Energy Return on Investment (EROI) of an Australian Wind Farm

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C. Haywood

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Abstract

Today, the shift towards more sustainable and environment-friendly sources of energy has become more prevalent in many societies. In Australia, the development of wind farms is seen to be on the rise. However, resources must be utilised in the most efficient way possible to ensure the least amount of environmental, economic, and ethical impacts accompany the development of the wind farm. This dissertation sought to understand the total energy required in wind farm development and the environmental impacts resulting from this process. The results reveal that 75.8 percent of the total embodied energy can be attributed to the manufacturing of the turbine, followed by 12.4 percent for site construction, 7.9 percent for the transportation, 3.9 percent for operation and maintenance, and lastly zero percent for the decommissioning of the wind farm due to the environmental credits from recycling, which offsets the energy used during the decommissioning phase. Some of the factors that significantly impact the total embodied energy include the weight and materials used in the turbine production and the mode and distance of transportation. EROI ranged from 19.92 (Moorabool North Wind Farm) to 38.16 (Cherry Tree Wind Farm) and has an average of 28.37. Meanwhile, the EPBT of Australian wind farms can vary from 0.89 years (10.63 months) to 1.60 years (119.20 months), with an average of 1.19 years (14.26 months). The results of this study will be useful to wind farm developers, operators, investors, inhabitants of the surrounding area of the wind farm and the general public, policy makers and future researchers.

Definition of Terms

The following terms are defined in order to help the reader understand the context of each term in this dissertation.

- *Annual Load Factor* – referred to as Capacity Factor by Fernando (2010) is a factor added to the electrical output equation to adjust for predicted suboptimal wind speeds.
- *Availability Factor* – relates to the portion of the year that the wind turbine will generate electricity (i.e., wind speeds between 3-25 m/s).
- *Embodied energy* – total energy consumed to produce any product or service.
- *Energy return on investment (EROI)* – also known as energy returned on energy invested; the ratio of usable energy produced, and the energy invested in the production of the energy source.
- *Energy payback time (EPBT)* – the amount of time that it takes for an energy system to generate the amount of energy equivalent to the amount it used to build the system.
- *Life cycle assessment* – a specific methodology for evaluating the environmental impacts associated to the lifecycle of a product or service.
- *Wind farm* – also known as wind park, wind power station, or wind power plant; a group of wind turbines in the same site location used to produce electricity
- *Wind turbine* – also known as wind energy converter; device that is used to convert the wind’s kinetic energy into electrical energy.

CHAPTER 1: INTRODUCTION

I. Introduction

This chapter introduces the topic of this dissertation covering the background, the statement of the problem, the purpose of the study, the research questions, the significance of the study and a definition of terms.

II. Background

It has been 50 years since the idea of global warming was first proposed wherein there has been an increase in the Earth's average surface temperature due to the greenhouse effect. In essence, the surface temperature of the Earth varies linearly with the amount of short-wave radiation absorbed by the Earth's atmosphere and the amount of infrared radiation emitted back into space by the Earth (Fernando, 2010). The burning of fossil fuels also adds anthropomorphic heat to the atmosphere through the conversion of chemical potential energy to thermal energy (McRae, 2019). Unfortunately, the greenhouse effect occurs due to the Earth's atmosphere being almost completely non-resistant to solar radiation while greenhouse gases (GHG) in the atmosphere absorb the infrared radiation being emitted by the earth. It is this very process that made the Earth inhabitable today for the current inhabitants (Jain, 1993).

One of the factors that contribute to the greenhouse effect is the increasing demand of electricity, heating and transportation, which over the years has led to the excessive burning of fossil fuels as a means of electrical generation. This process of burning fossil fuels releases large amounts of GHG such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxides (N_2O) into the earth's atmosphere, all of which contribute to the increase of temperature of the earth's surface (Fernando, 2010).

The resulting climate change concerns arising from the increase of GHG in the atmosphere are particularly concerning for the poorer and more disadvantaged populations. Some impacts are obvious in today's environment in the form of impaired food yields (i.e., farming) and storm surges. Though health effects occur through more complex casual pathways, it is stated in Bowen and Friel (2012) that these are serious concerns that occur due to "underlying social conditions and sectors such as water and sanitation, agriculture and urban planning".

These worsening conditions are demanding a cleaner alternative to fossil fuels. In the power generation industry, our environmental leaders are turning to renewable energy such as wind powered energy farms to transition into an era of sustainable power generation. The Clean Energy Council Website publicly states "Australia's Renewable Energy Target (RET) is a Federal Government policy designed to ensure that at least 33,000 gigawatt-hours (GWh) of Australia's electricity comes from renewable sources by 2020", showing true commitment to the goal.

Figure 1 identifies an increased trend towards renewable energy as a supply source of electricity. In 1993, only around 10 percent can be attributed to renewables. However, in 2019, renewable energy contributed 21 percent of the total electricity generation consisting of hydro (5 percent), wind (7 percent), and solar (7 percent)

(Commonwealth of Australia, Department of Industry, Science, Energy and Resources, 2020)).

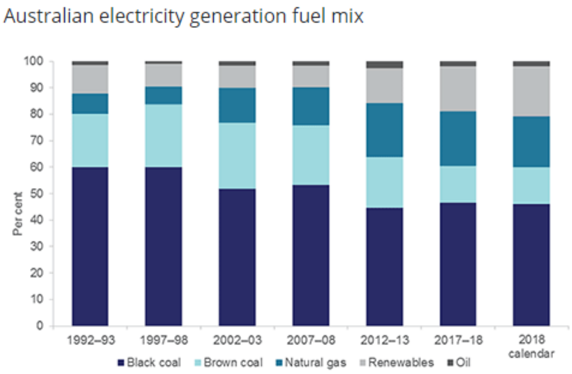


Figure 1: Australian electricity generation fuel mix (Commonwealth of Australia, Department of Industry, Science, Energy and Resources, 2020)

III. Statement of the Problem

While the commitment for renewable sources of energy is present, the resources in producing renewable energy remains to be limited. Moreover, the development process for a renewable energy project such as that of a wind farm is a long and complicated process. The development process basically starts with an initial site search suitable for a wind farm. After this, several investigations and feasibility studies will then by carried out. However, before construction, crucial to the success of a wind farm is its assessment and design. Just because the site is considered as feasible for a wind farm, it does not mean that it can be constructed right away. It still needs to undergo substantial assessments and planning in terms of design to ensure the efficiency of an operational wind farm (Energie Kontor, 2014). In order to do so, the wind farm developer must understand the economics of wind energy including the energy return on investment (EROI) of wind energy in order to be able to direct resources to the most efficient methods of producing renewable energy and ensure the least amount of environmental, economic, and ethical impacts accompany the development of the wind farm.

IV. Purpose of the Study

The primary purpose of this dissertation is to understand the total energy required in wind farm development and the environmental impacts resulting from this process. In order to achieve this, the following objectives have been prioritised:

1. Identify the typical processes in wind farm development.
2. Determine the embodied energy of each component/process in the typical Australian wind farm development process.
3. Itemise data and identify the most energy consuming processes within the wind farm life cycle.
4. Compare the different sized wind farms and discuss how/why the embodied energy in each wind farm (especially the wind farms similar in MW output) varies.
5. Calculate EROI rate for the standard wind farm.
6. Calculate the Lifecycle Energy Payback Time (EPBT) for each of the Australian wind farms.
7. Discuss alternative methods and materials to reduce embodied energy in wind farm development leading forward.

V. Research Questions

This dissertation will answer the following research questions:

1. What are the typical processes in wind farm development?
2. What is the embodied energy of each component in a typical Australian wind farm development process?
3. How does the size of the wind farm affect the embodied energy in each wind farm?
4. What is the EROI and the lifecycle EPBT for each of the Australian wind farms?
5. What are the alternative methods and materials to reduce embodied energy in wind farm development?

VI. Significance of the Study

This dissertation could potentially provide information on the issues and economics of wind energy particularly on the total energy required and the environmental impacts in the development of a wind farm. Therefore, the results of this study will be useful to the following stakeholders:

1. Wind farm developers and operators – The results of this dissertation can become a basis for wind farm developers and operators especially to the new ones in the field, in order to build a more economic and environment-friendly wind farm.

2. Wind farm investors – Wind farm investors can also benefit through the findings of this dissertation especially those concerning on the EROI of wind energy.
3. Inhabitants of the surrounding area of the wind farm and the general public – The inhabitants of the surrounding area of the wind farm and the general public will also benefit from wind farm developments that have less environmental impacts.
4. Policy makers – This dissertation can also become a basis for future policies concerning more environment-friendly wind farm developments in the future.
5. Future Researchers – Lastly, this dissertation can become a basis for future researchers who will also be studying wind farm development and other related studies.

VII. Conclusion

With global warming making the Earth inhabitable today for current inhabitants, the shift towards a more sustainable and environment-friendly source of energy is now stronger than ever. In Australia, while there is already favourable commitment to shifting towards renewable sources of energy such as wind farms, resources in producing renewable energy remains to be limited. Therefore, such resources must be utilised in the most efficient way to ensure the least amount of environmental, economic, and ethical impacts that accompany the development of the wind farm. This dissertation seeks to understand the total energy required in wind farm development and the environmental impacts resulting from this process. The results of this study will be useful to the wind farm developers and operators wind farm investors, inhabitants of the surrounding area of the wind farm and the general public, policy makers and future researchers.

CHAPTER 2: REVIEW OF RELATED LITERATURE

I. Introduction

This chapter provides a summary and analysis of relevant literature on the topic of this dissertation. The chapter starts with a description of the search terms used as well as search engines and libraries used, followed by a conceptual framework of the topic, and lastly a discussion of what has been written about the topic, specifically on the lifecycle analysis of a wind farm.

II. Search Description

For this literature review, the primary search engine used is Google Scholar using the following key terms: “embodied energy”, “energy return on investment”, “EROI”, “wind energy”, “wind turbines”, “wind turbine components”, “wind performance”, “lifecycle analysis”, and “wind farm development”.

III. Conceptual Framework

In order to understand the total energy required in wind farm development and the environmental impacts resulting from this process, one should also have an understanding of the theoretical concepts behind this process such as embodied energy, EROI, wind turbine components, and wind performance.

i. Embodied energy

In its simplest definition, embodied energy is the total energy consumed to produce a product or a service (Chen, Zhou, & Yang, 2019). By total energy, this is the energy consumed by all the processes in its production, “from the mining and processing of natural resources to manufacturing, transport and product delivery” (Milne & Reardon, 2013). There are two types of embodied energy: direct and indirect energy. Direct energy is the energy used in the main processes while indirect energy is the energy used to manufacture the products or services needed in the main processes (Fernando, 2010).

Applying this concept to power generation system, it is appropriate to examine the entire life cycle of the wind farm and ensure that this approach is applied to each phase of wind farm development. To illustrate, Figure 2 describes the different phases of the wind farm production and identifies the direction of energy (investment vs return) expected from each phase. As can be seen in Figure 2, to produce wind energy, each phase of the wind development will use energy, both with direct energy that will be used in the main processes and indirect energy that will be used the indirect processes such as those in the manufacturing of the core components/materials required to make the main processes possible. In wind farm application, indirect energy can be defined as that required to extract and transport raw materials to be used in the main processes. It does not include processes such as the energy involved in labour, financial services and the like (Hall, Lambert, & Balogh, 2013).

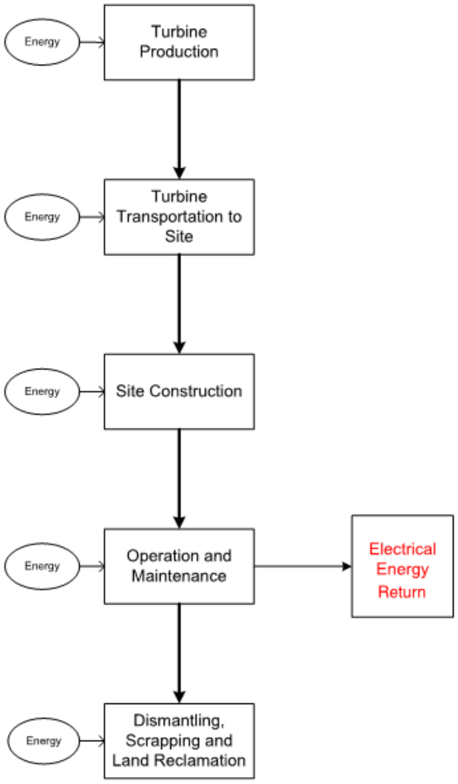


Figure 2: Lifecycle Energy Flows of a Wind Farm (Fernando, 2010)

The main methods of embodied energy evaluation are process chain analysis (PCA) and input-output (I/O) analysis. Performing life cycle analysis (LCA) is an accepted means of finding the total values of emission and energy produced by a process. Process chain analysis (PCA) is a form of LCA. PCA and Input/Output analysis (IOA) processes each have their negative and positive traits which will presented in detail.

PCA is used to investigate the energy and material flow in every process of production and it is based on the analysis of inventory utilising data collection. Issues that arise with PCA include the loss of accuracy due to the unavailability of information.

Since every byproduct produced during the process is tracked to its starting point, it evaluates the energy and emissions that is embedded as a result from material production. Due to PCA taking into consideration every energy point within a production process, it requires careful analysis of the energy flow and energy associated with the final materials. When this information is not available, errors can occur in the analysis.

IOA information is presented in I-O tables that presents the flow of services and goods in detail over a given period and its relationship to up flow and downflow industries. IOA can be utilised as a tool for clarifying the interrelationship between environmental impacts and economic activities. Moreover, it can be used to identify similar interrelationships within different sectors of a complicated economic system.

This approach assists in minmising the time-consuming issues of PCA. By providing a clear list of affected processes, up to infinite orders down production chains it provides a more time-effective means of data collection and calculation.

The errors that can occur from IOA are due to presenting average values of economic processes, so specialised processes could be lost and unaccounted for, as well as disaggregation.

Due to the limitation in each of these approaches, the combination of both PCA and IOA is used in the research project. Using this combination, it has become possible to evaluate the life cycle analysis in an accurate manner while also time efficient.

ii. Energy Return on Investment (EROI)

In order for an energy plant to be economically viable, it needs to have a higher energy output than the energy used to produce the energy. To know its economic viability, the energy return on investment (EROI) is used. The EROI is a means of measuring the quality of energy production methods by calculating the ratio between the energy produced (energy return) and the energy invested in the production of the energy source (Hall, et al., 2013).

$$\mathrm{EROI} = \frac{\text{quantity of energy supplied}}{\text{quantity of energy used in the supply process}}$$

The general premise in using EROIs is that if the EROI is large, then the energy produced is cheap and easy to get, whereas if the EROI is small, then the energy produced is expensive and difficult to get (Conca, 2015).

iii. How Wind Farms Compare to Other Clean Energy Sources

Among the different renewable energy sources, hydro power generation systems have the highest mean EROI value at 84:1 (Hall, et al., 2013). As can be seen in Figure 3, compared to the rest of the energy sources, hydro surpasses them all at a very significant difference. For the longest time, hydro energy has been the most popular form of renewable energy with some of the best hydro plants built a long time ago.

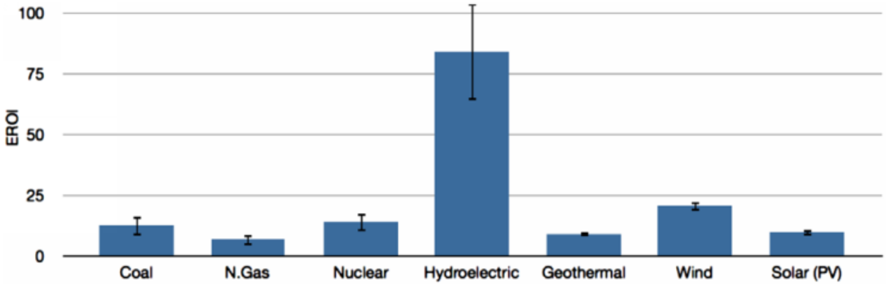
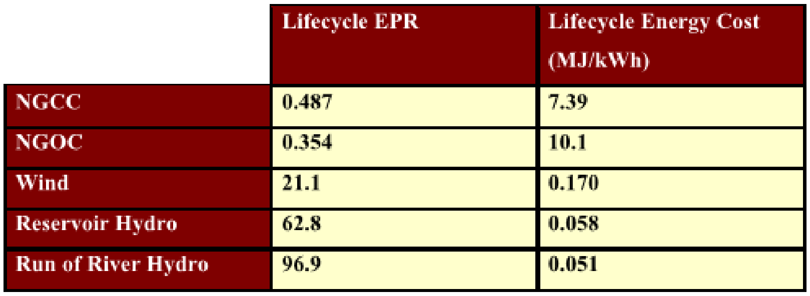


Figure 3. Mean EROI of power generation systems (Hall, et al., 2013)

Wind energy, on the other hand, only has an average EROI of 18:1 (Hall, et al., 2013). In other studies, EROI for wind farms was found to be as high as 27 (Huang, Gan & Chiueh, 2017), averaging 25.2 for operational and conceptual and 19.8 for operational only (Kubiszewski, Cleveland & Endres, 2010). Nevertheless, investments in wind energy are on the rise as they generally perform better than other renewable energy sources such as geothermal and solar generation systems. According to the Clean Energy Council (2018), “wind power is currently the cheapest source of large-scale renewable energy.” For this reason, there has been great interest and new investments in wind energy. In fact, for the first time, in 2019, wind power surpassed hydroelectricity as Australia’s leading source of renewable energy, supplying 35.4 per cent of the country's clean energy and 9.5 per cent of Australia's overall electricity (Clean Energy Council, 2018).

When it comes to clean energy sources, wind power is a high performer. Aside from the aforementioned EROI of wind energy, wind also has good lifecycle EPR at 21.1. As can be seen in Table 1, which shows a summary of the Lifecycle EPRs of five coal powered alternatives, while hydro energy plants show a larger lifecycle EPR, it is important to also consider the conditions in which these results are achieved to evaluate the adequacy for the Australian environment. To illustrate, the useful life given to wind power in Table 1 is 20 years whereas 200 years for both hydro generation examples. If both examples are reduced to EPR of one, it shows wind generation to return energy equal to investment much quicker than even the highest performing hydro power station (Runf o River Hydro).

Table 1. LEPRs and Lifecycle Energy Costs of the Different Power Plants (Fernando, 2010)



	Lifecycle EPR	**Lifecycle Energy Cost (MJ/kWh)**
NGCC	0.487	7.39
NGOC	0.354	10.1
Wind	21.1	0.170
Reservoir Hydro	62.8	0.058
Run of River Hydro	96.9	0.051

Natural Gas Combined Cycle (NGCC) and Natural Gas Open Cycle (NGOC) are not renewable sources so this paper will not take them into consideration.

iv. Wind Turbine Components

Technically, wind, as a natural resource, is made possible through a combination of three events, namely, the sun’s uneven heating of the atmosphere, the irregularities of the surface of the earth, and the rotation of the earth. In order to generate electricity, wind turbines are used wherein the kinetic energy of the wind is converted into mechanical energy, which is then used to generate electricity (U.S. Department of

Energy, n.d.). These turbines rely on electrical, mechanical, and civil ingenuity to function in a manner efficient enough to produce a positively geared EROI and financial ROI/IRR.

Figure 4 shows a typical wind turbine configuration consisting of the rotor blades, hub, nacelle, tower, and footing (Zafar, 2018).

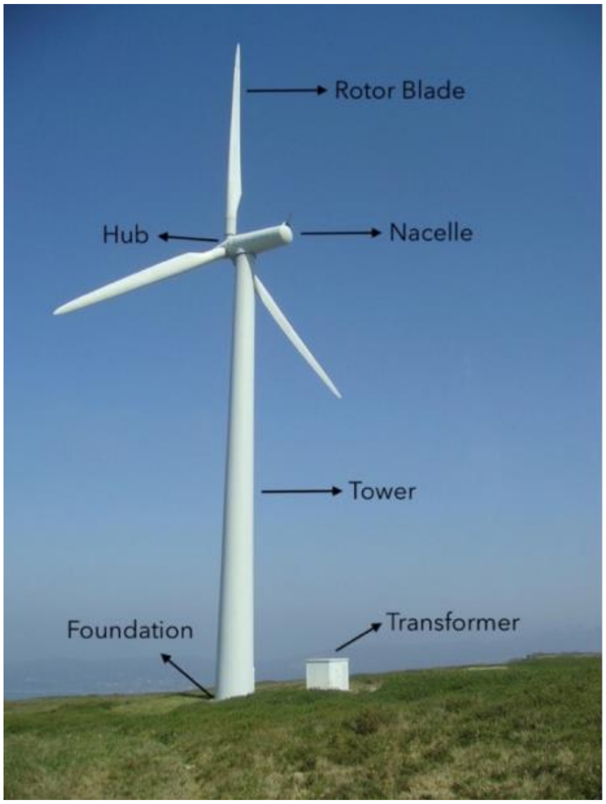


Figure 4. Typical Wind Turbine Configuration (Zafar, 2018)

1. Tower

A turbine's tower structure is considered as the heart of the wind turbine as it provides a safe and reliable operation of the turbine under different wind conditions (Rivkin, Liddell, & Silk, 2013). Aside from holding the turbine generator in its selected location in order to achieve the highest electrical output, the tower structure also holds the weight of the rotor blades, hub, nacelle and all electrical components contained within. During the lifetime of the wind farm, the tower can be expected to experience forces and bending moments arising from high wind conditions. Thus, the towers are expected to be durable with structural integrity to ensure the reliability and mechanical safety of the wind turbine system (Jha, 2010). There are several variations of towers in circulation today though a majority are of steel construction. The lesser used types of tower can be seen in Figure 5 including concrete, hybrid, steel lattice tower, three-legged tower, and guy-wired pole tower (Miceli, 2012).

Figure 5. Wind Turbine Tower Varieties (Miceli, 2012)

Some of the advantages of steel for fabrication include the ability to achieve taller towers, lighter in weight than concrete, easily fabricated and erected on site with a simple welded flange and nut/bolt assembly. In addition, steel is ductile allowing it to handle large deformations resulting from high winds. It also has a smaller foundation due to the smaller diameter tower base (Levandowski, 2015). On the other hand, disadvantages of steel tower construction include potentially higher costs for towers over 80m tall, significant transportation issues, lesser life span when compared to concrete (Levandowski, 2015)

2. Footing or Foundation

The footing or the foundation of the wind turbine is essentially the part wherein the load from the turbine are supported and transferred to the ground (Rivkin, Liddell, & Silk, 2013). The purpose of the footing is to ensure that stability is maintained and overturning is avoided. The foundation achieves this by countering a range of different loads including dead loads, wind loads, uplifting loads, overturning loads, vibrations, and long-term cyclic wave loadings (Razdan & Garrett, 2017a). In addition to the tower itself, vertical loads expected to be experienced by a turbine footing include a 438-tonne turbine (Razdan & Garrett, 2017a). Footing types can vary depending on their locations and soil structure as can be seen in Figure 6.

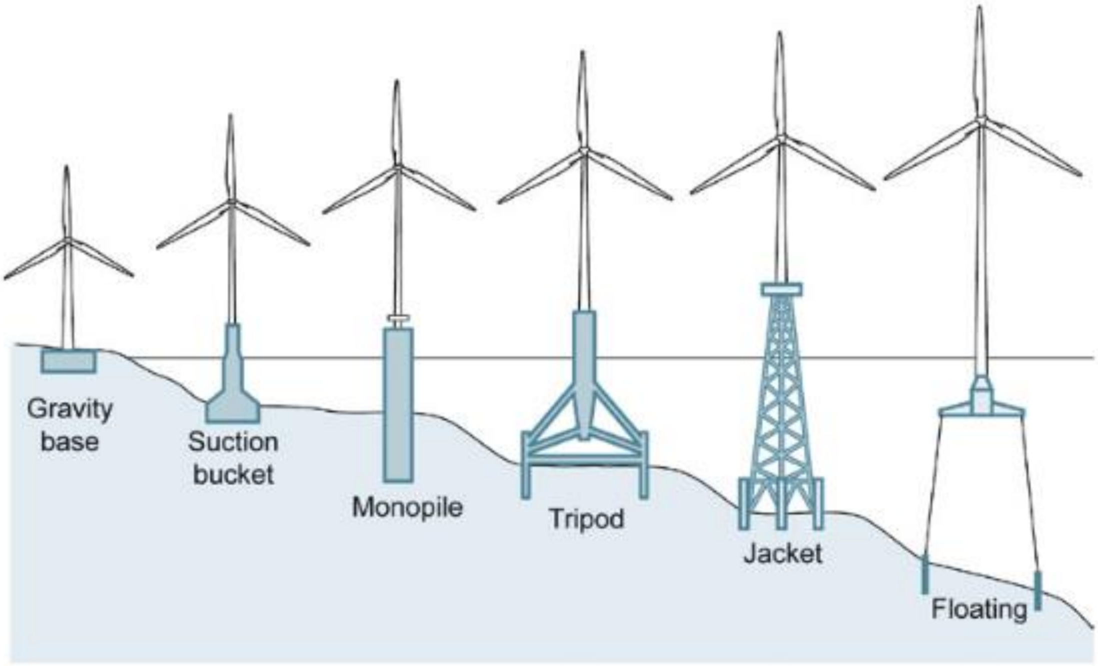


Figure 6. Wind Turbine Footing Varieties (World Steel Association, 2012)

The most common footing used for modern Australian wind turbine construction is the octagonal gravity footing as illustrated in Figure 7. This is a steel reinforced concrete footing which can be as deep as 4m, contain upwards of 70t of steel reinforcement and 598 cubic metres of concrete (iCubed Consulting Pty Ltd, 2018a)

Figure 7. Precast wind turbine footing (Miceli, 2013)

Occasionally, in addition to a gravity footing, rock anchors are also required to prevent uplift and overturning (iCubed Consulting Pty Ltd, 2018a). Less frequently used footings include jacket foundation, suction bucket foundation, tri-pile foundation, monopile foundation, and tripod foundation as shown in Figure 6.

3. Other Components

In addition to the tower and the foundation, other components of a wind turbine are as follows:

- Nacelle – The nacelle houses the mechanical and electrical components of the wind turbine including the generator, the yawing mechanism, and the gearbox. This component sits on top of the tower.

- Yaw mechanism – The yaw mechanism allows the nacelle, hub and blades to rotate on top of the tower around a vertical axis in order to ensure the wind is always approaching from the most effective direction. A good yaw mechanism can potentially reduce the cost of energy of the wind turbines as it increases not only the energy capture but also reduces the structure load as it points the rotor swept area consistent towards the incoming wind direction (Kim & Dalhoff, 2014).
- Hub – The hub connects the nacelle to the rotor blades.
- Rotor Blades – Angled at such a way to maximise the rotational force of the hub/shaft, the propeller blade is the most critical element of a wind turbine rotor. To ensure mechanical integrity, safety, and performance, the rotor blades must follow the principles of aerodynamics in order to achieve optimum performance without regard for the wind environment (Jha, 2010).
- Generator – Lastly, the generator transfers rotational forces within the shaft caused by the kinetic energy of the wind and transforms it into electricity (El-Mokadem, et al., 2009).

v. Wind Performance Characteristics

Efficiency in wind energy production is essential to fulfil the energy demand and provide adequate financial return on investment for developers. To ensure wind energy continues to produce electricity in a manner to satisfy these requirements, it is important to identify the major contributors of maximum output. Until recently, the limited technology of wind turbine design and construction meant that it was not economically feasible to install wind turbines in many locations due to low wind speeds. However, advancements in technology saw taller towers and longer rotor blades providing new opportunities to develop wind energy farms in areas with lower wind speeds that have been previously deemed unprofitable (Burt, et al., 2017).

This synchronicity of taller towers and longer blades solves two problems. Firstly, greater wind speeds are often correlated with increased heights (AEMO Map, 2020), providing an entirely new catalogue of suitable locations for potential wind farms. It is also the taller tower that provides the option for longer rotor blade, due to minimum ground clearance requirements for blades. This advantage of longer blades provides an increase in electricity production, making sites deemed once unfruitful suddenly a sound economic investment (Shankleman, 2016). In fact, Sharma (2012) shows that the economic value of a blade that can change in length in the field in varying wind conditions to be valued up to 4.3 times that of a typical fixed length rotor blade.

As Bauer (2020) illustrates in Figure 8, the electrical output of a wind turbine does not always correlate with the wind speed. For example, the cut-in and cut-out wind speeds of the Vestas V112-3.3 (3.3MW) turbine are 3.0m/s and 25m/s respectively with a rated wind speed of 13m/s.

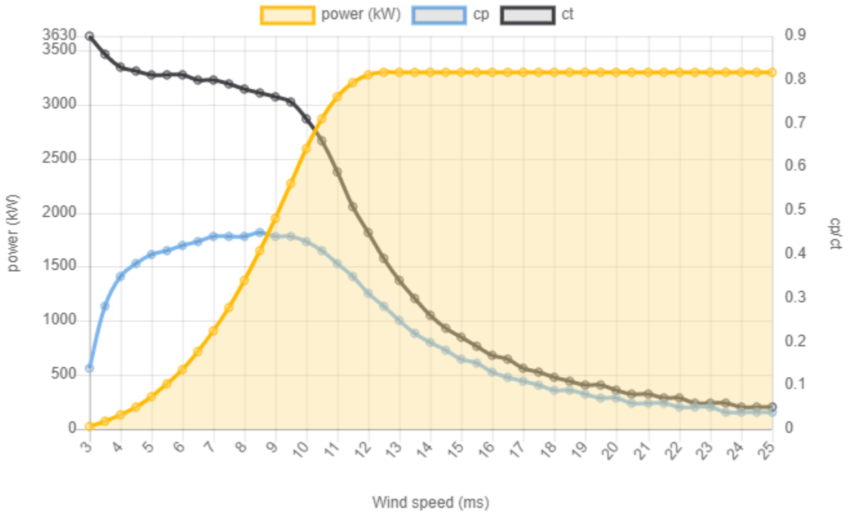


Figure 8. Vestas V112-3.3 Power Curve (Bauer, 2020)

The Vestas V112-3.3 Turbine has a 3-stage gearbox which allows it to continue operating at an output of 3300kW until cut-out wind speeds of 25m/s are reached. At this point, internal brakes are activated which bring the blade rotation and subsequently power generation to a halt. This is a safety function to prevent any damage to the turbine. Figure 8 also illustrates the decrease in efficiency of the turbine at higher wind speeds as power (cp) and thrust (ct) coefficients plummet while wind speeds increase.

IV. Review of Related Literature

A number of studies have been made that specifically focus on the lifecycle analysis of a wind farm. By lifecycle analysis, this includes the raw material acquisition, the processing and manufacturing, distribution and storage, use, maintenance and repair, and recycling options. A review of literature suggests varying results on which phase actually has the highest energy consumption. In one study conducted by Chipindula, et al. (2018), the material extraction or the processing stage was specifically recognised as the critical stage which is responsible for contributing 72 per cent of environmental impacts in onshore wind farms, 58 per cent in shallow water, and 82 per cent in deep water locations. Meanwhile, in Ghenai’s (2012) study, he found that it is during the primary production of the windfarm parts that consumes more energy and produces more of the emissions. This is consistent with Haapala and Prempreeda's (2014) study which found that the manufacturing of the turbine parts consumes the most energy creating an impact of 78 per cent in the total wind farm lifecycle.

In terms of the type of windfarm that has the most environmental impact, there are also some varying conclusions. According to Piasecka, et al. (2018), the environmental impact was found to be higher for land based wind farms compared to offshore wind farms. On the contrary, results from Huang, Gan and Chiueh’s (2017) study found that an offshore wind farm would actually lead to higher environmental impact. Nevertheless, some researchers such as Piasecka, et al. (2018) and Chipindala, et al. (2018) noted that these variations in LCA are common as results may vary depending on the manner of offshore wind power plant anchoring as well as axis of rotation, capacity factor, and rated power.

V. Conclusion

Given the varied results in the LCA of wind farms, this dissertation hopes to add important information in terms of this dissertation’s findings, discussion, and conclusions that will be used by future researchers in the field of wind farm development.

CHAPTER 3: METHODOLOGY

I. Introduction

This chapter will explain how this dissertation was conducted, specifically the methods used to collect and analyse data. This chapter will also explain the risks involved in the process of making this dissertation.

II. Research Design

This dissertation used a quantitative descriptive research design wherein quantifiable data was collected and processed to arrive at the different objectives of this dissertation. The primary focus of this dissertation is the life cycle of a wind farm as illustrated in Figure 9.

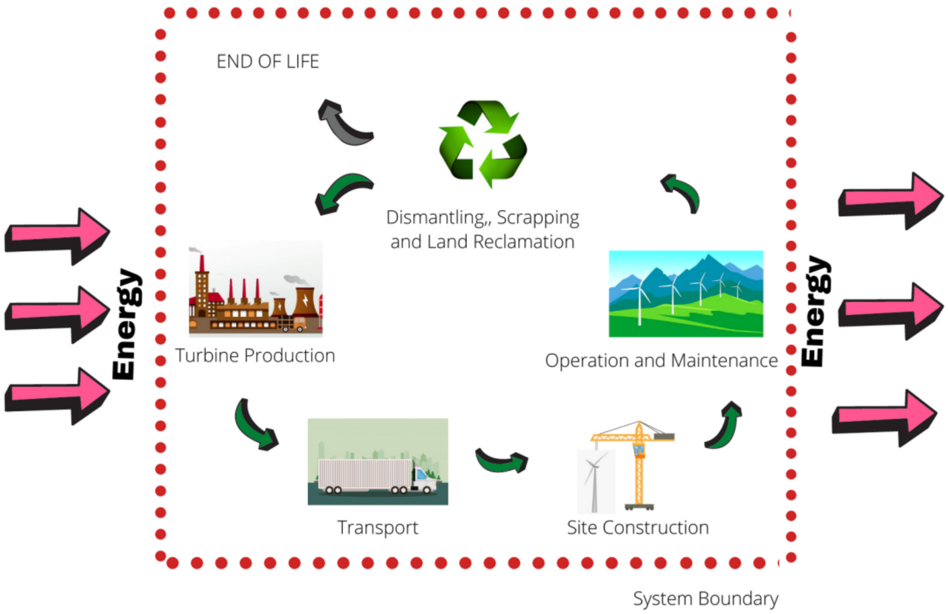


Figure 9. Lifecycle Analysis of Wind Farm Development

III. Research Questions

This dissertation will answer the research questions as mentioned in Chapter 1.

IV. Data Collection

Data was collected from a variety of sources. These include technical documents provided by iCubed Consulting and online sources such as research papers and journal publications. Where information was unavailable, assumptions were made based on industry averages. As some information is confidential, additional caution was taken to ensure all legal obligations were adhered to when submitting this paper for evaluation.

There were two main types of information required for the completion of this dissertation. The first type of data includes the site-specific information of the Typical Australian Wind Farm, for example the material quantities, construction material types and transportation distance. The first type of data was primarily obtained by accessing historical data from developed wind farms.

The second type of data is focused on the embodied energy coefficients of each material, measured in MJ/kg. The second type of information was obtained through the research of literature on embodied energy in Australia. Where information relevant to Australia is unavailable, information from international studies was used while prioritising recent studies over older ones. When it comes to PCA analysis to determine embodied energy coefficients of building materials, Milne and Reardon (2013) has been referenced. Meanwhile, when using the method of I/O analysis, the relevant intensity coefficients were adopted from the Australian National Accounts: Input-Output Tables, 2017-18 from the Australian Bureau of Statistics (2020). Where precise energy coefficients were unavailable, a result was achieved by identifying the closest economic sector available from Milne and Reardon (2013).

V. Data Analysis

This dissertation used a lifecycle analysis approach to analyse data wherein the total invested energy and returned was calculated through the five phases of the wind farm lifecycle. Several research studies have conducted a life cycle analysis of a wind farm. For the purposes of this paper, this dissertation has adapted Fernando’s (2010) life cycle with includes the following processes, namely, (1) turbine production, (2) turbine transport, (3) wind farm site construction, (4) operation and maintenance, and (5) dismantling, scrapping, and land reclamation.

Based on the identified phases of wind farm development, a comparison of known wind farms was undertaken across seven wind farm projects currently in development and/or construction. The values have been calculated for the following wind farm characteristics: (1) life of a wind farm, (2) number of turbines and total output, (3) turbine components’ transport by sea and by road, in addition to imported materials such as (5) footing steel and (6) footing concrete, as well as pavement materials such as (7) total earthworks. This list of characteristics served as the guidelines to answer the question of energy invested for the first three phases of wind farm development.

As for the operational phase of wind farm development, the power generation of the defined wind farm was calculated as part of this section. The lifecycle electrical energy output units were calculated in GJ, while the EROI components were calculated in kJ/kWh. To produce an accurate electrical output value, an availability factor was first determined. This factor relates to the portion of the year that the wind turbine will generate electricity (i.e., wind speeds between 3-25 m/s). It is predicted that wind speeds will vary considerably throughout the year and an optimal wind speed of 13m/s will not be constant. Due to this, an annual load factor (also known as Capacity Factor) was calculated and factored into the final output value (See Table 2 for example). The net generative power of the typical wind farm was then calculated by multiplying the capacity of the wind farm by the annual load factor (Fernando, 2010).

Table 2. White Hill Wind Farm Electrical Energy Output (Fernando, 2010).

Description	Quantity	Unit
Capacity	58	MW
Calendar Year Lifetime	20	Years
Availability Factor	90%	
Annual Load Factor	45%	
Full Power Lifetime	18	Years
New Power Output	26.1	MW
Lifetime Net Electrical Output	15,000,000	GJ

Lastly, dismantling, scrapping and land reclamation was calculated using an ‘avoided impacts approach’, which is also referred to as the closed-loop approach or the avoided burden approach to identify where credits can be granted for recycling (Norgate, 2013). The ‘avoided impacts approach’ is supported by the metals industry and complies with ISO 14044 (Atherton, 2006) in terms of environmental modelling, policy, and decision-making regarding recycling metal materials (Razdan & Garrett, 2017). This approach is important due to the range of materials on site. While all large metal components that are primarily mono-material (such as tower sections) are 98 per cent recyclable, other parts of a wind farm require additional categorisation.

A comparison of EROI economy of scale was then evaluated by comparing our seven case studies and discussing the findings.

VI. Risk Assessment

Risks associated with a research-based project include minor health and safety risk and resource risks. These are identified in the following sections below.

i. Health and Safety Risks

In order to minimize health and safety risks, the following steps have been applied as recommended by Ergonomics Now (2020):

- Adjust the chair height so that elbows are at desktop level.
- Sit fully back into chair, adjust the seat back for good lower back support, and use a lumbar roll if the back of the chair does not support the lower back.

- Locate the monitor so the top third of the viewing area is at or below eye level. Use monitor stand if required.
- With elbows at the desk level, ensure that the wrists are straight. Use wrist rest if required.
- Position the mouse as close as is practical to the keyboard, so that both elbows are directly under the shoulders while working. If this is not possible, consider purchasing a mini keyboard.
- To reduce stress on the neck when working from paper documents, a document holder can be placed between the keyboard and monitor.
- Always either put the phone on loudspeaker depending on the office environment or use a phone headset if there is a need to use the computer while talking on the phone; this will help avoid neck and shoulder strain.
- Adjust screen brightness and contrast for clear comfortable viewing and clean the screen regularly. Also, remember the 20-20-20 rule: look away from the monitor every 20 minutes to a distance of 20 metres for 20 seconds. This helps avoid eye strain.
- Take breaks regularly preferably every 45 minutes to an hour for 1 or 2 minutes. Go get a glass of water or talk to a colleague.

ii. Resource Risks

The resources required to complete the paper are illustrated in Table 3 below. The crucial component for producing a unique result of this paper lies in the access to technical data and design records. Approval has been given for access to these records though an ongoing consent by the employer was required as each component of information is collected and referenced. In the case that access is denied, the approach was modified to rely on publicly available data. Upon an initial literature review, there are several sources for this information which will enable successful completion. While the current employment condition remains intact, there will be no risk of losing access to these records. There have been no other risks identified.

Table 3. Resource Risks

Resource	**Access**	**Notes**
Technical data & design records	Employer	Mon-Fri 8am-8pm
Assistance navigating records	Employer	Mon-Fri 8am-5pm
Computer & Software – 12d, AutoCAD, Office	Employer	Mon-Fri 8am-8pm
Internet Access – Online	Personal/Employer	24/7 Access

VII. Conclusion

This chapter has discussed how this dissertation was conducted, specifically the methods used to collect and analyse data. As discussed in this chapter, this dissertation used a quantitative descriptive research design wherein quantifiable data was collected and processed to arrive at the different objectives of this dissertation, with primary focus on the life cycle of a wind farm. This chapter also explained the different risks involved in the process of making this dissertation.

CHAPTER 4: FINDINGS

I. Introduction

This chapter will show the different findings of this dissertation based on the primary objectives stated from Chapter 1.

II. Findings

i. Typical Processes in Wind Farm Development

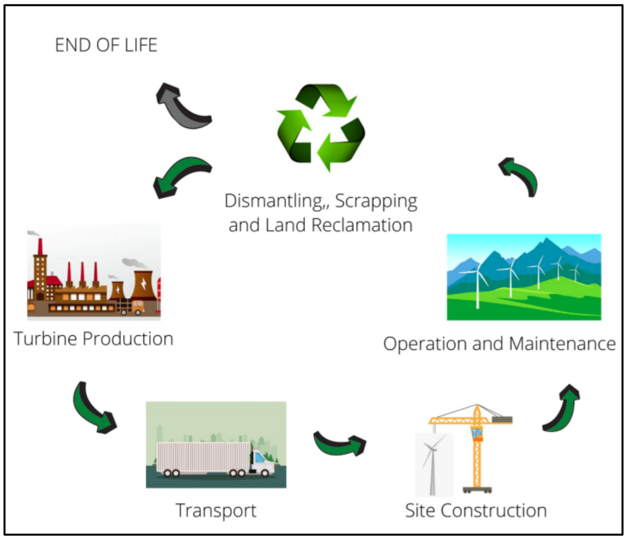


Figure 10. Typical Process in Wind Farm Development

ii. Australian Wind Turbines

For this dissertation, seven available wind farms are summarised in Table 4 along with their corresponding turbine manufacturer, turbine model and total weight of each turbine.

Table 4. Australian Wind Farm Turbines (Turbine Manufacturer, Model, Total Weight)

	Turbine Manufacturer	Model	Total Weight (t)
Moorabool North Wind Farm - VIC	Goldwind	GW 136	590
Moorabool South Wind Farm - VIC	Goldwind	GW 136	590
Murra Warra Wind Farm – VIC	Senvion	3.7M144 EBC	673
Cattle Hill Wind Farm – TAS	Goldwind	GW 140	396
Lal Lal Wind Farm – VIC	Vestas	V 136	601
Sapphire Wind Farm – NSW	Vestas	V 126	530
Cherry Tree Wind Farm – VIC	Vestas	V 136	601

It should be noted that there was no available public data in terms of the bill of materials for each of the aforementioned wind turbines. However, Vestas has disclosed a breakdown of the typical materials used in their wind turbines. Table 5 summarizes the materials composition for the following models: Vestas V-126 and V-136, which are used in Lal Lal Wind and Cherry Tree Wind Farms in Victoria and Sapphire Wind Farm in New South Wales (Vestas, 2018). Due to limitations in accessing commercially available information, this dissertation used the average of these two models as the standard for this dissertation as shown in Table 6.

Table 5. Materials Composition of a Wind Turbine (Vestas, 2018)

	V 136 - 3.60 MW	V 126 - 3.45 MW	AVERAGE
Steel and iron	89.00%	89.00%	89.00%
Aluminum and alloys	1.30%	1.30%	1.30%
Copper and alloys	0.50%	0.60%	0.55%
Polymer materials	2.70%	2.70%	2.70%
Glass/carbon composites	5.10%	5.70%	5.40%
Electronics/electrics	0.60%	0.70%	0.65%
Lubricant and fluids	0.30%	0.40%	0.35%

Table 6, 7, 8, and 9 summarises the data gathered from these wind farms. It should be highlighted that for the origin of Vestas turbines, their Tianjin factory in China was used as the point of origin for this dissertation since transport would be easier coming from the Chinese factory than from Denmark or the United States. Likewise, transportation distances for Vestas turbines were also separated in Table 8 since the whole turbine assembly came from the same factory (Vestas) as compared to the other turbines where other turbine parts were manufactured by a different company (e.g., towers manufactured by Keppel Prince Engineering (Victoria, Australia)).

Table 6. Australian Wind Turbines (Life, Total Number, Output, Topography Type, WTG Footing)

	Moorabool North Wind Farm – VIC	Moorabool South Wind Farm – VIC	Murra Warra Wind Farm – VIC	Cattle Hill Wind Farm – TAS	Lal Lal Wind Farm – VIC	Sapphire Wind Farm – NSW	Cherry Tree Wind Farm – VIC
Life of wind farm	25 years	25	25 years	20 years	30 years	25 years	30 years
Number of turbines	41	50	61	48	60	61	16
Turbine Output	2.5 MW	2.5 MW	3.7 MW	3.0 MW	3.6 MW	3.6 MW	3.6 MW
Total Output	102.5 MW	125 MW	225.7 MW	144 MW	216 MW	219.6 MW	57.6 MW
Topography Type	Flat/med	Flat/med	Flat	Medium	Medium	Medium	Medium
WTG Footing – Steel	28.8t	28.8t	37.7t	24.6t	26.0t	33.8t	28.5t
WTG Footing – Concrete	460 cu m	460 cu m	598 cu m	427 cu m	471 cu m	577 cu m	388 cu m

Table 7. Wind Turbines by Goldwind & Senvion (Origin, Weight of Turbine/Tower, Transportation Distance, Total Weight)

	Moorabool North Wind Farm - VIC	Moorabool South Wind Farm - VIC	Murra Warra Wind Farm - VIC	Cattle Hill Wind Farm - TAS
Origin of Turbine	Goldwind (Xinjiang, China)	Goldwind (Xinjiang, China)	Senvion (Germany)	Goldwind (Xinjiang, China)
Weight of Turbine (blade, hub, nacelle) (t)	191	191	240	215
Distance from factory to origin port (km)	3000	3000	16	3000
Distance from origin port to destination port (nm)	7462	7462	12134	7538
Distance from destination port to site (km)	121	121	343	280
Origin of Tower	Keppel Prince Engineering (Victoria, Australia	Keppel Prince Engineering (Victoria, Australia	Senvion (Germany)	Keppel Prince Engineering (Victoria, Australia)
Weight of Tower (t)	399	399	433	181
Distance from factory to origin port (km)	0	0	16	349
Distance from origin port to destination port (nm)	0	0	12134	215
Distance from destination port to site (km)	287	287	298	280
Total weight of turbine assembly (t)	590	590	673	396

Table 8. Wind Turbines by Vestas (Origin, Total Weight, Transportation Distance)

	Lal Lal Wind Farm - VIC	Sapphire Wind Farm - NSW	Cherry Tree Wind Farm - VIC
Origin of Turbine	Vestas (Denmark)	Vestas (Denmark)	Vestas (Denmark)
Origin of Tower	Vestas (Denmark)	Vestas (Denmark)	Vestas (Denmark)
Total weight of turbine assembly (t)	601	530	601
Distance from factory to origin port (km)	363	363	363
Distance from origin port to destination port (nm)	5520	4561	5520
Distance from destination port to site (km)	150	430	189

Table 9. Australian Wind Farms (Earthworks Data)

	Cut Volume (m^3)	Fill Volume (m^3)	Net Balance (m^3)	Pavement Volume (m^3)
Moorabool North Wind Farm – VIC	-120454	118269	-32541	138545
Moorabool South Wind Farm – VIC	-38931	101875	41495	71336
Murra Warra Wind Farm – VIC	-1357	229524	228167	102815
Cattle Hill Wind Farm – TAS	-196443	93673	-125905	67799
Lal Lal Wind Farm – VIC	-51037	78371	934	66305
Sapphire Wind Farm – NSW	-245270	192935	-52335	105771
Cherry Tree Wind Farm – VIC	-120246	77430.81	-48514.8	32026.52

iii. Embodied Energy of Australian Wind Farms

To determine the embodied energy of Australian wind farms, each phase in the wind farm's lifecycle will be analysed. In the first phase, the embodied energy was determined through the manufacture of the different materials used in a turbine. Using the materials breakdown from Table 5, the embodied energy for each turbine model during the manufacturing phase are summarized in Table 10. Detailed computations are found in Table 11 – 15.

Table 10. Embodied Energy (Phase 1 - Manufacturing)

	Turbine Manufacturer	Model	Total Weight (t)	Total Embodied Energy (MJ)
Moorabool North Wind Farm - VIC	Goldwind	GW 136	590	23,420,522
Moorabool South Wind Farm - VIC	Goldwind	GW 136	590	23,420,522
Murra Warra Wind Farm – VIC	Senvion	3.7M144 EBC	673	26,715,273
Cattle Hill Wind Farm – TAS	Goldwind	GW 140	396	15,719,537
Lal Lal Wind Farm – VIC	Vestas	V 136	601	23,857,176
Sapphire Wind Farm – NSW	Vestas	V 126	530	21,038,774
Cherry Tree Wind Farm – VIC	Vestas	V 136	601	23,857,176

Table 11. Embodied Energy (Phase 1 – Manufacturing – Goldwind GW 136)

Goldwind Turbine (GW 136) 590 tonnes

Material Used	Breakdown	Total Weight per material (kg)	Embodied Energy (Milne & Reardon, 2013)	Total Embodied Energy (MJ)
Steel and iron	89.00%	525100	38 mj/kg	19,953,800
Aluminum and alloys	1.30%	7670	170 mj/kg	1,303,900
Copper and alloys	0.55%	3245	100 mj/kg	324,500
Polymer materials	2.70%	15930	90 mj/kg	1,433,700
Glass/carbon composites	5.40%	31860	12.7 mj/kg	404,622
Electronics/electrics	0.65%	3835	no available data	-
Lubricant and fluids	0.35%	2065	no available data	-
			TOTAL	23,420,522

Table 12. Embodied Energy (Phase 1 – Manufacturing – Goldwind GW-140)

Goldwind Turbine (GW 140) 396 tonnes

Material Used	Breakdown	Total Weight per material (kg)	Embodied Energy (Milne & Reardon, 2013)	Total Embodied Energy (MJ)
Steel and iron	89.00%	352440	38 mj/kg	13,392,720
Aluminum and alloys	1.30%	5148	170 mj/kg	875,160
Copper and alloys	0.55%	2178	100 mj/kg	217,800
Polymer materials	2.70%	10692	90 mj/kg	962,280
Glass/carbon composites	5.40%	21384	12.7 mj/kg	271,577
Electronics/electrics	0.65%	2574	no available data	-
Lubricant and fluids	0.35%	1386	no available data	-
			TOTAL	15,719,537

Table 13. Embodied Energy (Phase 1 – Manufacturing – Senvion 3.7M144 EBC)

Senvion Turbine (3.7M144 EBC) 673 tonnes

Material Used	Breakdown	Total Weight per Material (kg) material (kg)	Embodied Energy (Milne & Reardon, 2013)	Total Embodied Energy (MJ)
Steel and iron	89.00%	598970	38 mj/kg	22,760,860
Aluminum and alloys	1.30%	8749	170 mj/kg	1,487,330
Copper and alloys	0.55%	3701.5	100 mj/kg	370,150
Polymer materials	2.70%	18171	90 mj/kg	1,635,390
Glass/carbon composites	5.40%	36342	12.7 mj/kg	461,543
Electronics/electrics	0.65%	4374.5	no available data	-
Lubricant and fluids	0.35%	2355.5	no available data	-
			TOTAL	26,715,273

Table 14. Embodied Energy (Phase 1 – Manufacturing – Vestas V-136)

Vestas Turbine (V136) 601 tonnes

Material Used	Breakdown	Total Weight per Material material (kg)	Embodied Energy (Milne & Reardon, 2013)	Total Embodied Energy (MJ)
Steel and iron	89.00%	534890	38 mj/kg	20,325,820
Aluminum and alloys	1.30%	7813	170 mj/kg	1,328,210
Copper and alloys	0.55%	3305.5	100 mj/kg	330,550
Polymer materials	2.70%	16227	90 mj/kg	1,460,430
Glass/carbon composites	5.40%	32454	12.7 mj/kg	412,166
Electronics/electrics	0.65%	3906.5	no available data	-
Lubricant and fluids	0.35%	2103.5	no available data	-
			TOTAL	23,857,176

Table 15. Embodied Energy (Phase 1 – Manufacturing – Vestas V-126)

Vestas Turbine (V126) 530 tonnes

Material Used	Breakdown	Total Weight per Material material (kg)	Embodied Energy (Milne & Reardon, 2013)	Total Embodied Energy (MJ)
Steel and iron	89.00%	471700	38 mj/kg	17,924,600
Aluminum and alloys	1.30%	6890	170 mj/kg	1,171,300
Copper and alloys	0.55%	2915	100 mj/kg	291,500
Polymer materials	2.70%	14310	90 mj/kg	1,287,900
Glass/carbon composites	5.40%	28620	12.7 mj/kg	363,474
Electronics/electrics	0.65%	3445	no available data	-
Lubricant and fluids	0.35%	1855	no available data	-
			TOTAL	21,038,774

As for the second phase, the embodied energy was determined through the transportation of the turbines. Using the project distance from the place of manufacture to the site construction area, the total embodied energy for each turbine in the second phase is shown in Table 16 while a breakdown of the distances is shown in Table 17 and 18.

Table 16. Embodied Energy (Phase 2 – Transportation)

	Energy Used (MJ)		Total Embodied Energy (MJ)
	Sea Freight	Land Transportation	
Moorabool North Wind Farm – VIC	249,173	2,565,353	2,814,526
Moorabool South Wind Farm – VIC	249,173	2,565,353	2,814,526
Murra Warra Wind Farm – VIC	1,351,314	801,860	2,153,175
Cattle Hill Wind Farm – TAS	290,011	2,955,583	3,245,594
Lal Lal Wind Farm – VIC	579,998	1,113,010	1,693,008
Sapphire Wind Farm – NSW	422,619	1,517,247	1,939,866
Cherry Tree Wind Farm – VIC	579,998	1,197,625	1,777,623

Table 17. Embodied Energy (Phase 2 – Sea Freight Only)

	Origin	Destination	Distance (nm)	Weight Transported (t)	Energy Used (MJ)
Moorabool North	Gwadar Port	Geelong Port	7462	191	249,173
Moorabool South	Gwadar Port	Geelong Port	7462	191	249,173
Murra Warra	Hamburg Port	Geelong Port	12134	637	1,351,314
Cattle Hill	Gwadar Port	Bell Bay Port	7538	215	283,208
Lal Lal	Tianjin Port	Geelong Port	5520	601	579,998
Sapphire	Tianjin Port	Brisbane Port	4561	530	422,619
Cherry Tree	Tianjin Port	Geelong Port	5520	601	579,998
Cattle Hill (Keppel)	Melbourne Port	Bell Bay Port	215	181	6,803

Notes:
[1] Energy Coefficient (Oil Bunker) = 94.4 KJ/kmt (SOURCE: Probas)

Table 18. Embodied Energy (Phase 2 – Land Transportation Only)

	Total Distance (km)	Weight Transported (t)	Energy Used (MJ)
Moorabool North - Goldwind Factory-Port, Port-Site	3121	191	2,151,961
Moorabool North - Keppel Factory-Site	287	399	413,392
Moorabool South - Goldwind Factory-Port, Port-Site	3121	191	2,151,961
Moorabool South - Keppel Factory-Site	287	399	413,392
Murra Warra - Senvion Factory-Port, Port-Site	359	240	311,038
Murra Warra - Keppel Factory-Site	314	433	490,823
Cattle Hill - Goldwind Factory-Port, Port-Site	3280	215	2,544,588
Cattle Hill - Keppel Factory-Site	629	181	410,995
Lal Lal - Vestas Factory-Port, Port-Site	513	601	1,113,010
Sapphire - Vestas Factory-Port, Port-Site	793	530	1,517,247
Cherry Tree - Vestas Factory-Port, Port-Site	552	601	1,197,625

Notes:

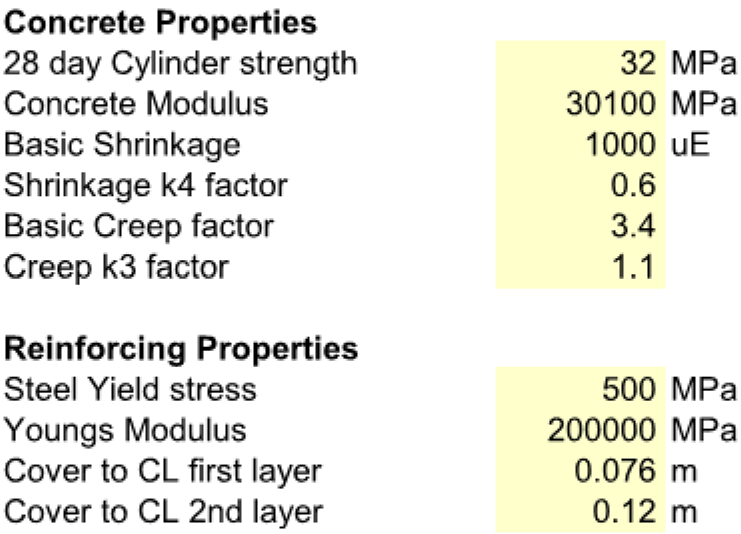
[1] Truck used complies to emission class 5 Euro

[2] Energy Coefficient (Diesel)= 3.61 MJ/kmt (SOURCE: Probas)

As for the third phase, the embodied energy was determined through the construction of the wind farm. For this phase, there were three kinds of embodied energy computed: (1) the energy used for the production of WTG Footing for steel and concrete, (2) the energy used for excavation, and (3) the energy used for the production of pavement. A summary of these calculations are found in Tables 19 – 22.

The steel reinforcement present in each footing is structural rebar with yield stress of 500MPa and young's modulus of 200000MPa. The bar is manufactured for primary use, therefore no recycling offsets can be applied. The concrete used across all footing is high strength 32 MPa mixed at 1 :1 :2 ratio.

Table 19. WTG Foundation Computations Report (iCubed Consulting Pty Ltd, 2018b)



Concrete Properties		
28 day Cylinder strength	32	MPa
Concrete Modulus	30100	MPa
Basic Shrinkage	1000	uE
Shrinkage k4 factor	0.6	
Basic Creep factor	3.4	
Creep k3 factor	1.1	
Reinforcing Properties		
Steel Yield stress	500	MPa
Youngs Modulus	200000	MPa
Cover to CL first layer	0.076	m
Cover to CL 2nd layer	0.12	m

Table 20. Embodied Energy (Phase 3 – Site Construction - WTG Footing Steel and Concrete Only)

	Energy Used (MJ)		Total Embodied Energy (MJ)
	WTG Footing - Steel (MJ)	WTG Footing - Concrete (MJ)	
Moorabool North Wind Farm – VIC	42,981,120	86,235,596	129,216,716
Moorabool South Wind Farm – VIC	52,416,000	105,165,361	157,581,361
Murra Warra Wind Farm – VIC	83,709,080	166,792,263	250,501,343
Cattle Hill Wind Farm – TAS	42,981,120	93,716,054	136,697,174
Lal Lal Wind Farm – VIC	56,784,000	129,216,222	186,000,222
Sapphire Wind Farm – NSW	75,049,520	160,935,009	235,984,529
Cherry Tree Wind Farm – VIC	16,598,400	28,385,503	44,983,903

Notes:

[1] Energy Coefficient (Steel bar & rod, primary) = 36.4 MJ/kg (Hammond & Jones, 2008)

[2] Energy Coefficient (In situ Concrete) = 1.9 MJ/kg (Milne & Reardon, 2013)

It should be worth noting that excavation volume in Table 21 was based on either the cut volume or fill volume, depending on whichever is higher. This is because the excavation process only takes place once, wherein they make a big quarry on site, taking into consideration the required amount to fill. Thus, if the fill volume is greater than the cut volume, this means that the excess fill has been excavated from another place on site. Meanwhile, if the cut volume is greater than the fill volume, this means that there may be excess soil excavated. As for the energy coefficient used in excavation, the actual data from Devi and Palaniappan (2017) ranges from 19 to 23 MJ/m^3. So the median 21 MJ/m^3 was used. In addition, this energy coefficient includes not just the energy used for excavation but also the energy used to transport the excavated soil to the dumping site since it is assumed that some degree of transport takes place. Moreover, the type of soil used in the energy coefficient is a combination of soft disintegrated rock, sandy clay and black cotton soil, loose soil, and weather rock (Devi & Palaniappan, 2017).

Table 21. Embodied Energy (Phase 3 – Site construction – Excavation Only)

	Excavation Volume (m³)	Embodied Energy (MJ)
Moorabool North Wind Farm - VIC	120,454	2,529,534
Moorabool South Wind Farm - VIC	101,875	2,139,375
Murra Warra Wind Farm – VIC	229,524	4,820,004
Cattle Hill Wind Farm – TAS	196,443	4,125,303
Lal Lal Wind Farm – VIC	78,371	1,645,791
Sapphire Wind Farm – NSW	245,270	5,150,670
Cherry Tree Wind Farm – VIC	120,246	2,525,166
Notes: [1] Energy Coefficient (Excavation) = 21 MJ/m³ (Devi & Palaniappan, 2017)		

Table 22. Embodied Energy (Phase 3 – Site Construction – Pavement Production Only)

	Transportation distances of pavement to site (km)	Pavement Volume (m³)	Pavement Mass (kg)	Embodied Energy (MJ)
Moorabool North Wind Farm - VIC	30	138,545	206,062,135	22,316,529
Moorabool South Wind Farm - VIC	30	71,336	106,100,173	11,490,649
Murra Warra Wind Farm - VIC	100	102,815	152,919,834	55,204,060
Cattle Hill Wind Farm – TAS	0	67,799	100,839,487	0
Lal Lal Wind Farm – VIC	15	66,305	98,617,416	5,340,133
Sapphire Wind Farm – NSW	30	105,771	157,316,381	17,037,364
Cherry Tree Wind Farm - VIC	20	32,027	47,634,009.94	3,439,176

Notes:
[1] Truck used complies to emission class 5 Euro
[2] Energy Coefficient (Diesel)= 3.61 MJ/kmt (SOURCE: Probas)
[3] Density (Fine Aggregate/Crushed Stone used for pavement) =1,487.33 kg/m³ (Aryani, et al. 2018)
[4] Cattle Hill pavement is manufactured on site

As for the fourth phase, turbines are expected to be maintained through oil changes and gear lubrications, which will use 1,170 GJ per turbine throughout its lifetime (Fernando, 2010 as cited in Walmsley, Walmslet, & Atkins, 2017). For this dissertation, it is assumed that it will also use the same amount of energy.

Table 23. Embodied Energy (Phase 4 – Operation and Maintenance)

	Total Embodied Energy (MJ)
Moorabool North Wind Farm - VIC	47,970,000
Moorabool South Wind Farm - VIC	58,500,000
Murra Warra Wind Farm - VIC	71,370,000
Cattle Hill Wind Farm - TAS	56,160,000
Lal Lal Wind Farm - VIC	70,200,000
Sapphire Wind Farm - NSW	71,370,000
Cherry Tree Wind Farm - VIC	18,720,000

Notes:
[1] Embodied Energy per Turbine = 1,170 GJ / turbine (Fernando, 2010 as cited in Walmsley, Walmslet, & Atkins, 2017)

Meanwhile, during the last phase of the wind turbine lifecycle, the embodied energy during this phase is assumed as zero. While energy would still be used for the decommissioning of wind turbines, a large percentage of the wind turbine is recyclable, thereby offsetting the energy used during the last phase due to the environmental credits that it gains from recycling. To illustrate, Table 24 shows the breakdown of materials used in Vestas V-126 and V-136 and their corresponding end-of-life treatments. As can be seen from the table, 90.85 percent of the wind turbine (or 83.58 percent of all of the materials used in the wind turbine) can be recycled. In addition, new developments on waste management have demonstrated that glass fibre composites, commonly used in wind blades, can also be recycled and used to fabricate value-added high-performance composite (Mamanpush, et al., 2018). This means that instead of 31.45 tonnes of wind blades ending up in landfills, a portion of it can possibly be used for a variety of applications like floor tiles or plastic road barriers, thereby adding to environmental credits.

Table 24. Vestas End-of-Life Treatment (Razdan & Garrett, 2017b, 2017c)

Material Used	Breakdown	Total Weight per Material	End-of-life Treatment
Steel and iron	89.00%	518.34t	92% recycled; 8% landfilled
Aluminum and alloys	1.30%	7.57t	92% recycled; 8% landfilled
Copper and alloys	0.55%	3.20t	92% recycled; 8% landfilled
Polymer materials	2.70%	15.72t	50% incinerated; 50% landfilled
Glass/carbon composites	5.40%	31.45t	100% landfilled
Electronics/electrics	0.65%	3.79t	100% landfilled
Lubricant and fluids	0.35%	2.04t	100% incinerated

iv. Lifetime Net Electrical Outputs

As for the production and operation phase, Table 25 summarises the Lifetime Net Electrical Outputs for the seven different Australian wind farms. Lifetime Net Electrical Output (GJ) is technically the total electrical output that each wind farm produces, taking into consideration the specifications of each wind turbine (i.e., capacity), the expected life of the wind turbine (i.e., calendar year lifetime), and the capacity factor and availability factor of the turbines.

Table 25. Lifetime Net Electrical Output

	Total Capacity (MW)	Calendar Year Lifetime (Years)	Availability Factor	Capacity Factor	Full Power Lifetime (Years)	Net Power Output (MW)	Lifetime Net Electrical Output (GJ)
Moorabool North Wind Farm – VIC	102.5	25	90%	35%	22.5	35.875	25,455,465
Moorabool South Wind Farm – VIC	125.0	25	90%	35%	22.5	43.75	31,043,250
Murra Warra Wind Farm – VIC	225.7	25	90%	35%	22.5	78.995	56,051,692
Cattle Hill Wind Farm – TAS	144.0	20	97%	32%	19.4	46.08	28,191,670
Lal Lal Wind Farm – VIC	216.0	30	96%	30%	28.8	64.8	58,853,745
Sapphire Wind Farm – NSW	219.6	25	90%	40%	22.5	87.84	62,327,750
Cherry Tree Wind Farm – VIC	57.6	30	96%	35%	28.8	20.16	18,310,054

v. EROI and the Lifecycle Energy Payback Time (EPBT) of Australian Wind Farms

Using the calculated embodied energy of the different phases of the wind farm lifecycle, the following EROI has been found and summarised in Table 26 below. Meanwhile, the lifecycle Energy Payback Time (EPBT) were also computed and summarised in Table 27.

Table 26. EROI of Australian Wind Farms

	Lifetime Net Electrical Output (GJ)	TOTAL Embodied Energy (Phase 1-4) (GJ)	EROI
Moorabool North Wind Farm - VIC	25,455,465	1,277,670	19.92
Moorabool South Wind Farm - VIC	31,043,250	1,541,464	20.14
Murra Warra Wind Farm - VIC	56,051,692	2,142,871	26.16
Cattle Hill Wind Farm - TAS	28,191,670	1,107,309	25.46
Lal Lal Wind Farm - VIC	58,853,745	1,796,197	32.77
Sapphire Wind Farm - NSW	62,327,750	1,731,240	36.00
Cherry Tree Wind Farm - VIC	18,310,054	479,825	38.16

Table 27. EPBT of Australian Wind Farms

	TOTAL Embodied Energy (Phase 1-4) (GJ)	Annual Electrical Output (GJ/yr)	EPBT (years)
Moorabool North Wind Farm - VIC	1,277,670	1,131,354	0.89
Moorabool South Wind Farm - VIC	1,541,464	1,379,700	0.90
Murra Warra Wind Farm - VIC	2,142,871	2,491,186	1.16
Cattle Hill Wind Farm - TAS	1,107,309	1,453,179	1.31
Lal Lal Wind Farm - VIC	1,796,197	2,043,533	1.14
Sapphire Wind Farm - NSW	1,731,240	2,770,122	1.60
Cherry Tree Wind Farm - VIC	479,825	635,766	1.32
NOTES: [1]Annual Electrical Output = Net Power Output converted in GJ/year unit, where 1MWh = 3.60GJ			

III. Conclusions

This chapter has presented the findings of the this dissertation including the typical processes in wind farm development, the technical specifications of the Australian wind farms used in this dissertation, the embodied energy in each phase of the wind turbine lifecycle including the total electrical output throughout its whole lifetime, and the EROI and EPBT for each of the windfarm.

CHAPTER 5: DISCUSSION, CONCLUSION AND RECOMMENDATIONS

I. Introduction

This chapter discuss the key findings of this dissertation with reference from relevant literature. The chapter will also present a conclusion and some recommendations for future research.

II. Discussion

i. Embodied Energy

Among the five phases of the wind farm development, the manufacturing process, in general, consumed the most energy per turbine. This is consistent with the findings of Ghenai (2012) and Haapala and Prempreeda (2014) which also found that the production or the manufacture of turbine parts consumes the most energy. In this case, approximately 75.8 percent of the total embodied energy can be attributed to the first phase, followed by 12.4 percent for the third phase which is site construction, then by 7.9 percent for the second phase which is transportation, 3.9 percent for operation and maintenance, and lastly zero percent for the decommissioning of the wind farm due to the environmental credits it gets from recycling, which offsets the energy used during the decommissioning of the wind turbine during the last phase.

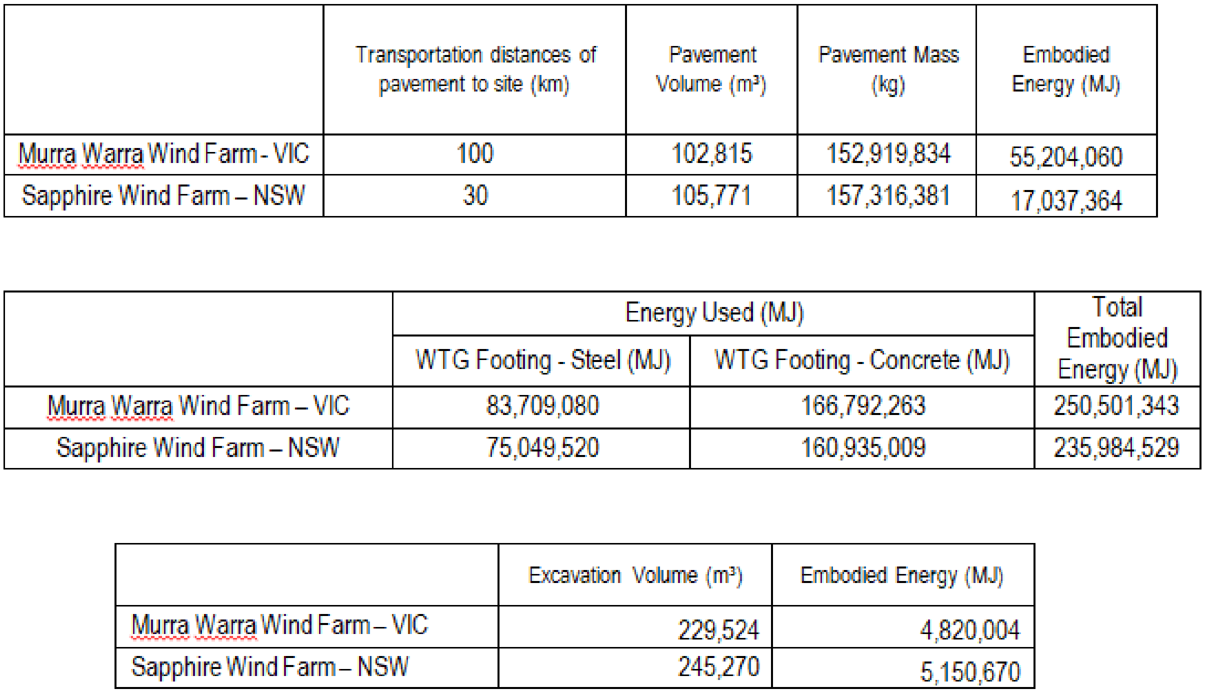
Table 28. Average Embodied Energy per Turbine

	Average Embodied Energy per Turbine (GJ)	**%**
Phase 1 – Manufacturing	22,575,569	75.8%
Phase 2 – Transportation	2,348,331	7.9%
Phase 3 – Construction	3,691,325	12.4%
Phase 4 – Maintenance	1,170,000	3.9%
Phase 5 – Decommissioning	0	0.0%
TOTAL	**29,785,225**	**100.0%**

From the findings, the size of the wind farm also proved to have a significant impact on the total embodied energy of each wind farm. Table 29 shows, as expected, Cherry Tree Wind Farm with the lowest number of wind turbines had the lowest embodied energy of only 479,825GJ. Interestingly though, even though Murra Warra Wind Farm and Sapphire Wind Farm had the same number of wind turbines (61 turbines), the Murra Warra Wind Farm consumed slightly more energy perhaps due to the fact that the turbines used in the Murra Warra Farm were heavier by 143 tonnes. In addition, Murra Warra Wind Farm also had a much longer transportation distance of pavement to site location as can be seen in Figure 12. The combination of a heavier turbine assembly weight and longer a transportation route for pavement has contributed to a higher embodied energy.

Table 29. A Comparison of Wind Farm Based on Size and Embodied Energy

		Total Embodied Energy per Phase (GJ)					TOTAL Embodied Energy (MJ)
	No of Turbines	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	
Murra Warra Wind Farm - VIC	61	1,629,632	131,344	310,525	71,370	0	2,142,871
Sapphire Wind Farm - NSW	61	1,283,365	118,332	258,173	71,370	0	1,731,240
Lal Lal Wind Farm - VIC	60	1,431,431	101,580	192,986	70,200	0	1,796,197
Moorabool South Wind Farm - VIC	50	1,171,026	140,726	171,211	58,500	0	1,541,464
Cattle Hill Wind Farm - TAS	48	754,538	155,789	140,822	56,160	0	1,107,309
Moorabool North Wind Farm - VIC	41	960,241	115,396	154,063	47,970	0	1,277,670
Cherry Tree Wind Farm - VIC	16	381,715	28,442	50,948	18,720	0	479,825



	Transportation distances of pavement to site (km)	Pavement Volume (m³)	Pavement Mass (kg)	Embodied Energy (MJ)
Murra Warra Wind Farm - VIC	100	102,815	152,919,834	55,204,060
Sapphire Wind Farm – NSW	30	105,771	157,316,381	17,037,364

	Energy Used (MJ)		Total Embodied Energy (MJ)
	WTG Footing - Steel (MJ)	WTG Footing - Concrete (MJ)	
Murra Warra Wind Farm – VIC	83,709,080	166,792,263	250,501,343
Sapphire Wind Farm – NSW	75,049,520	160,935,009	235,984,529

	Excavation Volume (m³)	Embodied Energy (MJ)
Murra Warra Wind Farm – VIC	229,524	4,820,004
Sapphire Wind Farm – NSW	245,270	5,150,670

Figure 12. Comparison of Murra Warra and Sapphire Wind Farm Phase 3 Embodied Energy

It should also be worth noting that in terms of transportation, transportation distance is not the only factor that can have an effect in embodied energy. The mode of transportation can also have a significant impact. The findings of this dissertation found that land transportation consumes more energy compared to sea freight. For example, even though the Murra Warra Wind Farm had the highest energy consumed in sea freight (turbines came from Germany – 12134km) with a transport distance almost double the next longest sea journey (Cattle Hill – 7538km), the total embodied energy of its total transport phase (sea and land) ranks it fourth among the highest energy used per turbine in phase 3. Even though the turbines came all the way from Germany, a shorter land transportation distance offset the total embodied energy during this phase, producing only 2,153,175 MJ. With Cattle Hill Wind Farm having a much longer land transportation distance, its embodied energy during this phase is equal to 3,245,594 MJ per turbine.

ii. Lifetime Electrical Output

There are five major factors that affect the electrical output of each wind farm: (1) the turbine power output specifications, (2) the number of wind turbines, (3) the calendar year lifetime, (4) availability factor, and (5) capacity factor. All these factors must be at optimal levels to achieve high electrical output. To illustrate, the Sapphire Wind Farm takes the lead in the lifetime electrical output at 62,327,750 GJ. Not only is Sapphire Wind Farm the biggest among the seven wind farms with 61 turbines, it also has a relatively high turbine power output of 3.6 MW, a lifespan of 25 years, a high availability factor of 90 percent and a capacity factor of 40 percent.

iii. EROI and EPBT

The EROI results in this dissertation ranges from 19.92 (Moorabool North Wind Farm) to 38.16 (Cherry Tree Wind Farm) and has an average of 28.37. In comparison with other studies, this average is near the results of another study by Walmsley, Walmsley and Atkins (2017). In Walmsley, et al. (2017), they found that the weighted average EROI for a New Zealand wind farm over a 20 year life span is 34.3. In another survey of the EROI of conceptual and operational wind farms conducted by Kubiszewski, Cleveland and Endres (2009), they found that EROIs can actually range to as little as 1.0 to as high as 125.8. Interestingly though, these relatively high values of EROI were for conceptual wind farms, which could reflect assumptions of more favourable conditions that those in real life (Hall, et al., 2013). Surprisingly, the smallest wind farm produced the highest EROI, possibly because it had the lowest embodied energy and had optimal levels of the factors that affect net lifetime electrical output.

Meanwhile, according to Wrixon, Rooney and Paz (1993), the EBPT of wind turbines can vary from a few months to one or two years at most. One study by Guezuraga, Zauner and Polz (2012) found the EPBT of a turbine to be 0.6 years or 7.2 months. As for this dissertation, the EPBT of Australian wind farms can vary from 0.89 years (10.63 months) to 1.60 years (19.20 months), with an average of 1.19 years (14.26 months).

III. Conclusion

Based on the findings and an analysis of the results of this dissertation, the following conclusions have been made:

1. The manufacturing process consumes the most energy in wind farm development, followed by the site construction, the transportation, and then turbine maintenance.
2. The weight and the materials used in the turbine can have a significant impact on the wind farms embodied energy.
3. The mode and distance of transportation matters, with preference for shorter distances especially in land transportation.
4. To achieve high electrical output, all five major factors must be at optimal levels: the turbine power output specifications, the number of wind turbines, the calendar year lifetime, availability factor, and capacity factor.
5. A bigger wind farm does not necessarily mean higher EROI (e.g., Cattle Hill Wind Farm).

IV. Recommendations

From the results and conclusions of this study, the following are recommended.

To reduce the embodied energy, always consider the materials used and the location of the turbine factory. Materials used must have lower embodied energy and preferably recyclable. If it is recyclable, the wind farm decommissioning can be offset by the environmental credits that it gains from recycling.

The factory of turbine/tower manufacturer and wind farm itself must be situated close to their respective shipping docks. The nearer it is, the lesser the road transportation distance, which would significantly lower the embodied energy during the transportation phase. To optimise shipping routes, the freighting company must choose artificial intelligence assessed shipping routes. This allows for minimisation of unnecessary fuel wastage due to predictable currents, winds, and waves.

To optimise the construction phase, where possible, manufacture the pavement on site to minimise transportation.

Extending the life of wind farms across Australia is a great means of improving EROI. As can be seen with Hydroelectric results in Figure 3, it is possible to attain a EROI of 84:1. This is due to its long life cycle of 200 years. Striving for a high EROI is key to ensuring a sustainable future in electrical generation.

Choosing taller towers will give access to more consistent and stronger winds. This would lead to an improved Availability Factor & Capacity Factor making for a larger electrical output – resulting in a larger EROI.

Other turbine manufacturers such as Senvion and Goldwind must fully disclose the materials they use in their wind turbines in order to get a clearer image of the embodied energy during the manufacturing stage. From this data, future studies must be made.

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Appendix A

ENG4111/4112 Research Project

Project Specification

For: Chad Haywood

Title: Energy Returned On Energy Invested (ERoEI) for an Australian Wind Farm in 2020

Major: Civil Engineering

Supervisors: Chris Snook/Andrew Wandel

Confidentiality: Permission will be required from the wind farm owner if a case study is to be published as an appendix as justification for this research paper's findings. The conditions of which this permission is granted is at the owner's discretion and subject to the owners' interests. As a result, the option to avoid full disclosure to public must be considered.

Enrolment: ENG4111 – EXT S1, 2020
ENG4112 – EXT S2, 2020

Project Aim: To determine Energy Returned On Energy Invested (ERoEI) of a pre-defined standard wind farm and investigate ways to optimise the most energy rich processes.

Programme: Version 1, 1st April 2020

The primary aims are prioritised around the following processes:

1. Identify the typical processes within a wind farm development.
2. Lit Review.
3. Determine the embodied energy of each component/process within the Typical Australian Wind Farm development process.
4. Itemise data and identify the most energy consuming processes within the wind farm life cycle.
5. Calculate 'EROI' (Energy Return on Investment) rate for the standard wind.
6. Calculate the Lifecycle Energy Payback Ratio (Lifecycle EPR) for standard Australian wind farm.
7. Discuss alternative methods and materials to reduce embodied energy in wind farm development leading forward."