the electricity generated in the first year of production according to Equation 4:

Simple payback period = (total cost) / (value of average year's electricity[12]) (4)

A cost per tonne of CO_2 emission reduction was calculated according to Equation 5:

Cost per tonne of reduction = (total cost of project) / (tonnes of CO_2 reduction) (5)

The CO_2 reduction of a project was calculated by inputting the 25 year electricity production estimate into the Department of Climate Change's online carbon dioxide emissions calculator[13] (Department of Climate Change 2010).

2.4. Campus Data

2.4.1. Overview

Campus data were provided by the Sustainability Office and the Office of Facilities Management at Macquarie University. This data included the size of campus buildings (in square meters), campus annual and monthly electricity use, future expansion plans, the size of the campus, and open space information. Concept plans, aerial photos, campus maps, and Master Plan information were also provided by these two offices. In addition, information on the University's annual greenhouse gas emissions was made available.

2.4.2. Campus Data Analysis

Campus annual electricity use was used to calculate the size of a solar system needed to provide the desired amount of electricity. For example, for a system to provide 10% of the campus' electricity, the system would need to generate 3,000,000 kWh per year. Based on the results from SAM, an appropriate sized solar system was then selected to meet that target. In addition, future electricity use was estimated for 2020 and 2030 based on the following assumptions: existing buildings will achieve 20% improvement in energy efficiency by 2020

[12] Simple payback is based on an average value of $0.36/kWh which is the estimated cost of electricity during the 13th year of system operation assuming a 10% annual increase in the price of electricity.
[13] Approximately 1,116 kWh of electricity produces 1 tonne of CO_2 emissions.

and all new building projects will achieve a Five Star Green Star rating on the Green Building Council of Australia's design scale (Bekmann 2010, personal communication, 22 April). To achieve this rating, the University assumes that new buildings will achieve an upper emissions limit of 55 kg CO_2/m^2/year (Green Building Council of Australia 2008, p. 155). For every 1,116 kWh of electricity produced in Australia, approximately 1 tonne of CO_2 is emitted (Department of Climate Change 2010). As a result, each square meter of new building area can be expected to use approximately 61.4 kWh of electricity per year.

From the campus building data, total roof space was calculated. The campus building data spreadsheet included the area in square meters of each floor of each building on campus. This spreadsheet was sorted by floor size and then had duplicate rows removed. This resulted in a spreadsheet listing the largest floor of each building on campus. For the purposes of this feasibility study, this served as a sufficiently accurate proxy of roof space. Existing buildings not scheduled for a major roof renovation were considered suitable for only photovoltaic panels. Future buildings still in the planning stages were considered suitable for photovoltaic panels and parabolic dishes[14]. This criterion was based on the stronger structural requirements of a parabolic dish system (Bekmann 2010, personal communication, 16 April). In addition, based on site surveys and aerial photographs, estimates of the usable percentage of space on each roof were made. From a combination of the campus maps, concept plans, and aerial photos, estimates of available space for ground based solar systems were made. All this information was combined to create a spreadsheet reflecting available roof and ground space as well as a color-coded map depicting the available roof spaces on campus.

2.5. Interviews

Interviews were conducted with students, faculty, and staff at Macquarie University (Table 2.1). The total number of people interviewed was nine. The interviews explored the reasons behind the University's commitment to sustainability, motivation behind pursuing alternative energy at Macquarie, and the non-financial benefits for the University of a solar project. The questions asked during the interviews are available in Appendix A.

Table 2.1. List of people interviewed for this project.

Name	Position at Macquarie University
Leanne Denby	Director of Sustainability
Hilary Bekmann	Manager of Operational Sustainability
John Macris	Biodiversity Planner
Adrian Emilsen	Sustainable Transport Officer

[14] Future buildings were assumed to be built to the maximum allowed height of 16 stories. By dividing the planned total gross floor area by 16, an estimate of roof space was calculated.

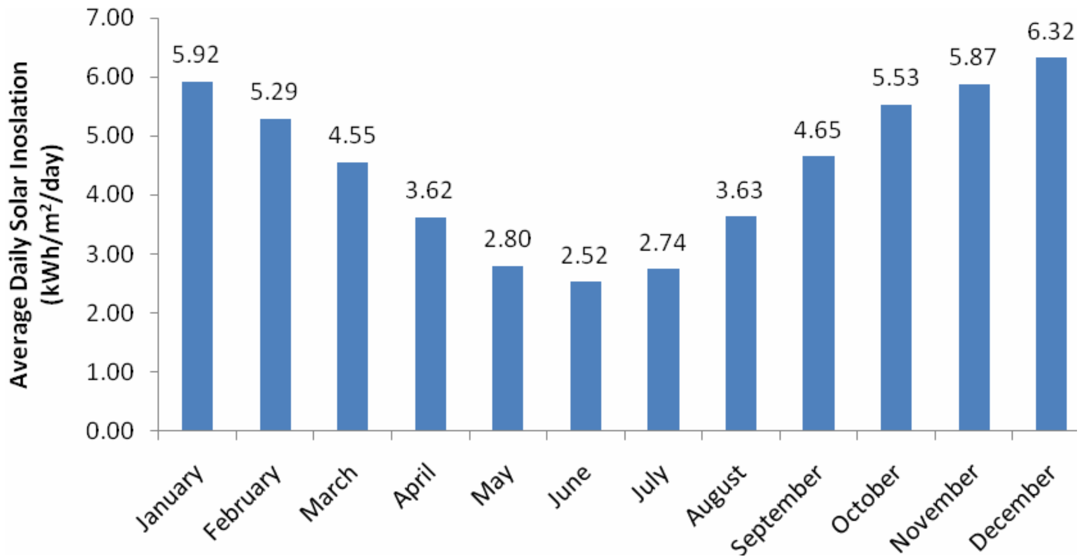
Belinda Bean	Sustainable Support Officer
Michelle Shackleton	Sustainable Research Assistant
Iain Brew	Sustainability Multimedia Administrator
Daniel Trees	Macquarie University Student
Eden Ottignon	Macquarie University Student

3. Results

3.1. Solar Energy

The average daily solar insolation in the vicinity of Macquarie University in Sydney, NSW, was calculated to be 4.45 kWh/m^2/day. This number is based on the daily averages of solar insolation of 23 years of data which ensures a reliable average. Figure 3.1 presents the average daily solar insolation of each month of the year. As expected, solar insolation is highest during the summer and lowest during the winter.

Figure 3.1. Average daily solar insolation by month for Macquarie University in NSW, based on data from July 1983 to June 2006.



Based on this solar insolation data, the SAM program was used to calculate monthly and yearly energy production figures of the solar systems evaluated in this report. Long term production estimates for 25 years of operation were made based on a 1% decrease in system performance each year (National Renewable Energy Laboratory 2010a).

3.1.1. Photovoltaic Electricity Production

Based on the solar insolation numbers calculated from the NASA data, a 1 kW photovoltaic array with no tracking system is expected to produce 1,285 kWh per year, a 1 kW system with one axis tracking is expected to produce 1,632 kWh per year, and a 1 kW system with two axes tracking is expected to produce 1,723 kWh per year. Figure 3.2 compares the monthly energy production from 1 kW arrays with no tracking, one axis tracking, and two axes tracking. The one axis and two axes systems produce higher amounts of electricity than the system with no tracking.

Figure 3.2. Estimated electricity production by month for a 1 kW photovoltaic array at Macquarie University in NSW.

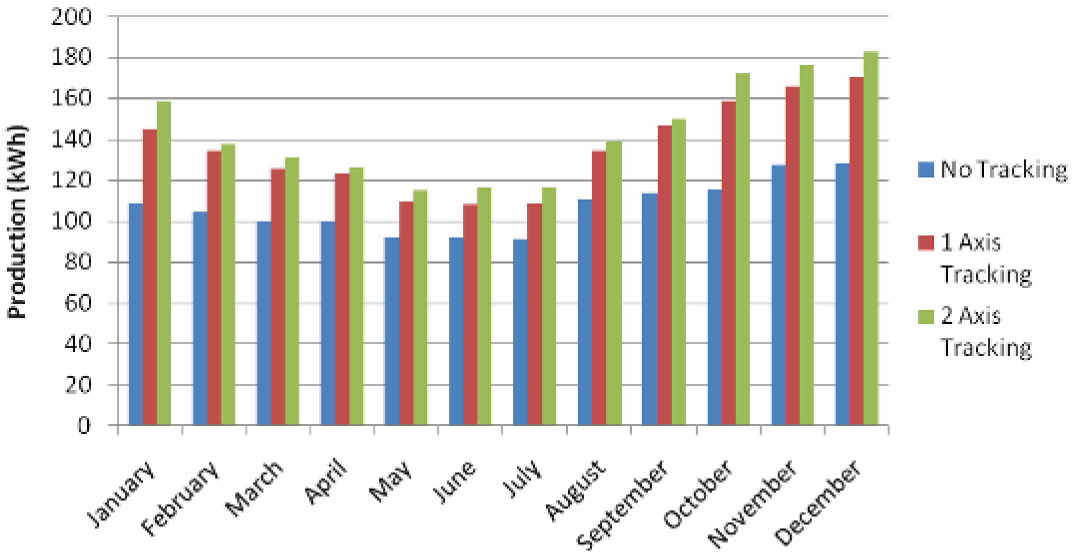


Table 3.1 provides a summary of the estimated annual electricity production of a variety of different sizes of solar systems. Also recorded in the table are the 25 year production figures of the systems. Since the electricity production scales as a linear function of the capacity rating of the system, calculating the estimated annual electricity production of systems of different sizes is a simple calculation. Finally, Table 3.1 also provides an estimate of the space requirements for each system.

Table 3.1. Estimated long term electricity production and space requirements for a variety of photovoltaic systems at Macquarie University in NSW.

System Capacity	Tracking	Annual Electricity Production (kWh)	25 Year Electricity Production (kWh)	Space Requirements (square meters)
1 kW	None	1,285 kWh	28,550 kWh	9 sq. meters
1 kW	1 axis	1,632 kWh	36,260 kWh	9 sq. meters
1 kW	2 axes	1,723 kWh	38,280 kWh	9 sq. meters
10 kW	None	12,850 kWh	285,500 kWh	90 sq. meters
10 kW	1 axis	16,320 kWh	362,600 kWh	90 sq. meters
10 kW	2 axes	17,230 kWh	382,800 kWh	90 sq. meters
100 kW	None	128,500 kWh	2,855,000 kWh	900 sq. meters
100 kW	1 axis	163,200 kWh	3,626,000 kWh	900 sq. meters
100 kW	2 axes	172,300 kWh	3,828,000 kWh	900 sq. meters
1,000 kW	None	1,285,000 kWh	28,550,000 kWh	9,000 sq. meters
1,000 kW	1 axis	1,632,000 kWh	36,260,000 kWh	9,000 sq. meters

1,000 kW	2 axes	1,723,000 kWh	38,280,000 kWh	9,000 sq. meters
10,000 kW	None	12,850,000 kWh	285,500,000 kWh	90,000 sq. meters
10,000 kW	1 axis	16,320,000 kWh	362,600,000 kWh	90,000 sq. meters
10,000 kW	2 axes	17,230,000 kWh	382,800,000 kWh	90,000 sq. meters

3.1.2. Parabolic Dish Electricity Production

Parabolic dishes produce electricity either through the use of a Stirling engine in the dish assembly or through transferring the heat of the sun to a fluid used to produce steam in a central turbine. Because Macquarie University is examining the possibility of installing parabolic dishes on the rooftops of campus buildings, this analysis will only consider the use of a Stirling engine to produce electricity. A single 25 kW parabolic dish occupies approximately 90 square meters of space. However, when constructing an array of these dishes, a spacing of approximately 15 meters between each dish in the array is necessary to avoid one dish blocking another dish. Thus, each interior dish requires approximately 225 square meters, each dish at a corner requires 156 square meters, and each dish along an edge requires 188 square meters. A single 10 kW parabolic dish occupies approximately 40 square meters of space, but requires approximately 10 meters of spacing between dishes when used in an array. Thus, each interior dish requires approximately 100 square meters, each dish at a corner requires 72 square meters, and each dish along an edge requires 85 square meters. (National Renewable Energy Laboratory 2010b).

A 10 kW parabolic dish is expected to produce 12,427 kWh per year. A 25 kW parabolic dish is expected to produce 35,553 kWh per year[15]. Production estimates of larger systems were calculated using the SAM program (Table 3.2). As the arrays become larger, the electricity production per dish decreases slightly due to minor shading effects.

Table 3.2. Estimated long term electricity production and space requirements for a variety of parabolic dish systems at Macquarie University in NSW.

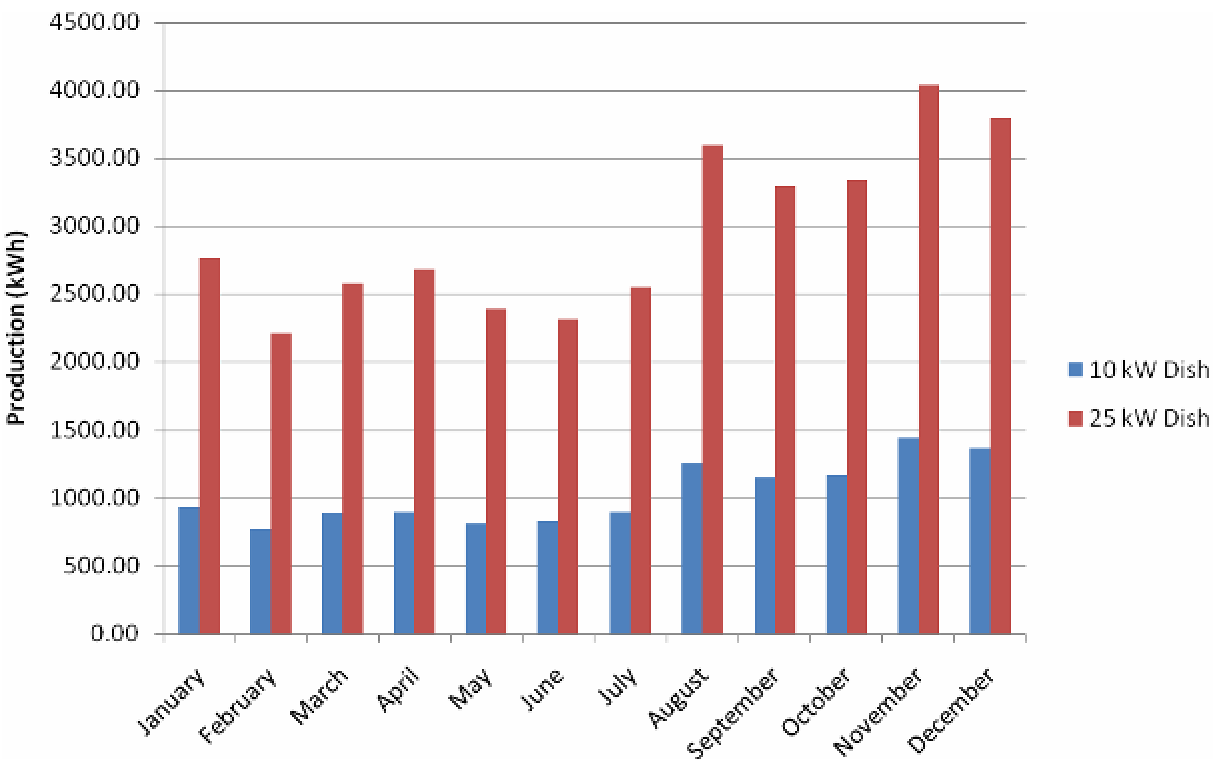
System Capacity (kW)	Dish Capacity (kW)	Number of Dishes in Array[16]	Annual Electricity Production (kWh)	25 Year Electricity Production (kWh)	Space Requirements (square meters)
10 kW	10 kW	**1**	12,400 kWh	276,100 kWh	40 sq. meters
40 kW	10 kW	2 x 2 = **4**	46,900 kWh	1,042,700 kWh	288 sq. meters
90 kW	10 kW	3 x 3 = **9**	106,100 kWh	2,357,200 kWh	728 sq. meters
160 kW	10 kW	4 x 4 = **16**	190,000 kWh	4,219,900 kWh	1,368 sq. meters
250 kW	10 kW	5 x 5 = **25**	298,400 kWh	6,630,500 kWh	2,208 sq. meters
1,000 kW	10 kW	10 x 10 = **100**	1,210,800 kWh	26,900,900 kWh	9,408 sq. meters
4,000 kW	10 kW	20 x 20 = **400**	4,884,500 kWh	108,523,500 kWh	38,808 sq. meters
25 kW	25 kW	**1**	35,600 kWh	789,900 kWh	90 sq. meters
100 kW	25 kW	2 x 2 = **4**	134,800 kWh	2,994,000 kWh	624 sq. meters
225 kW	25 kW	3 x 3 = **9**	303,900 kWh	6,751,500 kWh	1,601 sq. meters

[15] Unlike a photovoltaic array, a parabolic dish system always use tracking on two axes.
[16] Array does not have to be a square.

400 kW	25 kW	4 x 4 = **16**	542,900 kWh	12,062,300 kWh	3,028 sq. meters
625 kW	25 kW	5 x 5 = **25**	851,900 kWh	18,926,400 kWh	4,905 sq. meters
2,500 kW	25 kW	10 x 10 = **100**	3,445,500 kWh	76,551,400 kWh	21,040 sq. meters
10,000 kW	25 kW	20 x 20 = **400**	13,876,900 kWh	308,314,600 kWh	87,060 sq. meters

In one year, the 25 kW dish produces 1,422 kWh of electricity per kW of capacity, and the 10 kW dish produces 1,243 kWh of electricity per kW of capacity. Thus, when space permits, the 25 kW dish should be used instead of the 10 kW dish. As expected, monthly production for either dish is similar to the monthly production pattern of photovoltaic panels. Slight differences are due to the effect of temperature and wind on the operation of parabolic dish systems (Figure 3.3).

Figure 3.3. Estimated electricity production by month for 10 kW and 25 kW parabolic dish systems at Macquarie University in NSW.



3.1.3. Central Receiver Electricity Production

A central receiver system uses concentrated energy from the sun to produce steam to turn a turbine. Due to the configuration of a central receiver system, there is a minimum required size for the heliostat array to actually produce enough steam. This size depends on the site's solar insolation characteristics. According to the SAM program, an arrangement of 327 mirrors with a system capacity of 5,000 kW or 5 MW is the minimum size required for a central receiver in the Sydney area. Such a system will produce approximately 6,043,100 kWh of electricity per year (Table 3.3).

Table 3.3. Estimated long term electricity production and space requirements for a variety of central receiver systems at Macquarie University in NSW.

System Capacity (MW)	Number of Heliostats	Tower Height (m)	Annual Electricity Production (kWh)	25 Year Electricity Production (kWh)	Space Requirements (sq. m)
5 MW	327	63.3 m	6,043,100 kWh	134,264,300 kWh	400,000 sq. m
10 MW	458	63.3 m	13,058,000 kWh	290,120,800 kWh	506,000 sq. m
15 MW	629	63.3 m	21,772,900 kWh	483,747,300 kWh	690,000 sq. m
20 MW	802	90 m	27,637,500 kWh	614,046,000 kWh	676,000 sq. m
50 MW	2,125	116.7 m	71,766,600 kWh	1,594,499,500 kWh	1,680,000 sq. m
100 MW	4,036	170 m	143,309,600 kWh	3,184,033,700 kWh	2,700,000 sq. m

As the receiver tower becomes taller, the amount of space required for the heliostats decreases, resulting in a higher energy production per square meter of space. As expected, the monthly production pattern is very similar to the pattern of photovoltaic panel production (Figure 3.4).

Figure 3.4. Estimated electricity production by month for a 5 MW central receiver system at Macquarie University in NSW.

3.1.4. Parabolic Trough Electricity Production

Like a central receiver system, a parabolic trough system uses concentrated energy from the sun to produce steam to turn a turbine. Because the parabolic trough system does not require concentric circles of heliostats, the minimum size of a parabolic trough system is smaller than the minimum size of a central receiver system. According to the SAM program, the minimum system size is approximately 100 kW in the Sydney area. This number is limited by the size and efficiencies of the turbines required to convert the steam into electricity. While a smaller size is theoretically possible, such a system would barely produce enough steam to turn the turbine due to the high temperatures required. A 100 kW system will produce 156,700 kWh per year (Table 3.4).

Table 3.4. Estimated long term electricity production and space requirements for a variety of parabolic trough systems at Macquarie University in NSW.

System Capacity	Annual Electricity Production (kWh)	25 Year Electricity Production (kWh)	Space Requirements (sq. m)
100 kW	156,700 kWh	3,481,200 kWh	818 sq. m
500 kW	530,700 kWh	11,791,600 kWh	2,453 sq. m
1 MW	1,061,500 kWh	23,583,300 kWh	4,905 sq. m
5 MW	4,638,400 kWh	103,056,000 kWh	22,073 sq. m
10 MW	9,276,700 kWh	206,108,800 kWh	44,145 sq. m
15 MW	13,915,000 kWh	309,161,000 kWh	66,218 sq. m

Again, the monthly production pattern is very similar to the pattern of photovoltaic panel production (Figure 3.5).

Figure 3.5. Estimated electricity production by month for a 100 kW parabolic trough system at Macquarie University in NSW.

3.1.5. Electricity Production Summary

Due to the vast contiguous space requirements[17] for a central receiver system, it is not considered a viable option for solar power generation at Macquarie University and will not be considered in any further analysis. In addition, since the parabolic troughs are approximately 100 meters in length and require a turbine to produce power, they are not considered feasible for the University. The other two solar system options are compared based on the amount of electricity generated per year per 1 kW of capacity, and they are also compared based on the amount of electricity generated per year per square meter of space required for the system (Table 3.5). These numbers are generated based on the statistics for a system rated at 10 MW, a capacity size common to both system options.

Table 3.5. Comparison of the annual electricity produced per kW of capacity and per square meter for a variety of 10 MW solar systems based on solar data for Macquarie University in NSW.

[17] As previously discussed, the entire campus has approximately 490,000 square meters of open space; however, this space is not in one parcel. As a result, it would be impossible to find the 400,000 square meters of contiguous, flat land required to install the smallest practical central receiver tower.

System Type	Annual Production (kWh)	Space Requirements (sq. m)	Production per kW (kWh)	Production per Square Meter (kWh)
PV, no track	12,850,000 kWh	90,000 sq. m	1,285 kWh	143 kWh
PV, 1 axis track	16,320,000 kWh	90,000 sq. m	1,632 kWh	181 kWh
PV, 2 axes track	17,230,000 kWh	90,000 sq. m	**1,723 kWh**	**191 kWh**
Dish, 25 kW	13,876,900 kWh	87,060 sq. m	1,388 kWh	159 kWh

As Table 3.5 illustrates, on the basis of production per kW of capacity, a two axes tracking photovoltaic system has the highest production at 1,723 kWh per kW of system capacity. On the basis of production per square meter of system size, the two axes tracking system also has the highest production at 210 kWh per square meter. However, a single 25 kW parabolic dish actually has the highest production per square meter at 396 kWh per square meter. This number decreases as more parabolic dishes are added to an array due to the increased space requirements to prevent a dish from shading another dish in the array. As a result, a 10 MW array of parabolic dishes only produces approximately 159 kWh per square meter. For photovoltaic arrays, there is only a small difference between these metrics for smaller and larger capacity systems because the extra space needed to minimize shading is not as significant as in the case of parabolic dishes.

3.2. Costs

There are currently no rebates, incentives, or grants available for solar system projects of the size Macquarie University is pursuing. In New South Wales, there is currently a solar bonus scheme, but it only applies on projects up to 10 kW in size. This incentive provides $0.60 per kWh of electricity generated, but it is only applicable to residential settings (Alternative Technology Association 2010b). The federal government allows producers of renewable energy to sell the Renewable Energy Credits (RECs) associated with the "greenness" of the electricity. However, this currently only applies to solar systems of less than 100 kW in capacity. In addition, selling the RECs from a solar project means the owner of the installation can no longer claim the environmental benefits associated with the renewable energy (Alternative Technology Association 2010a). As a result, all costs listed in this section reflect the total cost of a solar project.

3.2.1. Photovoltaic System Costs

For a photovoltaic project, price per kilowatt of capacity decrease rapidly with a larger project (Table 3.6). For example, the cost per kW of a 10,000 kW system with no tracking is approximately 60% the cost of a 1 kW system with no tracking. There are large

Table 3.6. Costs associated with three different sizes of photovoltaic arrays at Macquarie University in NSW. Based on information from Sutula 2006, pp. 42-46.

System Type	Capacity (kW)	System Cost ($)[18]	Total Lifetime Cost ($)[19]	Cost per kW of Capacity ($)
No tracking	1 kW	$12,400	$14,600	$14,600
No tracking	100 kW	$921,000	$1,070,000	$10,700
No tracking	10,000 kW	$81,200,000	$85,600,000	$8,560
1 axis tracking	1 kW	$13,600	$16,100	$16,100
1 axis tracking	100 kW	$1,010,000	$1,180,000	$11,800
1 axis tracking	10,000 kW	$89,400,000	$94,100,000	$9,410
2 axis tracking	1 kW	$15,000	$17,500	$17,500
2 axis tracking	100 kW	$1,110,000	$1,280,000	$12,800
2 axis tracking	10,000 kW	$98,300,000	$102,700,000	$10,270

savings with increasing scale. The costs provided in this table can be used to estimate the costs of other systems based on the following intervals: the 1 kW cost data can be used for small scale systems in the size range of 1 to 9 kW, the 100 kW cost data can be used for medium scale systems in the size range of 10 kW to 499 kW, and the 10,000 kW cost data can be use for large scale systems in the size range of 500 kW to 10,000+ kW.

Based on the information in Table 3.6, several other useful metrics can be calculated[20] (Table 3.7). As shown in Table 3.7, all these photovoltaic systems have long payback periods.

Table 3.7. Additional cost metrics associated with three different sizes of photovoltaic arrays at Macquarie University in NSW.

System Type	Capacity (kW)	Cost per kWh ($)	Simple Payback (years)	Cost per tonne of CO_2 Reduction ($)
No tracking	1 kW	$0.51	32 years	$570
No tracking	100 kW	$0.37	23 years	$418

[18] System cost includes the cost of design, engineering, permitting, modules, inverters, and installation.

[19] Total lifetime cost includes all system costs plus 25 years of operation and maintenance costs adjusted for inflation. Adjustments are based on the average of yearly Australian inflation rates from 1990-2009 (Rate Inflation 2010).

[20] The numbers in this table are based on 25 year electricity production figures and total lifetime costs. Simple payback is based on an average value of $0.36/kWh which is the estimated cost of electricity during the 13th year of system operation assuming a 10% annual increase of electricity.

No tracking	10,000 kW	$0.30	19 years	$334
1 axis tracking	1 kW	$0.44	27 years	$495
1 axis tracking	100 kW	$0.33	20 years	$363
1 axis tracking	10,000 kW	**$0.26**	**16 years**	**$290**
2 axis tracking	1 kW	$0.46	28 years	$510
2 axis tracking	100 kW	$0.33	21 years	$373
2 axis tracking	10,000 kW	$0.27	17 years	$299

Based on all three metrics in Table 3.7, a photovoltaic system using one axis tracking is the most economical. As a result, this will be the system used when modeling solar installations that use photovoltaic systems in the discussion section.

3.2.2. Parabolic Dish System Costs

Unlike photovoltaic systems, parabolic dish systems are just becoming commercially available. In addition, they are mainly intended for a medium to large scale project. As such, there is not a significant decrease in price as the size of the project increases. The average system cost per watt of capacity is approximately $12.40 (Sutula 2006, p. 66). Based on this number, a single 25 kW dish would have a system cost of approximately $311,000 and a total lifetime cost of $339,000. Based on the total lifetime cost, the cost per kW of capacity for a parabolic dish system is approximately $13,560. Table 3.8 presents additional useful metrics for parabolic dish systems.

Table 3.8. Additional cost metrics for various sizes of parabolic dish systems at Macquarie University in NSW.

Capacity (kW)	**Cost per kWh ($)**	**Simple Payback (years)**	**Cost per tonne of CO_2 Reduction ($)**
25 kW	$0.43	26 years	$479
100 kW	$0.45	28 years	$505
225 kW	$0.45	28 years	$504
400 kW	$0.45	28 years	$502
625 kW	$0.45	28 years	$499
2,500 kW	$0.44	27 years	$494
10,000 kW	$0.44	27 years	$491

3.2.3. Costs Summary

As these numbers illustrate, photovoltaic systems have a lower cost per kWh, with the largest scale systems costing as little as $0.26 per kWh. In comparison, a parabolic dish system costs approximately $0.44 per kWh. Both parabolic dish systems and photovoltaic systems have relatively long payback periods. A large scale photovoltaic system may take 16 years to break-even while a large parabolic dish system may take 27 years. This payback period is directly dependent on the conservative assumptions made about the future value of electricity, cost of the systems, and long term cost associated with operating and maintaining the systems. As a result, payback periods may be several years shorter than predicted. For example, if electricity increases at 15% per year instead of 10%, the range of payback periods would be nearly cut in half to 9 to 18 years. Similar adjustments in assumptions can lead to significantly shorter payback periods. In addition, there is the possibility that Macquarie University could apply for a federal or state grant to help defray the cost of a solar installation. However, this report provides cautious estimates and in all likelihood overestimates the length of the payback periods. Overall, using one axis tracking photovoltaic arrays is the most affordable option for Macquarie University on the basis of the per kWh cost.

3.3. Campus Data

3.3.1. Energy Use

As of 2010, Macquarie University purchases approximately 32,329,307 kWh of electricity per year. Of that amount, only 1,574,637 kWh comes from a renewable energy source. The remaining 30,754,670 kWh comes from non-renewable energy sources and results in the emission of 27,400 tonnes of carbon dioxide. By 2020, this 30,754,670 kWh will have decreased to 27,679,203 kWh due to the planned 10% improvement in energy efficiency of existing buildings. By 2030, the expected 20% maximum improvement in energy efficiency will be achieved, which means existing buildings will use approximately 24,603,736 kWh per year. However, the construction of new buildings will counteract this downward trend in energy use. The 426,700 additional square meters of building space planned to be completed by 2020, will add 27,351,470 kWh per year, bringing the University's total demand to 55,030,673 kWh per year in 2020. Another 161,000 square meters will be added by 2030, increasing electricity demand by 10,320,100 kWh per year, bringing the University's total demand to 62,275,306 kWh in 2030. For the purposes of later discussion, several different target levels of annual electricity production from solar energy have been identified (Table 3.9).

Table 3.9. Different target levels of annual electricity production from solar energy at Macquarie University in NSW.

Target Level	2010 Electricity Production (kWh)	2020 Electricity Production (kWh)	2030 Electricity Production (kWh)
1%	307,547 kWh	550,307 kWh	622,753 kWh
2.5%	768,867 kWh	1,375,767 kWh	1,556,883 kWh
5%	1,537,734 kWh	2,751,534 kWh	3,113,765 kWh
10%	3,075,467 kWh	5,503,067 kWh	6,227,531 kWh
20%	6,150,934 kWh	11,006,135 kWh	12,455,061 kWh
30%	9,226,401 kWh	16,509,202 kWh	18,682,592 kWh
40%	12,301,868 kWh	22,012,269 kWh	24,910,122 kWh
50%	15,377,335 kWh	27,515,337 kWh	31,137,653 kWh
100%	30,754,670 kWh	55,030,673 kWh	62,275,306 kWh

Analysis of monthly electricity use data shows that monthly use patterns match fairly well with the pattern of electricity production from a solar installation (Figure 3.6). For most

Figure 3.6. Comparison of electricity use and solar electricity production by month for Macquarie University in NSW.

months, electricity production is closely matched to electricity use on campus. As a result, most electricity produced from solar energy will be consumed on campus. The months when solar electricity production may be higher than consumption are summer months. Since the summer is the time of highest electricity demand in the Sydney area, there will be high market demand for any excess electricity generated.

3.3.2. Available Space

The University consists of 71 buildings of various sizes. At most, the roof space of existing buildings on campus totals 92,000 square meters. However, some parts of this roof space are not suitable for solar installations. For example, usually only one half of a pitched roof will face the proper direction for solar installations. In addition, some roofs have heating, ventilation, and air conditioning (HVAC) systems that take up part of the roof. Furthermore, some of this roof space is from multi-deck parking that will soon be removed. As a result, current usable roof space is 54,500 square meters. Of this amount, there are nine buildings with more than 1,500 square meters of roof space available, eight buildings with between 1,000 and 1,499 square meters available, 18 buildings with between 500 and 999 square meters available, and 36 buildings with between 0 and 499 square meters available (Figure 3.7, Appendix B). The top nine buildings with the most roof space available account for 47% of total usable roof space and constitute 25,700 square meters. Between 2010 and 2020, approximately 26,700 square meters of roof space will be added. Between 2021 and 2030, another 10,000 square meters of roof space will be added bringing the total usable roof area on campus to approximately 91,200 square meters. Since these buildings are still in the planning phases, they can be designed to incorporate solar systems and thus their roofs can be assumed to be fully available. However, any estimates based on future building plans are highly speculative due to the possibility of changes in these plans.

For ground based systems, there are approximately 490,000 square meters of undeveloped space. By 2030, this will decrease to approximately 340,000 square meters. However, the University has made a commitment to maintaining this open space, so it will not be available for ground based solar systems. The University's sports fields cover approximately 170,000 square meters and parts of the unused space around the fields could potentially be used for solar (Denby[21] 2010, personal communication, 22 April). The suitable open space around the playing fields is estimated to be 8,500 square meters. If the tennis courts are removed, an additional 8,000 square meters of space would be made available.

[21] Leanne Denby is the Director of Sustainability at Macquarie University.

ersity campus as of April 2010 with potential sites for solar installations identified by square meters of roof available.

4. Discussion

4.1. Overview of Results

As the results demonstrate, with the proper amount of open space and sufficient funding, solar energy can be used to produce a significant amount of electricity. However, these two criteria are major hurdles. For Macquarie University to meet 100% of its current 30,754,670 kWh annual electricity needs, a 20,000 kW capacity one axis tracking photovoltaic system is needed. Such a system would occupy 180,000 square meters of space and require a capital expenditure of $179,000,000. Alternatively, a 21,250 kW capacity parabolic dish system would be needed. This type of system would occupy 183,000 square meters and require a capital expenditure of $264,350,000[22]. In 2020, Macquarie University's annual electricity consumption is expected to reach 55,030,673 kWh. By 2030, Macquarie University's electricity use is projected to reach 62,275,306 kWh per year. This doubling of electricity consumption compared to 2010's use is a result of the addition of several hundred thousand square meters of gross floor area. To meet 100% of this 2030 electricity consumption using a photovoltaic system would require over 360,000 square meters and over 366,000 square meters if a parabolic dish system were used.

Given that open space on campus currently consists of 490,000 square meters, a huge amount of this space would have to be covered with photovoltaic panels or parabolic dishes. However, much of this land would not be suitable for a solar installation. For instance, some of this space consists of courtyards that are shaded from the sun by surrounding buildings. In addition, some of this space is covered by vegetation or waterways. Furthermore, many of the parcels of open space are small chunks of land that would only be able to host a small solar installation, diminishing efficiencies of scale. Regardless of the availability of ground space, through discussions with Leanne Denby and Hilary Bekmann on 22 April 2010, it was made clear that the University intends to preserve its remaining open space.

This intention leaves the possibility of constructing solar systems on the roofs of buildings around campus. In total, there are currently 92,000 square meters of roof space among the buildings on the Macquarie University campus. However, not all this space is suitable for the installation of a solar system. Some of this roof space is occupied by HVAC and other building machinery. In addition, some of this space is shaded by the surrounding buildings or tall trees. Furthermore, some buildings have roofs that have pitches incompatible with positioning a solar system on the roof. As a result, there are approximately 54,500

[22] Given that cost is a primary concern for this project, the rest of this discussion will assume that a one axis tracking photovoltaic system will be used due to its lower cost per kWh of electricity generated.

square meters of usable roof space on campus. Of this amount, nine buildings (W10A, C7A, E7B, Y3A, E3A, C10A, C5C, E6A, and X5B) account for approximately 47% of total usable roof space and constitute 25,700 square meters. These should be the first buildings targeted for the installation of solar systems. Over the next twenty years, an additional 36,700 square meters of rooftop will be added across campus as 587,700 square meters of built area are added. Based on the assumption that all planned buildings can be designed to accommodate solar systems, there will be 91,200 square meters of suitable rooftop by 2030.

While open space on the main campus is to be preserved, there is the possibility of using some of the empty space around the school's sports fields for a ground based solar system (Denby 2010, personal communication, 22 April). At most, there is approximately 8,500 square meters of suitable space available around the playing fields. In addition, there are several tennis courts that could potentially be removed to provide another 8,000 square meters of space for a ground based solar system. However, the sports fields are not connected to the main electricity grid on campus, so there would be additional costs associated with connecting a solar system at the sports fields to the main campus grid. Overall, assuming that the area around the sports fields was fully utilized and the tennis courts were removed, there would be 71,000 square meters of space available on Macquarie University's land for solar systems. In 2020, there would be about 97,700 square meters. By 2030, this number would reach 107,700 square meters.

Based on the 181 kWh of electricity produced per square meter each year for a one axis tracking photovoltaic system, approximately 12,850,000 kWh could be produced per year at maximum assuming all 71,000 square meters of space currently available were utilized. In 2020, annual generation would at maximum be 17,680,000 kWh. By 2030, the maximum possible generation per year would be 19,500,000 kWh. These numbers could be increased marginally by using a two axes tracking photovoltaic system which produces approximately 191 kWh of electricity per square meter each year. However, the small increase in electricity production does not justify the increased cost of the two axes tracking system. As a result, a maximum of 42% of Macquarie University's electricity use could be generated in 2010, 32% in 2020, and 31% in 2030. Generating 100% of the University's electricity from solar energy is unattainable given the amount of space available on campus. The University will have to turn to other forms of energy for the production of approximately 69% of its electricity in 2030.

4.2. Non-Financial Benefits

The $0.26 cost per kWh of electricity generated from a large scale[23] one axis tracking photovoltaic system is relatively expensive compared to the current average price of $0.10 to $0.11 per kWh that the University pays for electricity. However, a large scale one axis tracking system has a relatively reasonable payback period of 16 years. Given the long term investment horizon of the University, this is a nearly acceptable payback period.

To further the case for solar energy, there are many non-financial benefits to take into account. Interviews with various staff affiliated with the Sustainability Office, Office of Facilities Management, and Vice Chancellor's Office and with Macquarie University students helped identify and explore these non-financial benefits. The University wants to be a leader in sustainability and the efficient use of resources (Denby 2010, personal communication, 22 April). A large scale solar project would help the University achieve leadership in this field. Very few universities around the world have undertaken large scale solar projects, and Macquarie University could set itself apart from its competition by pursuing such a project. The few universities that have undertaken a large scale renewable energy project receive ample amounts of publicity and media attention. In addition, with the local electricity grid nearing capacity, increasing on-campus generation would help ensure energy security for the University and have the added benefit of reducing the carbon dioxide emissions associated with the University's operations (Bekmann 2010, personal communication, 22 April). By reducing the University's demand for off-campus electricity, the University can help reduce the need for the construction of new coal-burning power plants. This reduction in emissions would help protect and preserve the environment at Macquarie University, the greater Sydney area, and the world.

Furthermore, a large solar project would help reinforce the University's goal of incorporating sustainability into learning and teaching. The University wants to encourage sustainability in everyday life, and solar projects would serve as a visible symbol to the students, staff, and faculty of the University. The University hopes to create a culture of sustainability that moves beyond simply operational sustainability (Denby 2010, personal communication, 22 April). Eden Ottignon, a current student at the University, explained on 22 April 2010 that many of Macquarie University's students do not see the need to pursue sustainability and are not aware of the magnitude of the environmental problems facing society. He continued to explain that the University needs to make people more cognizant of these problems. He felt that by installing and heavily promoting renewable energy projects on

[23] Defined as greater than 500 kW capacity.

campus this could be partially achieved. Eden also suggested incorporating hands-on exhibits such as mobile phone chargers powered by the solar installations to further promote the project. While the Office of Facilities Management and the Sustainability Office have been working to make the campus more efficient, many of these improvements are not readily visible; in contrast, a large solar project would be clearly visible and easily explained and incorporated into course curriculum.

Moreover, a solar project would help improve the image and branding of the University. As potential students become more aware of environmental issues, having a renewable energy project on campus would help draw in these students. This draw would give the University a competitive advantage in recruiting world class students and would help improve the University's national and international ranking. A solar project at the University can also demonstrate to students how a business can operate in an environmentally responsible manner. By leading by example, the University can encourage its students to be conscious of the environmental impact of any businesses they may operate in the future (Denby 2010, personal communication, 22 April). Finally, having a solar project on campus would motivate further research on solar energy by students and faculty, potentially leading the way for advancements in solar technology.

4.3. Guiding Design Principles from Interviews

In addition to gathering feedback on the non-financial benefits of a solar project, the interviews helped define some guiding principles for the installation of solar projects around campus. As previously explained, existing open space is to be preserved. However, aesthetics for systems installed on campus buildings is not a concern. The University would prefer for the systems to be as visible as possible to serve as a symbol of its commitment to the environment (Denby and Bekmann 2010, personal communication, 22 April). John Macris, the biodiversity planner at the University, offered the example of the lack of concern with aesthetics associated with the three 1,000,000 liter thermal storage tanks on campus. In addition, the roofs of future buildings can be designed to fully accommodate a solar system, which was taken into account during the calculations for this report (Bekmann 2010, personal communication, 22 April).

A discussion with Hilary Bekmann on 29 April 2010 helped guide the way recommendations for solar projects were developed. Since future building plans are highly speculative, recommendations for percentage goals of 2010 and 2020 electricity use will be discussed separately. In addition, 2030 buildings plans are very likely to change and as such, recommendations for solar projects will be limited to meeting the electricity needs of 2010 and 2020 based on the usable space available in the respective years.

4.4. 2010 Recommendations

For 2010, the maximum percentage of campus electricity that can be generated by solar energy is 42%. As such, the following percentage goals will be considered: 1%, 2.5%, 5%, 10%, 20%, 30%, and 40% (Table 4.1).

Table 4.1. 2010 target levels of total campus electricity use to be supplied by solar energy.

Target Level	2010 Electricity Production (kWh)
1%	307,547 kWh
2.5%	768,867 kWh
5%	1,537,734 kWh
10%	3,075,467 kWh
20%	6,150,934 kWh
30%	9,226,401 kWh
40%	12,301,868 kWh

The 1% target level can be considered as a sort of pilot project. This level can be achieved with a one axis tracking system with a capacity of approximately 200 kW. This system will require 1,800 square meters of space. Such a system will produce 326,400 kWh annually and will cost approximately $2,020,000 with a 20 year payback period. Each kWh of electricity will cost approximately $0.33. This project will reduce the University's carbon dioxide emissions by 275 tonnes per year. Any of the buildings colored green in Figure 3.7 except E6A and X5B would be suitable for this size project. Since this project may serve as a pilot, C10A, C7A, E7B, or C5C would be particularly well suited to maximize visibility of the system for students. While a parabolic dish system would further increase the visibility of the project, the costs associated with retrofitting a building's roof to support such a system would be prohibitively higher than the cost for a similar sized photovoltaic system.

The 2.5% target level will require a one axis tracking system with a capacity of approximately 500 kW. Such a system will require 4,500 square meters of space and will cost $4,470,000 with a 16 year payback period and a cost of $0.26 per kWh of electricity produced. This project will reduce the University's carbon dioxide emissions by 700 tonnes per year. This level could be reached with a single installation on the roof of W10A or through a combination of three 1,500 square meter systems split among any of the buildings colored green in Figure 3.7. While using a single system might reduce operations and maintenance costs, splitting the system among three buildings increases visibility and student awareness of the project.

The 5% target level will require a system with a capacity of approximately 1,000 kW. Such a system will require 9,000 square meters of space and will cost $8,940,000. Like the 2.5% target level system, this system will have a 16 year payback period and a cost of $0.26 per kWh of electricity produced. This project will reduce the University's carbon dioxide emissions by 1,400 tonnes per year. To achieve this 5% target, the system will have to be split among at least two buildings. By utilizing most of the available space on the roofs of C7A and W10A this project could fit on two buildings. Another option would be to split the project among three or four of the buildings colored green in Figure 3.7. As the University pursues systems of this size and bigger, there is the possibility to get significant grants to help reduce the cost of the project. For example, for a project of similar cost, the University of Queensland received a grant of $1.5 million.

The 10% target level will require a system with a capacity of approximately 2,000 kW. Such a system will require 18,000 square meters of space and will cost $17,880,000. The payback period will still be approximately 16 years with an average cost of electricity of $0.26 per kWh. This project will reduce the University's carbon dioxide emissions by 2,800 tonnes per year. To accommodate a project of this size, the buildings with the five largest usable roofs on campus will be required. These buildings include: W10A, C7A, E7B, Y3A, and E3A and have a combined usable roof space of slightly over 18,000 square meters. Again, it would be possible to split this project among many smaller roofs, but for financial and operational reasons, it makes the most sense to consolidate systems of this size. As a project expands to this size and larger, obtaining funding is a much more complicated exercise. With the smaller scale projects, the University could conceivable fund the project itself, but with a project of this size additional investors may need to be secured.

The 20% target level will require a solar system with a capacity of approximately 4,000 kW. Such a system will require 36,000 square meters of space and will cost approximately $35,760,000. The payback period will still be approximately 16 years with an average cost of electricity of $0.26 per kWh. This project will reduce the University's carbon dioxide emissions by 5,600 tonnes per year. This project will require using at least 18 buildings on campus. These 18 buildings include all of the buildings colored in green and yellow on Figure 3.7 plus one or two buildings colored orange.

The second highest achievable target level, 30%, will require a solar system with a capacity of approximately 6,000 kW. Such a system will require 54,000 square meters of space and will cost $53,640,000. As with the other large scale projects, the payback period will still be approximately 16 years with an average cost of electricity of $0.26 per kWh. This project will reduce the University's carbon dioxide emissions by 8,400 tonnes per year. This project will require the use of all 59 buildings on campus with usable roof space. This includes all of the buildings colored green, yellow, orange, and red on Figure 3.7.

The highest achievable target for 2010, 40%, will require a solar system of approximately 8,000 kW. Such a system will require 72,000 square meters of space and will cost $71,520,000. As with the other large scale projects, the payback period will still be approximately 16 years with an average cost of electricity of $0.26 per kWh. This project will reduce the University's carbon dioxide emissions by 11,200 tonnes per year. This project will require the use of all 59 buildings on campus with usable roof space. In addition, the 8,500 square meters at the sports fields will need to be used as will the 8,000 square meters occupied by the tennis courts. Using the space at the sports fields and tennis courts adds the complication of connecting the solar installation to the campus electrical grid. This connection will result in increased costs that must be taken into consideration before pursuing this option.

Overall, the projects meeting 1%, 2.5%, and 5% of the 2010 electricity use could relatively easily be undertaken in the near future. For the higher target levels, the high expenses and need to use much of the available roof space on campus makes the targets stretch goals. However, with the help of significant grants, they are still a possibility.

4.5. 2020 Recommendations

For 2020, the maximum percentage of campus electricity that can be generated by solar energy is 32%. As such, the following percentage goals will be considered: 1%, 2.5%, 5%, 10%, 20%, and 30% (Table 4.2).

Table 4.2. 2020 target levels of total campus electricity use to be supplied by solar energy.

Target Level	2020 Electricity Production (kWh)
1%	550,307 kWh
2.5%	1,375,767 kWh
5%	2,751,534 kWh
10%	5,503,067 kWh
20%	11,006,135 kWh
30%	16,509,202 kWh

By 2020, 26,700 square meters of new roof space will be added. As these buildings have yet to be designed, the roofs can be designed to incorporate solar systems into their construction. As such, to meet the target of 1% electricity production, the University could use a 400 kW array of 16 parabolic dishes. This project would cost $4,976,000[24] compared to the $3,535,000 cost for a one axis tracking photovoltaic system with a capacity of 350 kW producing a similar amount of electricity annually. Both of these systems would require approximately 3,000 square meters. This project will reduce the University's carbon dioxide emissions by 500 tonnes per year. The photovoltaic system could be placed on any of the bigger green colored buildings in Figure 3.7 while the parabolic dish system would have to be situated on one of the new building's roofs. Although the parabolic dish system costs almost $1.5 million more than the photovoltaic system, it would serve as a much more visible and unique symbol of the University's commitment to sustainability. If the University did not want to spend such a large premium on a parabolic dish system, it could consider using one parabolic dish in conjunction with a photovoltaic system to meet this 1% target. This combination would achieve the goal in a cost effective manner while also serving as a strong symbol of the University's commitment. Such a project would cost approximately $3,600,000 using a 25 kW parabolic dish and a 325 kW photovoltaic system.

To meet 2.5% of 2020's electricity use, a one axis tracking photovoltaic system with a capacity of 850 kW would be needed. Such a system will require approximately 7,650 square meters and will cost $7,600,000. For this project, the payback period will be approximately 16 years with an average cost of electricity of $0.26 per kWh. This project will reduce the University's carbon dioxide emissions by 1,250 tonnes per year. To accommodate this project, parts of the roofs of the new buildings on campus could be used or several of the green colored buildings in Figure 3.7 could be used.

To meet 5% of 2020's electricity use, a one axis tracking photovoltaic system with a capacity of 1,700 kW would be needed. Such a system will require approximately 15,300 square meters and will cost $15,200,000. For this project, the payback period will be approximately 16 years with an average cost of electricity of $0.26 per kWh. This project will reduce the University's carbon dioxide emissions by 2,500 tonnes per year. To accommodate this project, parts of the roofs of the new buildings on campus could be used or several of the green colored buildings in Figure 3.7 could be used.

To meet 10% of 2020's electricity use, a one axis tracking photovoltaic system with a capacity of 3,400 kW would be needed. Such a system will require approximately 30,600 square meters and will cost $30,400,000. For this project, the payback period will be approximately 16 years with an average cost of electricity of $0.26 per kWh. This project will

[24] These costs are given in 2010 dollars.

reduce the University's carbon dioxide emissions by 5,000 tonnes per year. To accommodate this project, parts of the roofs of the new buildings on campus could be used in conjunction with the roofs of several of the green colored buildings in Figure 3.7.

To meet 20% of 2020's electricity use, a one axis tracking photovoltaic system with a capacity of 6,800 kW would be needed. Such a system will require approximately 61,200 square meters and will cost $60,800,000. For this project, the payback period will be approximately 16 years with an average cost of electricity of $0.26 per kWh. This project will reduce the University's carbon dioxide emissions by 10,000 tonnes per year. To accommodate this project, parts of the roofs of the new buildings on campus could be used in conjunction with the green and yellow colored buildings in Figure 3.7.

To meet 30% of 2020's electricity use, a one axis tracking photovoltaic system with a capacity of 10,200 kW would be needed. Such a system will require approximately 91,800 square meters and will cost $91,200,000. For this project, the payback period will be approximately 16 years with an average cost of electricity of $0.26 per kWh. This project will reduce the University's carbon dioxide emissions by 15,000 tonnes per year. To accommodate this project, all of the roofs of the new buildings on campus, the roofs of all the green, yellow, and orange colored and some of the red colored buildings in Figure 3.7, and the sports fields and tennis court areas would need to be used.

Overall, the projects meeting 1% and 2.5% of the 2020 electricity use could relatively easily be undertaken in the near future. For the higher target levels, the high expenses and need to use much of the available roof space on campus makes the targets stretch goals. However, with the help of significant grants, they are still a possibility and are worth considering as future expansion plans allow.

4.6. Summary

As the previous discussion of 2010 and 2020 target levels illustrate, using solar energy to power the University will be expensive. However, the 1% target level of 2010 electricity can serve as a good starting point for future projects. As finances allow and solar installations become less expensive, the University can continue to expand its use of solar energy. At the same time as the University works toward generating more of its energy on campus, the University should also continue to pursue energy efficiency projects on campus. By improving the efficiency of existing buildings beyond the current projected 20%, the University could potentially use solar energy to meet a higher percentage of its electricity needs by 2030 than the predicted 31%.

5. Conclusions

5.1. Summary of Feasibility and Benefits

This report has explored the feasibility and associated benefits of Macquarie University installing solar electricity generation capacity on campus. This report has demonstrated that while solar energy can be used to provide up to 42% of the University's current electricity demands, it would be a very expensive undertaking. Such a project would cost upward of $70,000,000 and produce electricity at a cost of approximately $0.26 per kWh. A project of this scale would occupy the usable space on every single building on campus plus 16,500 square meters of space around the sports fields and the tennis courts. In addition, this sort of project would take approximately 16 years to break-even. However, this payback period could decrease if electricity prices increase faster than expected. In terms of meeting future energy needs, covering all usable space on new buildings, existing buildings, and sports fields with solar installations would result in meeting at most 32% of the University's electricity needs in 2020 at a cost of over $90,000,000. This report also identified the one axis tracking photovoltaic system as the most cost effective solar system option for Macquarie University.

While this report concludes that solar electricity might not be able to compete with electricity produced by coal power plants on the cost per kWh of electricity, this report also outlines many of the non-financial benefits of a solar installation. Among these benefits are the reduction in carbon dioxide emissions associated with a solar energy project and the associated decrease in the University's environmental impact. Sourcing just 10% of the University's 2010 electricity use from a solar project would decrease the University's carbon dioxide emissions by 2,800 tonnes per year. At the maximum 40% target level in 2010, emissions would be decreased by 11,200 tonnes. Given that the University's total carbon dioxide emissions from electricity use is approximately 27,400 tonnes, solar electricity could help to significantly reduce this number.

In addition, a solar energy project could help achieve the University's goal of being a leader in sustainability and the efficient use of resources. Furthermore, given the limited capacity of the local electricity grid, generating a portion of the University's electricity on campus helps ensure energy security for the future. Moreover, having a solar project on campus would help the University incorporate sustainability into learning, teaching, and campus culture. The symbolic value of a solar project on campus should not be underestimated. In addition, the possibility for hands-on learning could help Macquarie University become a leader in the development of future solar systems. By installing a large solar system, Macquarie University would also benefit from the increased branding and marketing opportunities that would help to entice future students to attend the University. When all these non-financial benefits are taken into consideration, the cost of a solar installation becomes more acceptable.

5.2. Recommendation for Action

Based on the data collected and analyzed in this report, it is recommended that the University pursue the installation of at least some solar energy on campus. Although the financials of a project might not be extremely attractive, when the non-financial benefits are considered, a solar project becomes more palatable. As such, it is worthwhile for the University to attempt to at least reach the 1% or 2.5% projects outlined in the discussion section. For both 2010 and 2020 electricity use, these target levels could be reached by using existing buildings' roofs. Prime candidates for solar systems include: W10A, C7A, E7B, Y3A, E3A, C10A, C5C, E6A, and X5B. In particular, C7A, C10A, C5C, and E7B are excellent options to showcase the technology on highly visible buildings near the center of campus. Depending on the future price of electricity and the penalties imposed on carbon dioxide emissions, the economics of solar may become more favorable. In that case, the University should consider increasing the percentage of its electricity that comes from solar energy.

In addition, the University should continue to pursue energy efficiency improvements in all of its buildings. By reducing energy use in existing buildings, significant amounts of money can be saved over the remaining lifespan of the buildings. Moreover, the University should consider building its new buildings to a high Green Star rating to reduce their environmental impact. Furthermore, the University should continue to increase its purchase of green electricity. As of now, the University purchases 6% of its electricity from green sources, incrementing this percentage by 1% each year. Going forward, the University should consider incrementing this percentage by 2% or 3% each year to more rapidly achieve its goal of being a leader in sustainability. Finally, the University should help promote behavioral changes in its student, staff, and faculty. By encouraging people to turn off lights, and raise thermostats, electricity use can be further reduced.

5.3. Recommendations for Further Study

While this report attempted to serve as a comprehensive analysis of solar energy for Macquarie University, there are several areas for further exploration. First, more research is necessary on the costs associated with a large scale solar project in an Australian setting.

Most of the cost data were based on estimates from projects in the United States and more accurate estimates could potentially be made by using data from projects in Australia. In addition, further study should be conducted on the possibilities for financing large scale solar projects. Moreover, research should be undertaken comparing solar energy at Macquarie University to other forms of alternative energy at the University. For example, a future report could explore whether wind energy or geothermal energy would make more sense for the University than does solar energy. Finally, research should be done on the possibility of the University investing in a large scale solar energy project at an off-campus site. For example, the University could partner with a solar developer to construct a large central receiver tower in a more suitable location for such a project than the University's campus. Further exploration of these topics will help inform the decisions of members of the Vice Chancellor's Office, the Sustainability Office, the Office of Facilities Management, and the Office of Major Projects as they decide how to proceed with this project.

6. References

Ailworth, E. 2009, *Harvard to Install Solar Array in Watertown*, Boston Globe (online), http://www.boston.com/business/articles/2009/08/11/harvard_to_install_solar_array_at_watertown_complex/ (14 April 2010).

Alternative Technology Association 2010a, *Federal – Renewable Electricity RECs* (online), Available: http://www.ata.org.au/rebates/federal-recs-renewable-electricity/ (21 April 2010).

Alternative Technology Association 2010b, *NSW Rebates* (online), Available: http://www.ata.org.au/rebates/nsw-rebates/ (21 April 2010).

Association of Energy Engineers 2010, *Baseload Plant* (online), Available: http://www.energyvortex.com/energydictionary/baseload_plant.html (15 April 2010).

Australian Academy of Science 2009, *Australia's Renewable Energy Future* (online), Available: http://www.science.org.au/reports/documents/AusRenewableEnergyFuture.pdf (12 April 2010).

Australian Research Institute in Education for Sustainability 2009, *Education for Sustainability: The Role of Education in Engaging and Equipping People for Change*, Commonwealth of Australia (online), Available: http://www.aries.mq.edu.au/publications/aries/efs_brochure/pdf/efs_brochure.pdf (27 March 2010).

Bankier, C. & Gale, S. 2006, *Energy Payback of Roof Mounted Photovoltaic Cells*, Post Carbon Institute (online), Available: http://www.energybulletin.net/node/17219 (26 March 2010).

Bekmann, H. 2010, *Request for Proposal for the Development of the Macquarie University Greenhouse Gas Reduction Targets and Action Plan*, Unpublished report prepared for Macquarie University by the University's Sustainability Office, Sydney.

Department of Climate Change 2010, *NGERS Calculator*, Commonwealth of Australia (online), Available: https://www.oscar.gov.au/deh.oscar.extension.web/Content/NgerThresholdCalculator/Default.aspx (21 April 2010).

Department of Energy, Utilities and Sustainability 2005, *Guidelines for Energy Savings Action Plan* (online), Available: http://www.environment.nsw.gov.au/resources/sustainbus/08595energyguidelines.pdf (26 March 2010).

Department of Resources, Energy and Tourism 2009, *Energy in Australia 2009*, ABARE (online), Available: http://www.ret.gov.au/energy/Documents/facts%20statistics%20publications/energy_in_aus_2009.pdf (10 March 2010).

Diesendorf, M. 2007, *Greenhouse Solutions with Sustainable Energy*, University of New South Wales Press, Sydney.

Doty Energy 2010, *Solar Photovoltaic* (online), Available: http://www.dotyenergy.com/Markets/PV_Solar.htm (14 April 2010).

Dunne, A. 2010, *UQ Goes Solar in a Big Way*, University of Queensland (online), Available: http://www.uq.edu.au/news/index.html?article=20999 (27 April 2010).

Ecoworld 2010, *How Much Solar Energy Hits Earth?* (online), Available: http://www.ecoworld.com/energy-fuels/how-much-solar-energy-hits-earth.html (13 April 2010).

Fthenakis, V., Mason, J. & Zweibel, K. 2009, "The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US," *Energy Policy* (online), vol. 37, no. 2, pp. 387-399, Available: Gale Group, Expanded ASAP (16 April 2010).

Green Building Council of Australia 2008, *Technical Manual: Green Star Office Design and Office as Built Version 3 – 2008*, Green Building Council of Australia, Sydney.

Green, R. 2010, *Eco Global Fuels & Solar Energy*, EcoGlobal Fuels (online), Available: http://www.ecoglobalfuels.com/solar.php (14 April 2010).

Harvey, L. 2006, *A Handbook on Low-Energy Buildings and District-Energy Systems*, Earthscan, London.

Johns, A. 2010, *Sustainability at Williams*, Williams College (online), Available: http://www.williams.edu/resources/sustainability/ (14 April 2010).

Jones, S. 2003, *Solar Power of the Future: New Ways of Turning Sunlight into Energy,* The Rosen Publishing Group, New York.

Macquarie University 2009, *About the University* (online), Available: http://www.mq.edu.au/university/about/index.html (15 April 2010).

Macquarie University Sustainability Office 2008, *Macquarie University: Energy Savings Action Plan*, MPI Group Australia (online), Available: http://www.mq.edu.au/sustainability/resources/documents/e/EnergySavingsActionPlane-1108.pdf (15 February 2010).

Macquarie University Sustainability Office 2009, *Macquarie University Sustainability*, Macquarie University (online), Available: http://www.mq.edu.au/sustainability/index.html (15 April 2010).

Narrative Network 2009, *Alternative Energy: Narrative Network Analysis of Media Coverage*, Waggener Edstrom (online), Available: http://waggeneredstrom.com/downloads/III_AltEnergy_NarrativeNetwork_Print.pdf (14 April 2010).

National Renewable Energy Laboratory 2010a, *Renewable Resource Data Center*, U.S. Department of Energy (online), Available: http://www.nrel.gov/rredc/pvwatts/ (18 March 2010).

National Renewable Energy Laboratory 2010b, *Solar Adviser Model*, U.S. Department of Energy (online), Available: https://www.nrel.gov/analysis/sam/ (16 April 2010).

Nature Education 2010, *Solar Energy* (online), Available: http://www.nature.com/scitable/spotlight/Solar-Energy-8731061 (13 April 2010).

New South Wales Government 2010, *Solar Power* (online), Available: http://www.industry.nsw.gov.au/energy/sustainable/renewable/solar (21 April 2010).

Nice, Karim 2010, *How Stirling Engines Work*, How Stuff Works (online), Available: http://auto.howstuffworks.com/stirling-engine1.htm (13 April 2010).

O'Loughlin, S. 2010, *Solar Panels Reflect Environmental Commitment*, Monash University (online), Available: http://www.monash.edu.au/news/newsline/story/1573 (14 April 2010).

Parry, T. 2007, *Looking to the Sun: Revolutionary Solar Power from Israel*, Canadian Broadcasting Corporation (online), Available: http://www.cbc.ca/news/reportsfromabroad/parry/20070815.html (26 March 2010).

Rate Inflation 2010, *Australia – Historical Inflation Rates* (online), Available: http://www.rateinflation.com/inflation-rate/australia-historical-inflation-rate.php?form=ausir (16 April 2010).

Reid, L. 1999, *Solar Energy: An Overview*, North Carolina Solar Center (online), Available: http://www.ncsc.ncsu.edu/include/_upload/media/pubs/11overvw.pdf (12 April 2010).

REN21 2009, *Renewables Global Status Report: 2009 Update*, Renewable Energy Policy Network for the 21st Century (online), Available: http://www.ren21.net/pdf/RE_GSR_2009_update.pdf (13 April 2010).

Research Institute for Sustainable Energy 2009, *Concentrated Solar*, Murdoch University (online), Available: http://www.rise.org.au/info/Tech/hightemp/index.html (8 April 2010).

Roberts Environmental Center 2010, *Sustainability Reporting of the Top 50 Liberal Arts Colleges*, Claremont McKenna College (online), Available: http://www.roberts.cmc.edu/PSI/PDF/LiberalArtsColleges2010.pdf (27 March 2010).

Rozenblat, L. 2009, *Power and Energy Primer* (online), Available: http://www.generatorguide.net/watt-acpower.html (12 April 2010).

Schlager, N. & Weisblatt, J. 2006, *Alternative Energy*, Thomson Gale, New York.

Solar Systems 2009, *SolarSystems* (online), Available: http://www.solarsystems.com.au/ (12 April 2010).

Stackhouse, P. & Whitlock, C. 2010, *Surface Meteorology and Solar Energy*, NASA (online), Available: http://eosweb.larc.nasa.gov (8 April 2010).

Stapleton, G. & Milne, G. 2008, *Photovoltaic Systems*, Commonwealth of Australia (online), Available: http://www.yourhome.gov.au/technical/fs67.html (12 April 2010).

Sutula, R. 2006, *Solar Energy Technologies Program: Multi-Year Program Plan 2007-2011*¸ U.S. Department of Energy (online), Available: http://www1.eere.energy.gov/solar/pdfs/set_myp_2007-2011_proof_1.pdf (21 April 2010).

Taylor, R. 2008, "The sun rises slowly for Australian solar," *Ecos* (online), vol.145, no. 3, p. 14, Available: Gale Group: Expanded ASAP (15 April 2010).

Thomas, S. 2007, *Energy Debate: Solar Power*, Wayland, London.

University Leaders for a Sustainable Future 1990, *The Talloires Declaration* (online), Available: http://www.ulsf.org/programs_talloires_td.html (28 March 2010).

U.S. Department of Energy 2007, *The Potential Benefits of Distributed Generation and Rate-Related Issues That May Impede Its Expansion* (online), Available: http://www.oe.energy.gov/DocumentsandMedia/1817_Study_Sep_07.pdf (13 April 2010).

U.S. Department of Energy 2008, *International Energy Annual* (online), Available: http://www.eia.doe.gov/emeu/iea/contents.html (13 April 2010).

U.S. Department of Energy 2009a, *Country Analysis Brief: Australia 2009* (online), Available: http://www.eia.doe.gov/emeu/cabs/Australia/Full.html (10 March 2010).

U.S. Department of Energy 2009b, *International Energy Outlook 2009* (online), Available: http://www.eia.doe.gov/oiaf/ieo/world.html (10 March 2010).

U.S. Department of Energy 2010, *Solar Explained: Photovoltaics and Electricity* (online), Available: http://tonto.eia.doe.gov/energyexplained/index.cfm?page=solar_photovoltaics (14 April 2010).

U.S. News and World Report 2010, *Best Colleges 2010* (online), Available: http://colleges.usnews.rankingsandreviews.com/best-colleges/liberal-arts-rankings (28 March 2010).

7. Appendices

7.1. Appendix A: Interview Questions

1) What do you think are the reasons behind Macquarie University's commitment to sustainability?

2) What would you like to see happen at the University in terms of sustainability?

3) What do you think is the motivation behind pursuing an alternative energy project at Macquarie University?

4) What do you think would be the benefits of alternative energy projects at Macquarie University?

5) What do you think would be the aesthetic guidelines for solar installations at Macquarie University?

6) What do you think are the perceptions and expectations of staff and students in relation to the University adopting sustainable practices like installing alternative energy technology?

7) What do you see as the barriers to such a project?

8) Do you think there is enough political will at Macquarie University to undertake a large scale solar project?

9) Would you like to add anything else?

7.2. Appendix B: Available Roof Space

Table 7.1. Available roof space on campus as of 2010.

Facility	Space Available (sq. meters)	Facility	Space Available (sq. meters)	Facility	Space Available (sq. meters)
W10A	5,702	E4A	788	E14B	210
C7A	4,244	X5A	783	S1A	194
E7B	3,215	W5A	709	C1A	153
Y3A	2,500	W6A	698	E12C	121
E3A	2,404	E7A	696	E12B	106
C10A	2,296	E14A	654	C9B	92
C5C	2,257	W3A	642	W6C	78
E6A	1,591	C5B	609	W19-21	68
X5B	1,505	C3A	586	F7A	53
E6B	1,422	E4B	533	Y1A	34
C5A	1,312	F7B	531	W19F	10
E11A	1,233	C4B	497	F3A	0
BD	1,150	Y4A	466	F5A	0
Y6A	1,114	W11A	453	C1	0
F9C	1,045	E8B	401	F5B	0
E3B	1,010	F9A	399	LCR	0
W6B	1,004	E14D	397	S11A	0
C8A	971	Y6B	396	SPTB	0
E8A	903	F9B	386	C3B	0
E5A	879	W5C	386	SPTA	0
C9A	845	E5B	366	CHI-SHILL	0
C4A	807	E12A	342	CHI-EAS	0
W5B	806	E14C	337	W16A	0
E8C	791	X6A	305		