EMBODIED ENERGY ANALYSIS OF NEW

ZEALAND POWER GENERATION SYSTEMS

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Abstract

Embodied energy is the energy consumed in all activities necessary to support a process in its entire lifecycle. For power generation systems, this includes the energy cost of raw material extraction and transportation, plant construction, energy generation and the recycling and disposal stages following actual use. Embodied energy analysis is a crude method of estimating the environmental impacts and depletion of natural resources consequent to a certain process. In effect, the higher the embodied energy of a process, the greater the green house gas emissions and the depletion of the natural resources.

This thesis presents the embodied energy analysis carried out on some New Zealand power plants belonging to various methods of generation, namely, natural gas combined cycle (NGCC), natural gas open cycle (NGOC), wind, reservoir hydro and run of river hydro power plants. The analysis was carried out using a combination of process chain analysis and input output analysis, which are the two fundamental methodologies for embodied energy analysis. It follows the standards set out by the International Organisation for Standardisation 14040 series, and uses some guidelines given in the International Federation of Institutes for Advanced Study workshop on energy analysis methodology and conventions.

From the analysis, it was found that for renewable generation power plants, the exploration and plant construction phase of the lifecycle contributes the largest amount of embodied energy, while for the non renewable power plants, the largest amount of embodied energy is contributed by the plant operation and maintenance phase of the lifecycle. The lifecycle energy payback ratio, which corresponds to the ratio of electrical energy output over the total lifecycle energy input, of the power plants are 96.9, 62.8, 7.96, 0.487 and 0.354 for run of river hydro, reservoir hydro, wind, NGCC and NGOC, respectively. Therefore, the lifecycle performance of renewable electricity generation is superior to non renewable electricity generation. Hence, the environmental impacts and depletion of natural resources from non renewable electricity generation is higher than renewable electricity generation. From

the generation methodologies, hydro power plants have exceptional performance characteristics.

Acronyms

CGPI - Capital Goods Price Index

CPI - Consumer Price Index.

GHG - Greenhouse Gas

HRSG - Heat Recovery System Generator

I/O - Input Output

IFIAS - International Federation of Institutes for Advanced Study

IPCC - Intergovernmental Panel on Climate Change

ISO – International Organisation for Standardisation

LCA - Life Cycle Assessment

LEPR - Lifecycle Energy Payback Ratio

MHI - Mitsubishi Heavy Industries

NGCC - Natural Gas Combined Cycle

NGOC - Natural Gas Open Cycle

PCA - Process Chain Analysis

PPI - Producer Price Index

ppm - Parts Per Million

US - United States

1. Introduction

Embodied energy is the energy consumed in all activities necessary to support a process [1]. For power generation systems, this includes the energy cost of the entire life-cycle process chain, from raw materials extraction and transportation, plant construction, energy generation, and the recycling and disposal stages following actual use [2]. Although a crude method, embodied energy analysis can be used to estimate the environmental impacts and the depletion of natural resources. Broadly speaking, the higher the use of energy, the greater the greenhouse gas (GHG) emissions, and the greater the effect on the environment and depletion of natural resources [3].

Though the main environmental concern today is GHG emissions and climate change there are many other factors of a process which affect the environment such as acidification, eutrophication, human toxicity and ozone depletion. Embodied energy cannot be considered as an environmental problem in itself, but there exits a strong correlation between embodied energy and environmental impacts. Therefore embodied energy analysis can be used to estimate the total environmental impacts due to a process in it's lifecycle [4],[5]. It allows an analyst with a means of assessing the ultimate impact on the environment without need to identify each of the intermediate mechanisms and effects [6].

The aim of this thesis is to calculate the embodied energy of some New Zealand power plants belonging to various methods of generation, which may influence the decision making process of future investments, in the New Zealand electricity generation industry. In this thesis, embodied energy analysis is undertaken on natural gas combined cycle (NGCC), natural gas open cycle (NGOC), wind, reservoir hydro and run of river hydro generation systems.

The analysis for NGCC and NGOC generation systems are based on the Huntly power station, owned and operated by Genesis Energy Ltd. Analysis for the reservoir hydro and wind generation systems are based on Benmore power station and White Hill wind farm respectively, both of which are owned and operated by Meridian

Energy Ltd. For the run of river hydro generation system, analysis is be based on the Aratiatia power station, owned and operated by Mighty River Power Ltd.

This thesis is structured as follows. Chapter 2 presents some background information about the negative effects of climate change as a result of anthropogenic GHG emissions. The underlying theory of embodied energy analysis and a summary of the overall approach taken in the analysis of this thesis are discussed in chapter 3. Chapters 4 through to 8 focus on the analysis carried out on specific power plants/systems and elaborate on the findings of each power plant. In chapter 9, results from the different power stations are compared and discussed, while in chapter 10 overall conclusions are drawn.

2. Background

About four decades ago the concept of global warming was introduced. The earth's surface temperature is a result of the equilibrium between short-wave solar radiation absorbed and the infrared radiation emitted back into space by the earth. The natural greenhouse effect occurs due to the earth's atmosphere being nearly transparent to solar radiation, and some gases in the atmosphere, known as greenhouse gases (GHG), absorbing infrared radiation emitted by the earth. This results in the warming of the earth by about 30°C making it habitable by its current species [7].

Since industrialisation, combustion of fossil fuels has dominated the global energy market to meet the ever increasing demands for heat, electricity and transportation. The combustion of fossil fuels release GHGs such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxides (NO_x) into the earth's atmosphere. This global overdependence on fossil fuels has led to the release of over 1100Gt of GHGs into the earth's atmosphere since the mid 19th century [8]. Over the last three decades, GHG emissions have increased by an average of 1.6% per year. Atmospheric CO_2 concentrations have increased by almost 100 parts per million (ppm) in comparison to their pre-industrial level, reaching 379 ppm in 2005 [9].

 The largest growth in CO_2 emissions has come from the power generation and road transport sectors. In the year 2004, 26% of GHG emissions were derived from energy supply (electricity and heat generation). Since 1970, GHG emissions from the energy supply sector have grown over 145% while those from the transport sector have grown by over 120% [9].

The high rates of anthropogenic GHG emissions have resulted in an enhanced natural greenhouse gas effect which has led to an increase in the earth's surface temperature. This is known as anthropogenic global warming. According to the Intergovernmental Panel on Climate Change (IPCC) estimates, the earth's surface temperature has risen by 0.74°C over the last century. This increase in the earth's surface temperature has resulted in a sea level rise due to the melting of the earth's ice poles. The global average sea level rose at an average rate of 3.1mm per year from 1993 to 2003 [10].

Figure 2.1 shows the changes in temperature, sea level and northern hemisphere snow cover extracted from [10]. The increased GHG emissions from anthropogenic activities are no longer environmentally sustainable and may cause adverse environmental effects such as extreme weather conditions, imbalances in the earth's ecological systems and species extinction.

Until recently the decisions on which electrical generation systems, that are to be utilised, were made purely based on the monetary cost of, building the generation station, operating and maintaining it, and disposing of it. However, it was revealed that the rate of fossil fuel and natural gas consumption would lead to the exhaustion of these resources in the future [11]. Scientists and engineers then carried out more detailed investigations on renewable energy sources that were not widely used, such as wind energy and solar energy. Previously, thorough investigations were not carried out on these resources because, the starting up costs of these types of power plants were high, there was lack of awareness of environmental damage caused by the consumption of fossil fuels and natural gas, and fossil fuels were available in vast amounts.

Embodied energy analysis will provide decision makers with a better understanding of the environmental impacts and natural resource depletion associated with each alternative. It will give insight as to which stages of different system development alternatives result in major impacts and thus help decision makers in the various stages of the electricity generation life cycle in energy conservation [2]. Hence, embodied energy analysis helps to perceive the difference between significant and insignificant environmental impacts and demonstrate that some environmental impacts maybe worth incurring while others may not, so as to reduce the total environmental impacts [6].

Also, with respect to decision-making, embodied energy analysis is a useful complement to conventional economic analysis. It can provide additional information on which to base energy resource allocations. Furthermore, the combined use of energy analysis with economic evaluation can correct implicit errors in economic analysis that can lead to the misallocation of resources [12].

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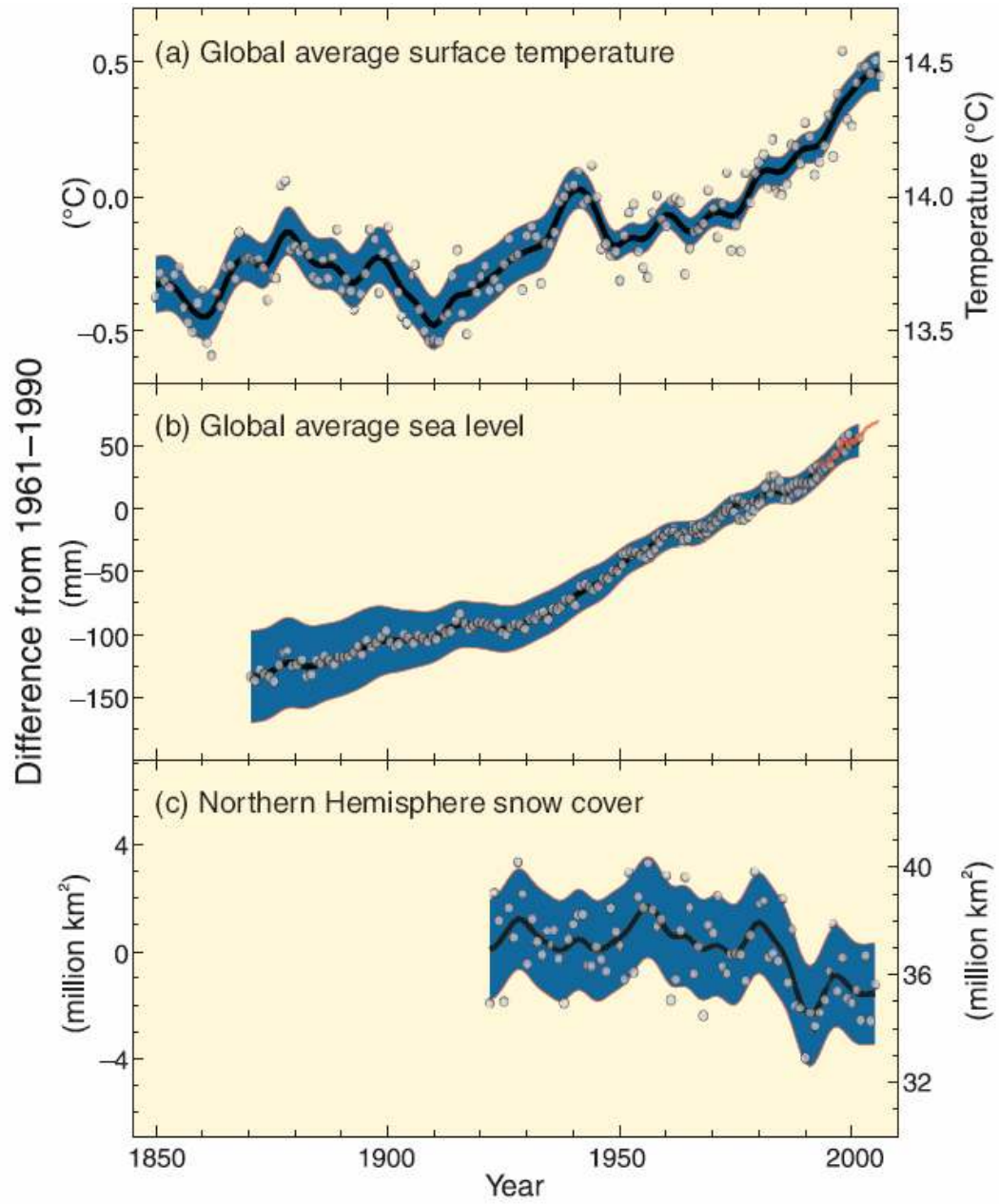
Figure 2.1. Changes in Temperature, Sea Level and Northern Hemisphere Snow Cover [10]

3. Embodied Energy Analysis

3.1 Overview of Embodied Energy Analysis in Electricity Generation

Embodied energy is the energy consumed in all activities necessary to support a process [1]. For power generation systems, this includes the energy cost of the entire life-cycle process chain from raw materials extraction and transportation, plant construction, energy generation and the recycling and disposal stages following actual use [2]. Figure 3.1 shows a representation of embodied energies for each of the life-cycle phases of a power generation system along with the useful electrical output, which is the desired product [13].
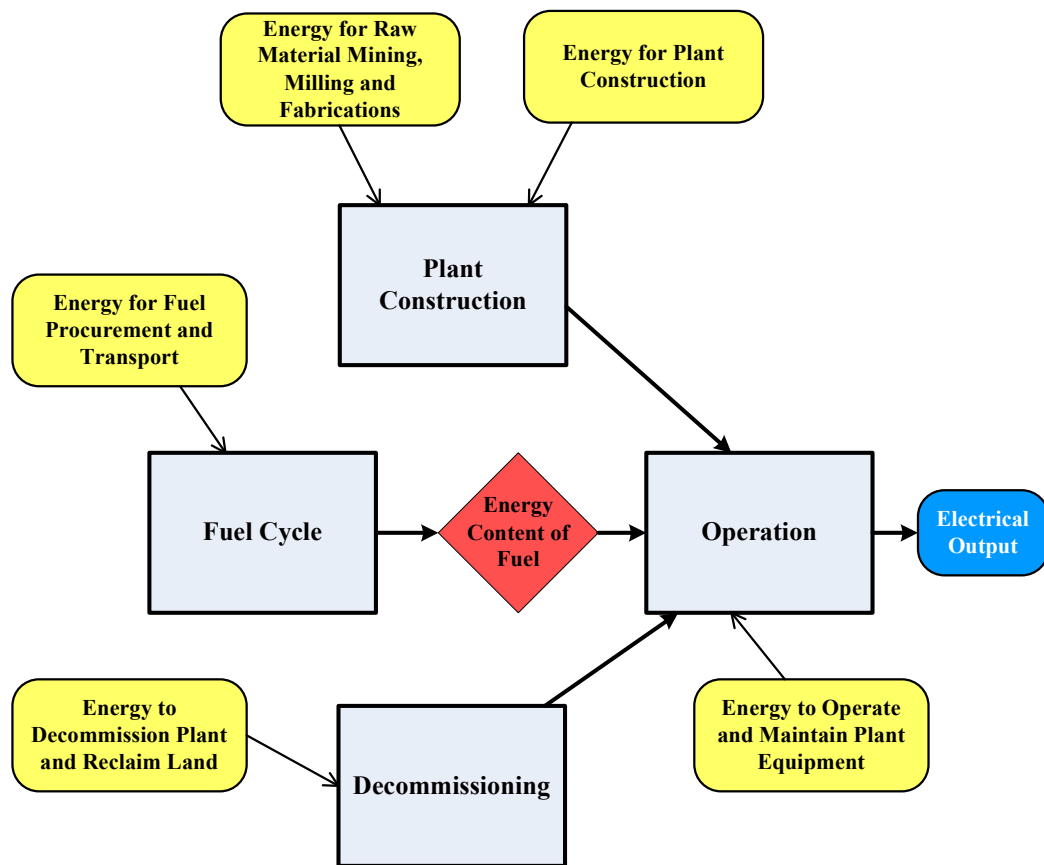
Figure 3.1. Embodied Energy Analysis of a Power Generation System [13]

Embodied energy consists of direct and indirect energy. Direct energy is that used during the main processes, while indirect energy is that required for the manufacture of goods and services that are used in the main processes [14]. For a power generation station, direct energy is that required to produce electricity, while indirect energy is that required in raw material extraction and transportation, plant construction, and recycling and decommissioning of the plant.

The fundamental methods for embodied energy analysis can be classified as input-output (I/O) analysis and process chain analysis (PCA). I/O analysis employs the economic input-output tables of a nation's economy [15]. The input-output tables are an economic tool used to examine dollar flows between sectors of a national economy. Statistics NZ publishes these results approximately every five years. The I/O method correlates dollar cost to energy consumption by examining the dollar flows to and from the energy-producing sectors of the economy and comparing these with the known amount of energy produced by each energy sector. This makes it possible to trace the energy flows within the national economy and to equate the dollar output of each sector with its energy usage. The main advantage of I/O analysis is that every energy transaction across the entire national economy is captured. The principal disadvantage is that the aggregation of the whole economy makes the results less specific and hence less accurate for the study concerned [16].

In PCA, each material that makes up the final system is traced back through each manufacturing process to it's initial extraction [17]. PCA normally begins with the final production process and works backwards through each stage of the production process. It is the most common method of energy analysis. This is because the data required can usually be obtained. The main advantage of PCA is that it produces accurate and specific results, while the main disadvantage is that it requires a considerable amount of time and effort [16]. However, the almost infinite inflows into the process means that a large number of energy inputs to the process are not calculated and the analysis has to be terminated at a point where the input is believed to add a negligible amount to the total energy use [18]. Therefore, PCA tends to underestimate the total embodied energy of a process. There is in fact no guarantee that the energy terms not considered in each stage of the process add up to a negligible quantity.

3.2 Standards Used and Overall Methodology

When carrying out embodied energy analysis, either International Federation of Institutes for Advanced Study (IFIAS) standards or International Organisation for Standardisation (ISO) 14040 series can be used [19], [20-23]. The ISO standards give generic guidelines for any life cycle assessment (LCA), whereas the IFIAS standards focus specifically on energy analysis methodology and conventions. The analysis in this thesis follows standards set out by the ISO 14040 series, whilst also using some useful guidelines set out in the IFIAS standards. There is much common ground in the conventions set out by both standards. This section presents the main ideas used, from both standards, when carrying out the analysis in this thesis.

The four main phases of the ISO standards are goal and scope definition, inventory analysis, impact assessment and interpretation of results, as shown in Figure 3.2. The goal of this thesis is to calculate the embodied energy of some New Zealand power plants belonging to various methods of generation, as a mean of comparison among the different methods of generation and to give decision makers a better understanding of the energy intensity of the different generation methods and the various phases in their life cycles. The scope includes elements specific to the plant studied, such as data requirements, assumptions, system boundaries and allocation procedures. Most of the elements mentioned in the scope of study in the ISO standards are also covered in the IFIAS standards.
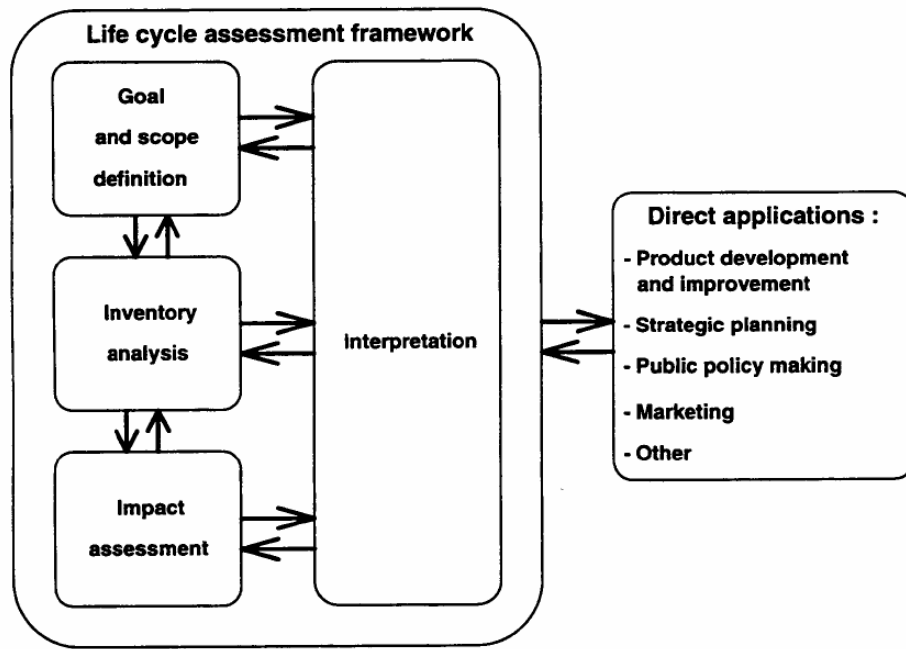
Figure 3.2. Phases of an LCA [20]

The elements specified in the scope of the study of ISO standards are:

- The functions of the product system, or, in the cases of comparative studies, the systems - Electricity generation.
- The functional unit - Unit amount of electricity produced (kWh)
- The product system to be studied - Plant specific.
- Allocation Procedures - Plant specific.
- Types of impact and methodology of impact assessment, and subsequent interpretation to be used
- Data Requirement - Details on data acquisition are given in section 3.3.
- Assumptions - Plant Specific.
- Limitations - Plant Specific.
- Type and Format of the report required for the study [20].

The details for the components requiring plant specific information are given in chapters 4 to 8.

An important element that is mentioned in the scope of study in the ISO standards is the functional unit. The functional unit is stated as "a measure of the performance of the functional outputs of the product system". The primary purpose of a functional

unit is to provide a reference to which the inputs and outputs are related [20]. The functional unit for this thesis is the unit amount of electricity produced (i.e. kWh).

The other phases of LCA, according to the ISO standards, are inventory analysis, impact assessment and interpretation of results. A lifecycle inventory analysis is concerned with data collection and calculation procedures. This is used to quantify relevant inputs and outputs of a product or system [20], [21]. The inputs to the inventory analysis in this thesis are quantity of building materials and the monetary cost of various construction and operation and maintenance processes of the power stations analysed. The output of the inventory analysis is the energy embodied in the construction materials and the monetary costs. Whilst and overview of the embodied energy analysis methodology and methods of data collection and addressed in sections 3.2 and 3.3, the precise data collection methodologies and sources, and calculation procedures are explained in detail in the plant specific chapters.

The impact assessment phase of LCA is aimed at evaluating the significance of potential environmental impacts using the results of the life cycle inventory analysis [20]. Embodied energy analysis is a crude method of evaluating environmental impacts, as mentioned previously. Hence, evaluating the embodied energy is inclusive of impact assessment. The objectives of lifecycle interpretation are to analyse results, reach conclusions and provide recommendations based on the findings of the lifecycle analysis [23]. The results are analysed in chapter 9 by comparing the energy intensity of each phase of the life cycle with the other phases for each of the plants as well as among the different plants. Also, the performances of different methods of generation are compared using the lifecycle energy payback ratio (LEPR) and the lifecycle energy cost of the power plants stated in Equations 3.1 and 3.2, respectively. The limitations of the study are discussed in chapter 9. The overall conclusions and the recommendations are formulated in chapter 10.

$$LEPR = \frac{Lifecycle\ Electrical\ Output\ (in\ GJ)}{Lifecycle\ Energy\ Input\ (in\ GJ)} \qquad \textbf{Eq. 3.1}$$

$$Lifecycle\ Energy\ Cost = \frac{Lifecycle\ Energy\ Input\ (in\ MJ)}{Lifecycle\ Electrical\ Energy\ Output\ (in\ kWh)} \qquad \textbf{Eq. 3.2}$$

The IFIAS standards suggest the following four levels of energy analysis.

Level 1: Is the direct energy involved in the process only. It is typically less than 50% of the total embodied energy for the process.

Level 2: Contains energy required in extracting raw materials. This is frequently around 40% of the total embodied energy of the process.

Level 3: Includes the energy required to make the capital equipment for the process. This is rarely more than 10% of the total embodied energy.

Level 4: Takes into account the energy to make the machines that make the equipment. The embodied energy is usually very low as compared to the other levels.

The IFIAS standards have also made a clear distinction between stored energy resources and flux sources. A stored energy resource, such as fossil fuels and nuclear fuels, has the potential capacity to provide a finite amount of energy units. Flux sources are sources from which a flow of energy occurs over extended periods of time. Common examples of energy flux sources are solar radiation, water power, wind, waves, tides, ocean thermal gradients and biomass (including wood waste) [24].

In this thesis the energy obtained from energy resources are included in the embodied energy of the process, while energy captured from flux sources are not. The reason for this is that consuming resources depletes natural resources of the earth while capturing energy from flux sources do not. The analysis is carried out to level 4 of the IFIAS standards where possible. In the IFIAS standards, it is stated that for analysis referring to developed or industrialised economies, it is not necessary to consider the energy for life-support of man power [19]. Hence, for this analysis, the energy for life-support of man power, or the energy cost of labour, is ignored.

Initially, frameworks are created for carrying out embodied energy analysis of the power generation systems under study. These frameworks are based on Huntly power station for NGCC and NGOC power plants, White Hill wind farm for wind generation and, Benmore and Aratitia power stations for reservoir and run of river hydro power plants respectively. The frameworks were created using a hybrid of PCA and I/O analysis, with prominence given to PCA, following the conventions of the ISO 14040 series and the IFIAS standards.

The overall methodology and conventions set out in this section were not strictly followed when carrying out the analysis. Many assumptions had to be made according to the availability of data and the nature of the power station. The major assumptions made are addressed in the specific chapters, while detailed assumptions are recorded in the appendices.

3.3 Data Acquisition

One of the major tasks when carrying out the analysis for this thesis was data acquisition. There were two types of data that needed to be acquired. The first type consists of aggregate data, for example the embodied energy coefficients in MJ/kg of a specific type of building material, and the amount of energy that correlates to each dollar in various sectors of the New Zealand economy . The second type consists of data specific to the power plant concerned, for example the construction material types and quantities of the power plant.

The first type of data was obtained from literature regarding embodied energy data concerning New Zealand and a vast amount of literature in other countries, such as the US. If data was unavailable for New Zealand, overseas data was adopted accordingly. When carrying out the PCA analysis, references [25] and [26] were mainly used to determine the embodied energy coefficients of various building materials. When carrying out the I/O analysis, the I/O energy intensity coefficients were extracted from [27]. The I/O energy intensity coefficients of only 48 sectors within the New Zealand economy are stated in [27]. Therefore, for sectors of the economy for which the I/O energy intensity coefficients were not available, the energy coefficients were approximated by those of the closest economic sector present in [27].

The second type of data was difficult to obtain. Most of the power stations for which the analysis has been carried out, were built four to five decades ago. Also, the operating companies of the power stations were very reluctant to provide commercially sensitive information such as power station equipment values and

operation and maintenance expenses. It was only possible to get the required data for Benmore power station. Most of the data were gathered by going through the relevant files at Meridian Energy archives located in Twizel. For the other power stations, data were extracted from previous studies and adjusted accordingly. Plant specific details on data acquisition are covered in chapters 4 to 8.

Because the I/O energy intensity coefficients are in 2004 dollars, appropriate price indices had to be used to convert the monetary costs of each plant concerned to 2004 dollars. The main price indices used in this study are the Producer Price Index (PPI), Capital Goods Price Index (CGPI) and the Consumer Price Index (CPI). The PPI measures the movement of price levels relating to the production sector of the economy, while the CGPI measures the movement of price levels of fixed capital assets within New Zealand. However, these price indices are only available from 1977 and 1999 respectively [28], [29]. Consequently, to evaluate the 2004 monetary values in the production sector of the economy, for prices that are stated in dollar values prior to 1977, the CPI was used instead of the PPI. Similarly, for fixed assets for which prices are stated in terms of 1977 to 1999 dollar values, the PPI was used, and for prices stated in dollar values prior to 1977, the CPI was used.

The PPI is made up of two types of indices. They are the output PPI index, which measures the changes in the prices received by producers, and the input PPI index, which measures the changes in the cost of production. For the analysis in this thesis, the input PPI index was mainly used, because the aim was to calculate the energy embodied in the production of electricity. Hence, using the input PPI yields more accurate results. The price indices were extracted from references [30-32].

4. Natural Gas Combined Cycle

The NGCC power plant, used for the embodied energy analysis in this thesis, is located at Huntly power station, owned and operated by Genesis Energy Ltd. It was commissioned in June 2007. The Huntly power station consists of three separate generation plants. They are a coal and gas fired steam plant, an NGOC plant and an NGCC plant [33]. Each of the generation plants is segregated and the operation of one plant does not affect the operation of another. Hence, embodied energy analysis can be carried out on all three plants as separate entities.

The NGCC plant consists of an M701F gas turbine and a TC2F-30 steam turbine, both manufactured by Mitsubishi Heavy Industries (MHI). The gas turbine has a capacity of 250 MW and the steam turbine has a capacity of 135MW. The combined turbines power a 385MW generator, manufactured by MELCO located in Kobe, Japan. The configuration of the NGCC unit at Huntly power station is shown in Figure 4.1 [34].
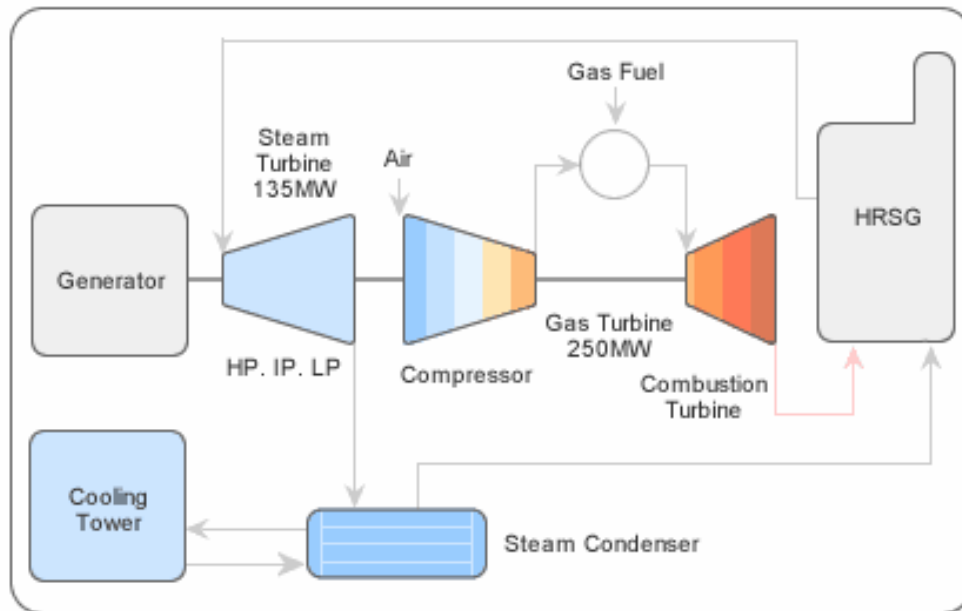
Figure 4.1. Configuration of the NGCC Unit at Huntly Power Station [34]

The incoming air is compressed before entering the combustion turbine where it is mixed with natural gas and burned. The hot gas from the combustion expands and drives the gas combustion turbine, which in turn rotates the generator shaft to produce electricity. Some of the exhaust heat is recovered by the heat recovery system generator (HRSG), which generates steam by passing the exhaust gas through a labyrinth of water filled finned tubes. The steam produced by the HRSG drives the steam turbine, which in turn helps rotate the generator shaft to produce electricity. The exhaust steam is directed to the steam condenser. After the steam is condensed, the hot water from the steam condenser is pumped to the top of the cooling tower. The cooled water flows back into the steam condensing process to serve as a coolant once more [34], [35].

4.1 Embodied Energy Analysis for NGCC Power Plant

The life cycle of an NGCC plant consists of plant construction (which includes plant equipment), natural gas exploration, production and transmission (fuel cycle), plant operation, and plant decommissioning and land reclamation. The useful product is the electrical energy generated by the plant. Figure 4.2 illustrates the life cycle of a NGCC power plant with the energy flows in each phase. When carrying out the analysis, the components specified in the scope of the ISO standards needed to be addressed. Some of these were covered in sections 3.2 and 3.3. The plant specific ones that still need to be addressed are data requirements, assumptions and limitations.

The framework for the analysis on the Huntly NGCC unit was adapted from a study on a US NGCC power plant, in [13]. The necessary data to carry out the embodied energy analysis were not available from Genesis energy. The required data were also extracted from [13] and adjusted to the Huntly power station accordingly.
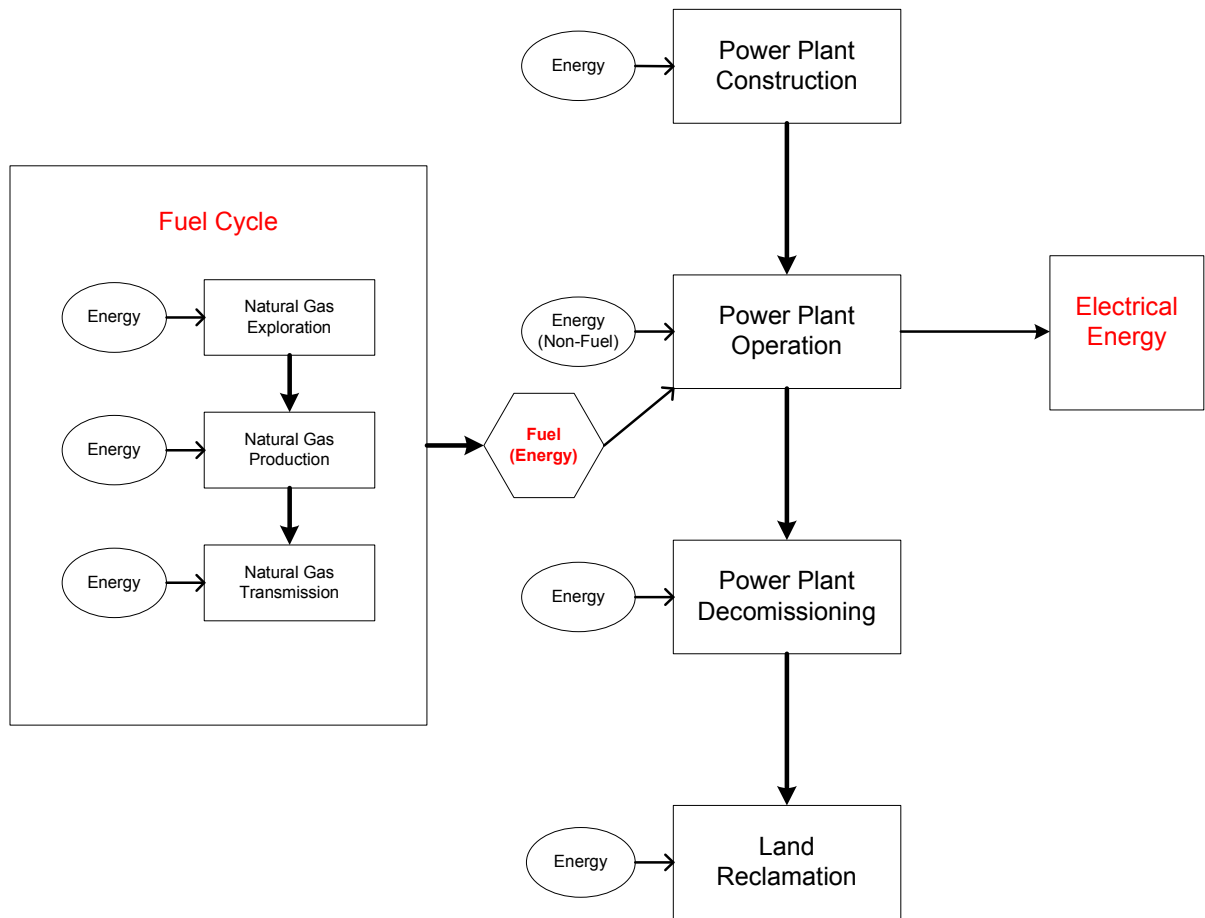
Figure 4.2. Life Cycle Energy Flows of an NGCC Power Plant

4.2 Methodology and Results

This section presents a summary of methodology, data and results of embodied energy analysis carried out on the NGCC power plant. The major assumptions made, when carrying out the analysis, are also addressed in this section. Detailed tables and calculations of the analysis are presented in Appendix 1.1. Appendix 1.2 provides a detailed list of assumptions made, explanations on the calculations, and the citations for specific data and calculations. The references for the detailed assumptions are recorded in Appendix 6.

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4.2.1 Electrical Energy Output

The operational characteristics and estimated lifecycle electrical energy output of the NGCC plant are summarised in Table 4.1. The capacity factor of 86% means the plant is in operation for 86% of the calendar year. Hence, the full power life of the power plant was calculated by multiplying the calendar year lifetime by the capacity factor. The lifetime electrical energy output from the plant was estimated to be 417,900,000 GJ. This was calculated by multiplying the net power output of the plant by the full power lifetime and multiplying the result by the appropriate factors to convert this amount to GJ. The life cycle direct fuel (natural gas) input was estimated by dividing the net electrical output by the thermal efficiency of 57%. This was calculated to be 733,200,000 GJ. Detailed calculations are given in Table GC2, in Appendix 1.1.

Table 4.1. NGCC Plant Operational Characteristics and Useful Electrical Energy Output

Description	Quantity	Unit
Net Power Output	385	MW
Calendar Year Lifetime	40	Years
Capacity Factor	86%	
Full Power Lifetime	34.4	Years
Lifetime Net Electrical Output	417,900,000	GJ
Thermal Efficiency	57%	
Direct Fuel Input	733,200,000	GJ

4.2.2 Fuel Cycle

The life cycle of natural gas, also known as the fuel cycle, contains exploration, production and transmission, as shown in figure 4.2. The embodied energy of natural gas exploration was calculated using I/O analysis. It was calculated by estimating the energy cost of New Zealand natural gas exploration and multiplying this by the life time natural gas production required by the Huntly NGCC plant. The embodied energy of natural gas production and transmission were estimated by calculating these

figures for the whole of New Zealand and multiplying by a plant factor of 0.0987 (9.87%). The factor 0.0987 is the proportion of New Zealand produced natural gas consumed by the Huntly NGCC unit, per annum. A summary of embodied energy in the fuel cycle of the NGCC power plant is given in Table 4.2.

Table 4.2. Embodied Energy of NGCC Power Plant Fuel Cycle

Process	Embodied Energy (GJ)
Natural Gas Exploration	5,709,000
Natural Gas Production	70,700,000
Natural Gas Transmission	7,117,000

Detailed calculations for energy embodied in natural gas exploration are given in Table GC3 in Appendices 1.1 and 1.2. The average cost of adding proved reserves, in $/GJ, was estimated using data from [36]. The I/O intensity for natural gas exploration was extracted from [27]. Detailed calculations and explanation of calculations for energy embodied in natural gas production are given in Table GC9 in Appendices 1.1 and 1.2, respectively. The natural gas production losses per year was estimated by calculating the total gas production minus the net gas production each year between 2000 and 2007, and averaging the result. The data for total gas production per year and net gas production per year were extracted from [37] and [38] respectively.

The embodied energy of natural gas transmission includes pipeline materials and installation, compressor stations, transmission systems operation and maintenance and transmission losses. The only information available on New Zealand gas transmission pipelines is that there is a total length of over 15,000km of transmission pipelines [39]. This fact, in conjunction with the details available on US gas distribution system from [13], was used to estimate the embodied energy of the New Zealand gas transmission pipelines. It was assumed that the New Zealand gas transmission pipelines were identical in nature, in terms of materials and cross sectional diameters, to that of the US gas transmission pipelines. To calculate the corresponding lengths of the New Zealand transmission pipelines, of the various cross sectional diameters, the US pipeline lengths were multiplied by a factor of 0.0317. This corresponds to the

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ratio of the total length of New Zealand transmission pipelines to the total length of US transmission pipelines.

When calculating the embodied energy of pipeline materials, pipeline construction and pipeline engineering and administration, PCA was used. The embodied energy coefficients for New Zealand pipelines in GJ/km were estimated by adjusting the US coefficients in [13] accordingly. Detailed calculations and explanations are given in Tables GC4-GC8 in Appendix 1.1 and Appendix 1.2.

The embodied energy of compressor stations (construction materials and engineering), equipment in compressor stations, and operation and maintenance of the New Zealand natural gas transmission system, were calculated using I/O analysis. The costs for New Zealand natural gas transmission facilities, as mentioned above, were not available. Hence, the costs were estimated using the US costs from [13]. It was assumed that the cost of transmission equipment has a direct correlation with the length of the transmission pipelines. Therefore, to calculate the New Zealand costs, the US costs were multiplied by the factor of 0.0317. Detailed calculations are given in Tables GC11 and GC12 in Appendix 1.1. A list of detailed assumptions, assumed economic sectors and assumed price indices for the I/O analysis are recorded in Appendix 1.2.

4.2.3 Plant Construction Material

The types and quantities of structural building materials of the NGCC unit of the Huntly power station were not available. It was assumed that the building structures are identical to those of the NGCC plant in [13]. Hence, the building materials and quantities used were estimated to be equivalent to the NGCC power plant in [13]. The embodied energy analysis carried out for NGCC plant's building materials is shown in Table 4.3.

Table 4.3. Embodied Energy of NGCC Power Plant Building Materials

Material	Mass (Tonnes)	Energy Intensity (GJ/Tonne)	Embodied Energy (GJ)	Percentage of Total (%)
Aluminium	1.8	201.057	362	0.91
Chromium	0.32	82.9	27	0.07
Concrete	29,660	1.003	29,749	74.47
Copper (Refined)	4	97.6	390	0.98
Iron	73	23.5	1,176	4.29
Structural Steel	134	25.04	3,355	8.40
Manganese	17	51.5	876	2.19
Molybdenum	0.17	378	64	0.16
Plastic	15	60.9	914	2.29
Silicon	3.8	158.6	603	4.51
Vanadium	0.51	3711.2	1,893	4.74
Total			**39,900**	

To calculate the embodied energy of plant building materials, PCA was used. The embodied energy coefficients for the building materials were mainly extracted from [25] and [26]. For iron, chromium, manganese, molybdenum, silicon and vanadium, New Zealand embodied energy coefficients could not be found. Therefore, for these materials, the coefficients were estimated using the US embodied energy coefficients given in [13]. Detailed information is given in Table GC13 in Appendix 1.1 and 1.2.

Concrete accounts for nearly 75% of the embodied energy of plant construction materials. Structural steel is the second highest contributor and accounts for 8.4% of material embodied energy. Chromium and molybdenum are the smallest contributors of embodied energy in plant building materials, and account for 0.07% and 0.16% respectively.

4.2.4 Plant Construction, Plant Equipment and Plant Operation and Maintenance

Table 4.4. Plant Construction, Plant Equipment and Plant Operation and Maintenance Embodied Energy

Description	Embodied Energy (GJ)
Plant Construction	419,000
Plant Equipment	257,000
Plant Operation and Maintenance	39,875,000

The plant construction embodied energy, shown in Table 4.4, corresponds to energy associated with plant construction that does not relate to building materials. This includes engineering and administration, plant and equipment assembly, facility testing and completion, site assessment and permitting, and business administration. The embodied energy associated with plant construction was calculated using I/O analysis. Again, as Huntly power station construction costs were not available, costs were extracted from [13] and adjusted for the Huntly power station NGCC unit.

The costs in [13] are in 1999 US dollars. These were converted to 1999 New Zealand dollars using an exchange rate of 1 NZ\$ = 0.5296 US\$ [40]. The costs were then converted to equivalent 2004 New Zealand dollars using inputs PPI for construction [30]. The plant construction costs were adjusted to the Huntly power station NGCC unit by multiplying by a factor of 0.621. The factor of 0.621 corresponds to the ratio of the ratings of the Huntly NGCC unit to the rating of the US NGCC plant in [13], as shown in Equation 4.1. These are 380 MW and 620 MW respectively. Hence, it was assumed that the plant construction costs are directly correlated to the rating of the power station. Detailed calculations and assumption are given in Table GC14 in Appendices 1.1 and 1.2.

$$Plant\ Adustment\ Factor = \frac{Rating\ of\ Huntly\ NGCC\ unit\ (MW)}{Rating\ of\ U.S.\ NGCC\ Plant\ (MW)} \qquad \textbf{Eq. 4.1}$$

The embodied energy of plant equipment and plant operation and maintenance were calculated using I/O analysis, in a similar manner to plant construction. The plant

operation and maintenance includes day to day maintenance of plant, such as contract services, materials and supplies (excluding fuel input to the plant), and repairing and replacement of parts. As with the plant construction, the costs were approximated using the costs in [13]. These were adjusted for the Huntly NGCC unit by converting to New Zealand dollars and multiplying by the factor of 0.621, which corresponds to the ratio in Equation 4.1. For plant equipment, the costs were adjusted to equivalent 2004 New Zealand dollars using the appropriate CGPI indices [31]. In section 4.1 it was conveyed that some of the plant equipment are imported. However, the I/O energy intensity coefficients of imported machinery is not available in [27]. Hence, the I/O energy coefficient of machinery and equipment manufacturing was used when calculating the embodied energy. The plant operation and maintenance costs were adjusted to 2004 New Zealand dollars using the inputs PPI for generation and supply. Detailed calculations and assumptions for plant equipment and plant operation and maintenance are given in Tables GC15 and GC16, respectively, in Appendices 1.1 and 1.2.

4.2.5 Plant Decommissioning and Land Reclamation

Table 4.5. Embodied Energy of Plant Decommissioning and Land Reclamation

Description	Embodied Energy (GJ)
Plant Decommissioning	27,000
Land Reclamation	4,900

The embodied energies for plant decommissioning and land reclamation are shown in Table 4.5. These were calculated using I/O analysis. The plant decommissioning included plant dismantling and building demolition. The plant dismantling costs were estimated to be 10% of equipment costs, as done in the analysis in [13]. The plant demolition costs are estimated to be equivalent to that of [13]. Detailed calculations and assumptions are given in Table GC17 in Appendices 1.1 and 1.2.

The area of land that needs to be reclaimed from transmission pipelines in New Zealand was estimated by multiplying the area of land that has to be reclaimed for US

transmission pipelines by a factor of 0.0146. This corresponds to the ratio of 116,219 km^2 to 7,979,266 km^2, which are the areas of New Zealand North Island and contiguous US, respectively [41],[42]. The plant area that needs to be reclaimed is estimated to be equal to that of [13]. Other unavailable data in New Zealand, such as the seeding costs and lifetime of New Zealand natural gas transmission pipelines were estimated to be equivalent to that of the US. Detailed calculations and assumptions are given in Tables GC18 and GC19 in Appendices 1.1 and 1.2.

4.3 Discussion

A graphical representation of the proportions of embodied energy in the various phases of the plant life cycle is shown in Figure 4.3. The life cycle is divided into 5 main phases, namely, plant materials and construction, fuel cycle, plant fuel input, operation and maintenance, and decommissioning and land reclamation. The plant fuel input and operation and maintenance account for the direct energy input, whilst the other phases of the plant life cycle account for the indirect energy input.

The plant fuel input accounts for about 86% of the total embodied energy of the plant, but the fuel cycle contributes about 10% of the NGCC power plant's total embodied energy. The plant materials and construction and plant decommissioning and land reclamation contribute the least amount of embodied energy. These are 0.08% and 0.004 % respectively. The direct energy input accounts for 90% of the total embodied energy of the power plant, while indirect energy is only 10%. Hence, the most energy intensive phase of an NGCC power plant's life cycle is the plant fuel input. Also the direct energy input is significantly higher than the indirect energy input.
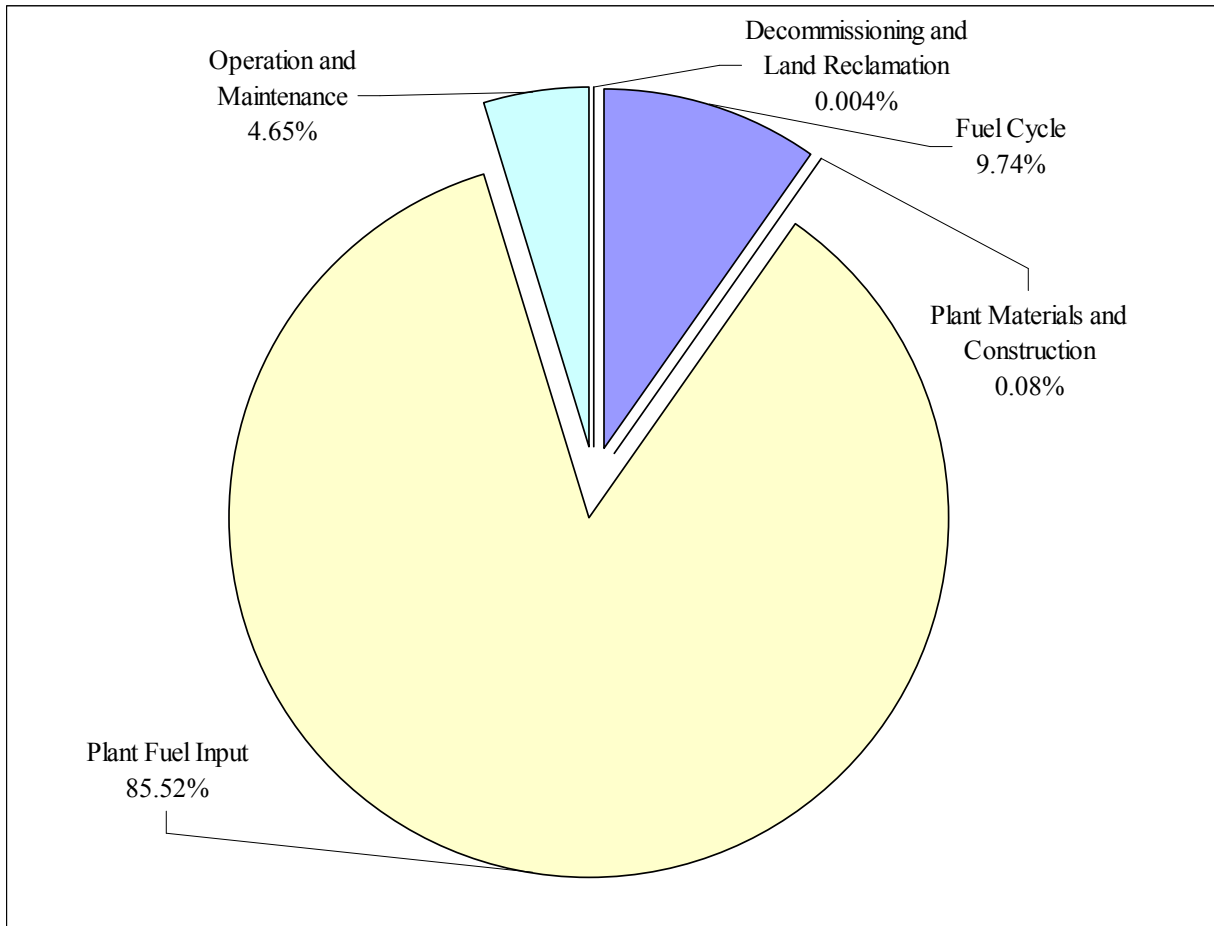
Figure 4.3. Distribution of Total Embodied Energy among the Various Phases of the NGCC Power Plant's Lifecycle

The proportions of indirect energy embodied in the various phases of the NGCC power plant's life cycle are shown in Figure 4.4. The fuel cycle is illustrated as three separate components of the plant's life cycle, rather than as a single entity. They are natural gas exploration, production and transmission. Natural gas production alone accounts for 83.89% of plant's indirect energy input, while natural gas exploration and transmission accounts for 6.77% and 8.44% respectively. The complete fuel cycle itself, which includes natural gas exploration, production and transmission, accounts for more than 99% of plant's indirect energy.
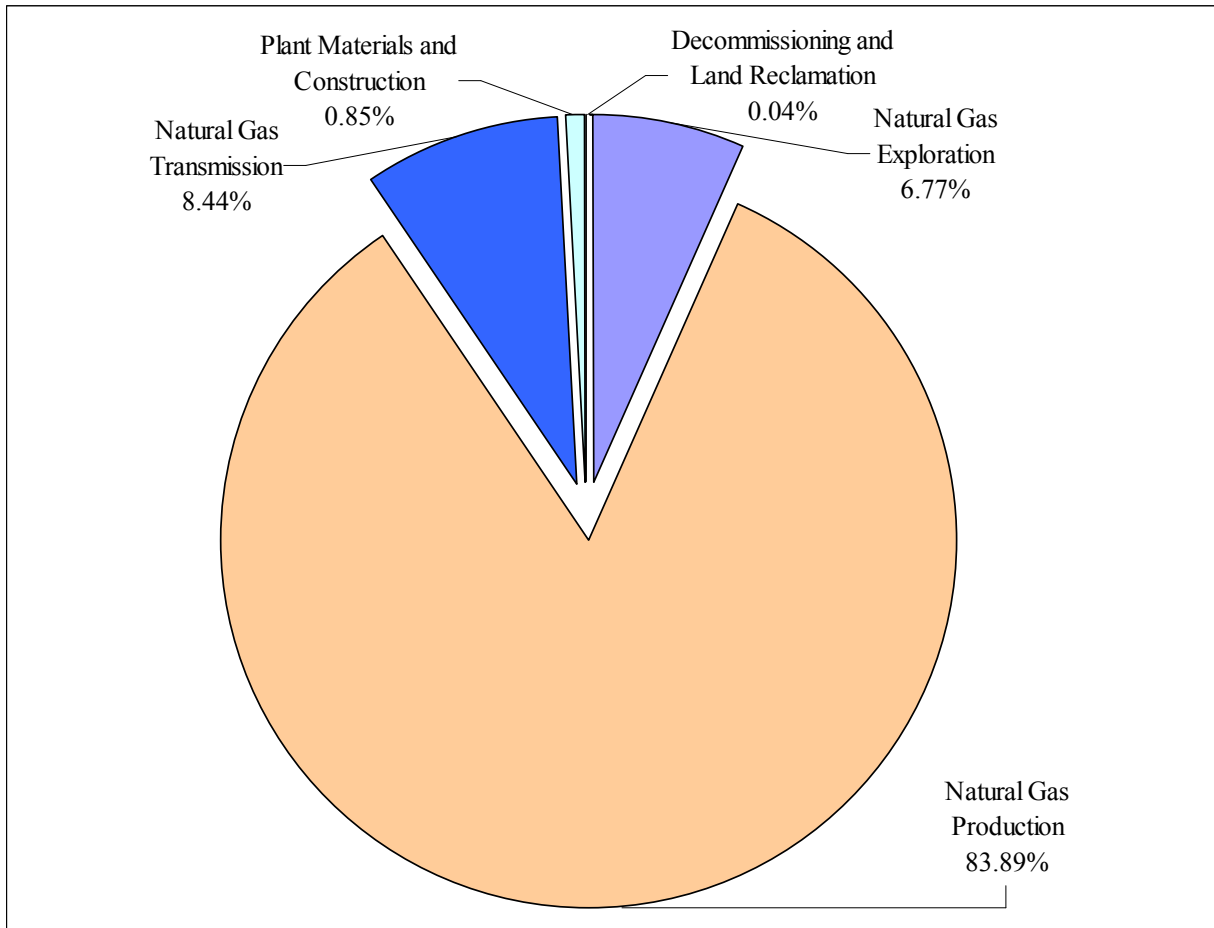
Figure 4.4. Distribution of Indirect Energy among the Various Phases of the NGCC Power Plant's Lifecycle

Plant materials and construction, and plant decommissioning and land reclamation account for very small proportions of the indirect energy input to the plant. These are 0.85% and 0.04% respectively. These figures, in conjunction with the proportions illustrated in Figure 4.3, show that the plant materials and construction, and plant decommissioning and land reclamation energy contributions are insignificant when compared to the other phases of an NGCC plant's life cycle.

The ratios given in Equations 3.1 and 3.2 are shown in Table 4.6 (refer to Table GC1 in Appendix 1.1 for the numerical values used when calculating these ratios). These ratios are compared with the ratios for the other power plants analysed in this thesis, in chapter 9.

Table 4.6. Ratios of the NGCC Power Plant used for Plant Comparison

Description	Quantity	Unit	Calculation
Lifecycle Electrical Output	417,948,854	GJ	A
Lifecycle Electrical Output	1.161×10^{11}	kWh	B
Lifecycle Energy Input	857,391,727	GJ	C
LEPR	**0.487**		A/C
Lifecycle Energy Cost	**7.39**	**MJ/kWh**	C/B

The parameters calculated in Table 4.6 are not exact. They are approximations of the LEPR and lifecycle energy cost of the Huntly NGCC plant. There are many small processes that have not been included in the analysis. Hence, 48.7% would be the maximum value of the LEPR, whereas 7.39 MJ/kWh is the minimum required life cycle energy cost of the Huntly NGCC power plant.

The LEPR of the Huntly NGCC power plant, estimated to be 48.7%, is slightly higher than the LEPR of the NGCC power plant in [13], which is 43%. The Huntly NGCC unit was commissioned later than the plant studied in [13], hence the efficiency of the plant equipment used to generate electricity should be higher. Therefore, the assumptions made in carrying out the analysis are accurate and are applicable. However, there are limitations in the analysis. These limitations are discussed in detail in Chapter 9, as some of the limitations are mutual for all the power stations for which embodied energy analysis was undertaken.

5. Natural Gas Open Cycle

The NGOC power plant used for the analysis in this thesis, located at Huntly power station, is also owned and operated by Genesis Energy Ltd. It was commissioned in June 2004. The NGOC power plant consists of an LM6000 General Electric gas turbine, which drives a generator via a gear box. The total capacity of the power plant is 48 MW. Air is passed through a compressor. The high-pressure air then enters a combustion turbine where it is mixed with fuel and ignited. The hot gas creates thrust that rotates the gas turbine shaft. The shaft in turn drives the generator producing electricity [33],[43]. A block diagram of NGOC power generation is shown in Figure 5.1 [35].
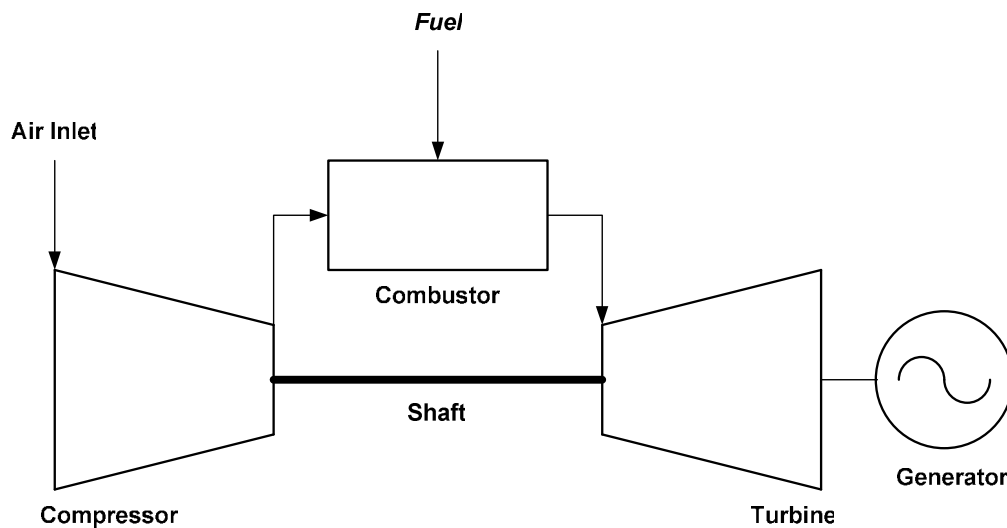
Figure 5.1. Block Diagram of NGOC Power Generation

5.1 Embodied Energy Analysis for NGOC Power Plant

The lifecycle of the NGOC power plant, illustrated in Figure 4.2, is equivalent to that of the NGCC power plant. It consists of plant construction (which includes plant equipment), natural gas exploration, production and transmission (fuel cycle), plant

operation, and plant decommissioning and land reclamation. The useful product is the electrical energy generated by the plant.

The framework for the analysis on the Huntly NGOC unit was adapted from a study on a US NGCC power plant in [13], as with the Huntly NGCC power plant. This was due to the fact that NGCC and NGOC plants have identical lifecycles. The necessary data to carry out the embodied energy analysis were not available from Genesis Energy. Hence, the required data were also extracted from [13] and adjusted to the Huntly power plant accordingly.

5.2 Methodology and Results

This section presents a summary of data and results of embodied energy analysis undertaken on the NGOC power plant. The results, along with the major assumptions, are presented in a similar manner to the NGCC power plant. Detailed tables and calculations of the analysis are presented in Appendix 2.1. Appendix 2.2 provides a detailed list of assumptions made, explanations on the calculations, and the citations for specific data and calculations. The references for the detailed assumptions are recorded in Appendix 6.

5.2.1 Electrical Energy Output

The estimated life cycle electrical energy output of the NGOC plant, along with it's operating characteristics, are presented in Table 5.1. The NGOC power plant's electrical energy output was calculated using the same methodology as for the NGCC power plant. Detailed calculations are given in Table GO2, in Appendix 2.1. The lifetime electrical energy from the plant was estimated to be 47,300,000 GJ and the life cycle direct fuel (natural gas) input was estimated to be 115,300,000 GJ.

Table 5.1. NGOC Plant Operational Characteristics and Useful Electrical Energy Output

Description	Quantity	Unit
Net Power Output	48	MW
Calendar Year Lifetime	40	Years
Capacity Factor	78%	
Full Power Lifetime	31.2	Years
Lifetime Net Electrical Output	47,300,000	GJ
Thermal Efficiency	41%	
Direct Fuel Input	115,300,000	GJ

5.2.2 Fuel Cycle

The fuel cycle embodied energy of Huntly NGOC power plant was calculated in a similar manner to that of the NGCC power plant in section 4.2.2. The embodied energy of natural gas exploration was calculated by multiplying the energy cost of New Zealand natural gas exploration by the lifetime natural gas production required for the Huntly NGOC power plant. The embodied energies of natural gas production and transmission were estimated by multiplying the corresponding New Zealand embodied energies by a plant factor of 0.0155 (1.55%), which is the proportion of New Zealand produced natural gas consumed by the Huntly NGOC unit, per annum. A summary of embodied energy analysis in the fuel cycle of the NGOC power plant is given in Table 5.2. Detailed calculations and explanations are given in Tables GO3-GO12 in Appendices 2.1 and 2.2.

Table 5.2. Embodied Energy of NGOC Power Plant Fuel Cycle

Process	Embodied Energy (GJ)
Natural Gas Exploration	870,000
Natural Gas Production	11,114,000
Natural Gas Transmission	1,119,000

5.2.3 Plant Construction Material

The types and quantities of structural building materials of the NGOC unit at Huntly power station were not available. It was assumed that the building structures are identical to those of the NGCC plant in [13]. However, the actual quantities of building materials used in the Huntly NGOC power plant would be smaller, as an NGOC plant contains less equipment than an NGCC power plant, and the rating of the Huntly NGOC power plant is much smaller than the NGCC power plant in [13]. The embodied energy analysis undertaken for Huntly NGOC plant's building materials is shown in Table 5.3. The embodied energy of the building materials of the NGOC plant was calculated using the same methodology as for the NGCC plant in section 4.2.3. Detailed information is given in Table GO13 in Appendices 2.1 and 2.2.

Table 5.3. Embodied Energy of NGCC Plant Building Materials

Material	Mass (Tonnes)	Energy Intensity (GJ/Tonne)	Embodied Energy (GJ)	Percentage of Total (%)
Aluminium	1.8	201.057	362	0.91
Chromium	0.32	82.9	27	0.07
Concrete	29,660	1.003	29,749	74.47
Copper (Refined)	4	97.6	390	0.98
Iron	73	23.5	1,176	4.29
Structural Steel	134	25.04	3,355	8.40
Manganese	17	51.5	876	2.19
Molybdenum	0.17	378	64	0.16
Plastic	15	60.9	914	2.29
Silicon	3.8	158.6	603	4.51
Vanadium	0.51	3711.2	1,893	4.74
Total			39,900	

5.2.4 Plant Construction, Plant Equipment and Plant Operation and Maintenance

The plant construction embodied energy, shown in Table 5.4, corresponds to energy associated with plant construction that does not relate to building materials. This includes engineering and administration, plant and equipment assembly, facility testing and completion, site assessment and permitting, and business administration. The analysis was carried out using the same methodology as for the NGCC power plant in section 4.2.3. The plant adjustment factor, stated in Equation 4.1, for the Huntly NGOC plant is 0.0774. Detailed calculations and assumptions are given in Tables GO14-GO16 in Appendices 2.1 and 2.2.

Table 5.4. Plant Construction, Plant Equipment, and Plant Operation and Maintenance Embodied Energy

Description	Embodied Energy (GJ)
Plant Construction	52,300
Plant Equipment	32,000
Plant Operation and Maintenance	4,970,000

5.2.4 Plant Decommissioning and Land Reclamation

The embodied energies of plant decommissioning and land reclamation are shown in Table 5.5. These were calculated using I/O analysis using the same methodology and conversion factors used in the NGCC plant in section 4.2.4. Detailed calculations and assumptions are given in Table GC17-GC19 in Appendices 2.1 and 2.2.

Table 5.5. Embodied Energy of Plant Decommissioning and Land Reclamation

Description	Embodied Energy (GJ)
Plant Decommissioning	3,900
Land Reclamation	1,200

5.3 Discussion

The results from the embodied energy analysis of the NGOC plant are interpreted using the same techniques used for the NGCC power plant. The life cycle is divided into 5 main phases, namely, plant materials and construction, fuel cycle, plant fuel input, operation and maintenance and decommissioning and land reclamation. The direct energy input includes the plant fuel input and operation and maintenance, whilst the other phases of the plant life cycle account for the indirect energy input. The proportions for the total embodied energy in the different phases of the plant life cycle are illustrated in Figure 5.2.
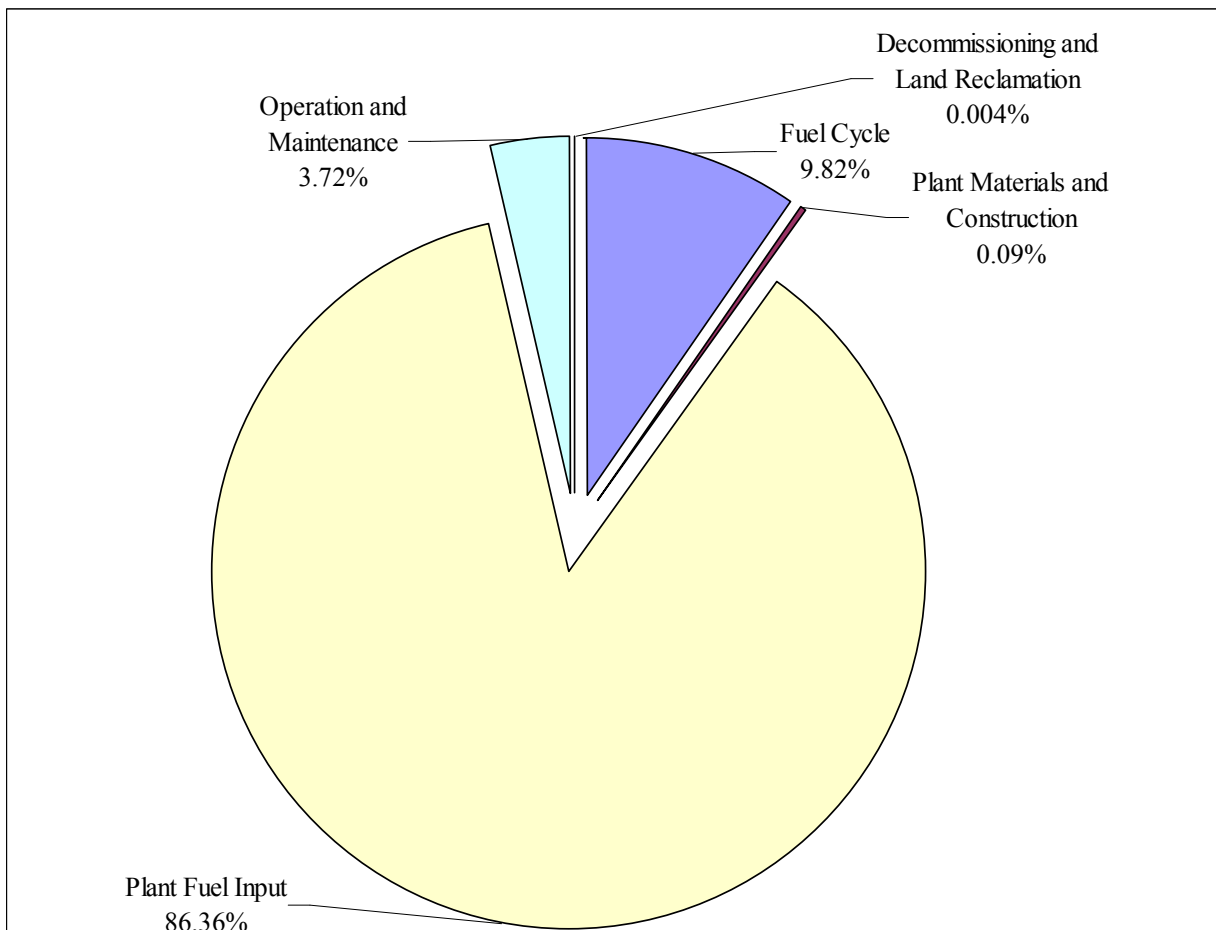
Figure 5.2. Distribution of Total Embodied Energy among the Various Phases of the NGOC Power Plant's Lifecycle

The plant fuel input accounts for about 86% of the total embodied energy of the plant, and the fuel cycle contributes about 10%. The plant materials and construction, and plant decommissioning and land reclamation, contribute the least amount of embodied energy. They are 0.09% and 0.004% respectively. The direct energy input accounts for about 90% of the total embodied energy, while indirect energy accounts for 10%. Therefore, the most energy intensive phase of an NGOC plant is the direct fuel input. Also the direct energy input is significantly higher than the indirect energy input.

The actual embodied energy of plant materials and construction would be lower than that estimated in this analysis because the quantities of materials were approximated to be equivalent to a larger NGCC power plant, as mentioned in section 5.2.3. However, this would not make a significant difference in the proportions of embodied energy in various lifecycle phases of the power plant, as building materials, which is included in plant materials and construction, accounts for only 0.03% of the total embodied energy of the plant.

The proportions of indirect energy embodied in the various phases of the NGOC power plant's life cycle are shown in Figure 5.3. The fuel cycle is broken down into the three main components, which are natural gas exploration, production and transmission. Natural gas production alone accounts for 84% of plant's indirect energy input, while natural gas exploration and transmission accounts for 6.6% and 8.5% respectively. The complete fuel cycle itself, which includes natural gas exploration, production and transmission, accounts for nearly 99% of plant's indirect energy.
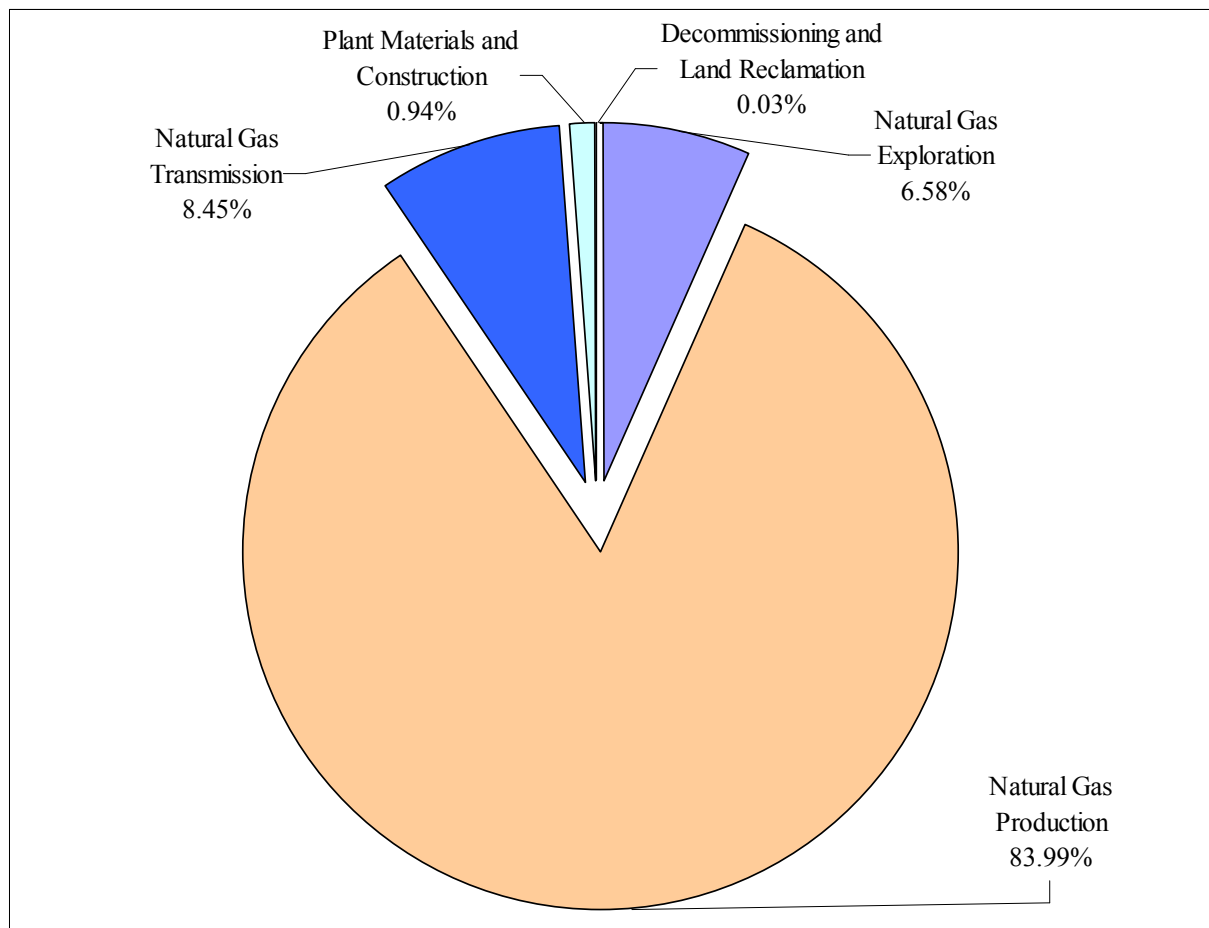
Figure 5.3. Distribution of Indirect Energy among the Various Phases of the NGOC Power Plant's Lifecycle

Plant materials and construction, and plant decommissioning and land reclamation account for very small proportions of the indirect energy input to the plant. These are 0.94% and 0.03% respectively. These figures, in conjunction with the proportions illustrated in Figure 5.2, show that the plant materials and construction, and plant decommissioning and land reclamation energy contributions are insignificant when compared to the other phases of an NGOC plant's life cycle.

The ratios given in Equations 3.1 and 3.2 are shown in Table 5.6 (refer to Table GO1 in Appendix 2.1 for the numerical values used when calculating these ratios). These ratios are compared to the ratios of the other power plants in Chapter 9.

Table 5.6. Ratios of the NGOC Power Plant used for Plant Comparison

Description	Quantity	Unit	Calculation
Life Cycle Electrical Output	47,260,662	GJ	A
Life Cycle Electrical Output	1.313×10^{10}	kWh	B
Life Cycle Energy Input	133,472,233	GJ	C
LEPR	**0.354**		A/C
Life Cycle Energy Cost	**10.17**	**MJ/kWh**	C/B

As with the Gas NGCC plant, the parameters calculated in Table 5.6 are not exact, and are approximations. It can also be said that 35.4% would be the maximum value of the LEPR and 10.17 MJ/kWh is the minimum required life cycle energy cost of the Huntly NGOC power plant. The limitations of this analysis are discussed in chapter 9.

6. Wind

The embodied energy analysis of wind generation was based on the White Hill wind farm, owned and operated by Meridian Energy Ltd. It is located south-east of Mossburn in the South Island. It started producing electricity on the 8th of June 2007. The White Hill wind farm contains 29, 2MW wind turbines, and hence has a total capacity of 58MW. The wind turbines are Vestas V80 turbines and they were supplied by Vestas, a Danish wind turbine manufacturing company [44],[45].

A wind turbine usually consists of 4 main parts. They are the rotor, nacelle, tower and the foundation, as shown in Figure 6.1 [46]. The rotor blades intersect the wind and capture the energy it contains, which causes them to rotate in a vertical plane about the shaft axis. The slow rotation of the shaft is normally increased by use of a gearbox, by which the rotational motion is delivered to a generator. The electrical output from the generator is then transferred through cables, down the turbine tower to a substation where the power is eventually fed into the electricity grid. The mechanical components at the top of the turbine tower - the rotor, gearbox, and generator- are all mounted in the nacelle that can pivot, or yaw, about the vertical axis, so that the rotor shaft is always aligned with the wind direction [35].

Figure 6.1. A Typical Wind Turbine [46]

6.1 Embodied Energy Analysis of Wind Generation

The life cycle of a wind farm consists of turbine production, turbine transportation to site, site construction (which includes wind farm fixed assets), wind farm operation and maintenance, and dismantling, scrapping and land reclamation. The various phases of the life cycle with energy inputs and the electrical energy output, which is the useful product, are illustrated in Figure 6.2. The framework for undertaking the embodied energy analysis was based on Figure 6.2, and the life cycle assessments carried out on wind farms in [47] and [48] .
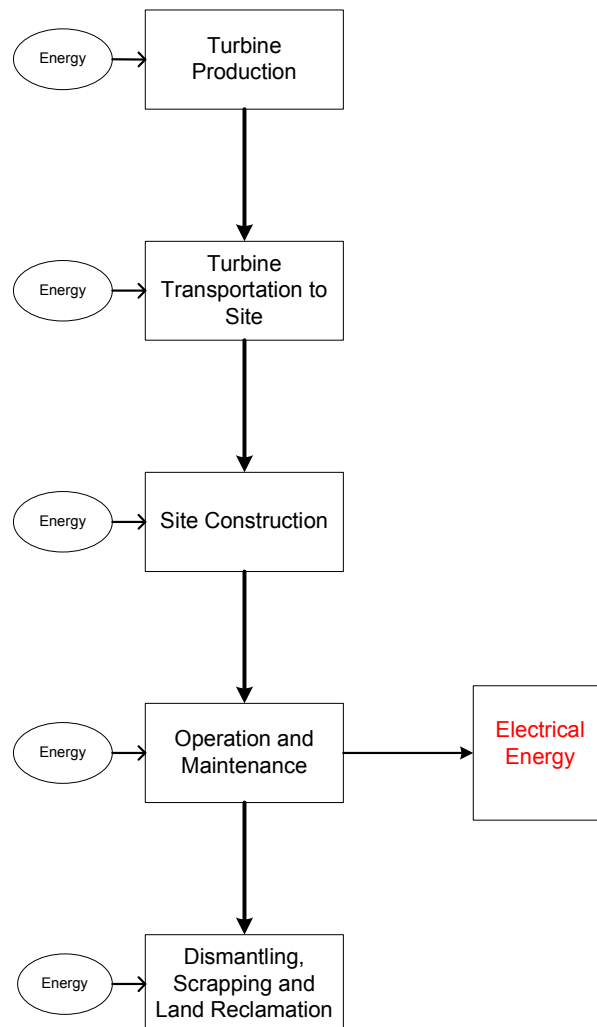
Figure 6.2. Lifecycle Energy Flows of a Wind Farm

As with the NGCC and NGOC power plants, the necessary data to carry out the analysis were not available. Hence, data from other sources, mainly [47-51], were adopted and adjusted to the White Hill wind farm accordingly. Detailed tables and calculations, and detailed assumptions and explanations on calculations are presented in Appendices 3.1 and 3.2, respectively. The references cited in Appendix 3.2 are recorded in Appendix 6.

6.2 Methodology and Results

6.2.1 Electrical Energy Output

The operational characteristics and the estimated lifecycle electrical energy output of the White Hill wind farm are presented in Table 6.1. The useful life of White Hill wind farm was not available and hence was assumed to be 20 years, which is the life of the Vestas V80 wind turbines. The availability factor of 90% means that the turbine will generate electricity for 90% of the year. This takes into consideration that the turbines only operate under certain wind speeds, which are 4-25 m/s (14.4-90 kph) for wind turbines at White Hill. Within this range the turbines can only generate electricity at full generation capacity at a nominal speed of 15 m/s. This is accounted for by the annual load factor of 45%, which corresponds to the ratio of actual generation to that of generation at full capacity [44], [52].

The full power life of the wind farm was calculated by multiplying the calendar year lifetime by the availability factor. The net power output of the wind farm was calculated by multiplying the capacity of the wind farm by the annual load factor. The lifecycle electrical energy output of 15,000,000 GJ was calculated by multiplying the full power life time by the net power output, and multiplying the result by the appropriate factor to convert this amount to GJ. Detailed calculations and explanations on calculations are given in Table WN2 in Appendices 3.1 and 3.2.

Table 6.1. Wind Farm Operational Characteristics and Useful Electrical Energy Output

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

6.2.2 Turbine Production and Dismantling

The embodied energy of turbine production and dismantling was calculated using PCA. The energy embodied in wind turbine materials is shown in Table 6.2. The construction materials and quantities of the wind turbines were extracted from [47]. To calculate the energy embodied in the turbine materials, New Zealand embodied energy coefficients were used, because the Danish embodied energy coefficients were not available. Detailed calculations and explanations on calculations are given in Table WN3 in Appendices 3.1 and 3.2. Steel accounted for the highest proportion of embodied energy contributing approximately 71% of the total embodied energy in wind turbine materials.

The energy embodied in the manufacturing, (excluding wind turbine construction materials), and dismantling of a Vestas V80 turbine is 3,283,000 kWh per turbine [47]. The total embodied energy of turbine manufacturing and dismantling at the White Hill wind farm was calculated to be 343 GJ. This is presented in Table 6.3. Detailed calculations and explanations on calculations are given in Table WN4 in Appendices 3.1 and 3.2.

Table 6.2. Embodied Energy of Wind Turbine Construction Materials

Material	Mass (Tonnes)	Energy Intensity (GJ/Tonne)	Embodied Energy (GJ)	Percentage of Total (%)
Steel	223	32.614	7,277	71.34
Stainless Steel	13	74.8	997	9.77
Cast Iron	21	23.5	486	4.77
Glass Fibre	22	29.265	629	6.17
Plastic	3	60.9	188	1.84
Copper	3	97.6	275	2.69
Aluminium	1.678	201.057	337	3.31
Zinc	0.2	51	10	0.10
Embodied Energy per Turbine			**10,000**	
Total Embodied Energy			**296,000**	

Table 6.3. Energy Embodied in Wind Turbine Production

Description	Amount	Unit
Energy Embodied in Turbine Manufacturing/Dismantling	3,300,000	kWh/Turbine
Number of Turbines at White Hill wind farm	29	
Total Embodied Energy	**95,199,000**	**kWh**
Total Embodied Energy	**343**	**GJ**

6.2.3 Turbine Transportation to Site

The energy embodied in turbine transportation to site was calculated using PCA. It was calculated by multiplying the corresponding distances and the total mass of the turbines by the transport energy intensity coefficients (in MJ/net tonne km) in [53]. It was assumed that the turbines were shipped from Copenhagen harbour in Denmark to Lyttelton port. From Lyttelton port, the turbines were transported to White Hill wind farm by rigid plus articulated trucks. The sailing distance between Copenhagen harbour and Lyttelton port and the driving distance from Lyttelton port to White Hill wind farm were estimated to be 21,852 km and 600 km from [54] and [55], respectively. The mass of each turbine was estimated to be 230.4 tonnes, making the total mass of all the turbines at the White Hill wind farm, 6681.6 tonnes [44]. The results are summarised in Table 6.4. Detailed calculations and explanations are given in Table WN5 in Appendices 3.1 and 3.2.

Table 6.4. Embodied Energy of Turbine Transportation to Site

Description	Embodied Energy (GJ)
Transportation from Copenhagen to Lyttelton	204,000
Transportation from Lyttelton to White Hill Wind Farm	8000
Total Embodied Energy	**212,000**

6.2.4 Site Preparation and Construction

The embodied energy of site preparation and construction include site construction building materials, non material related site preparation and construction processes, and fixed assets and equipment (excluding wind turbines). The site construction building materials include the wind turbine foundations, cable trenches and cables, paths and roads, and the site office. The results are summarised in Table 6.5. Detailed calculations and explanations on calculations are given in Tables WN6-WN11 in Appendices 3.1 and 3.2.

Table 6.5. Embodied Energy of Site Preparation and Construction

Description	Embodied Energy (GJ)
Turbine Foundation Construction Materials	34,000
Cable Trenches and Cable Construction Materials	23,000
Paths and Road Construction Materials	45,000
Site Office Construction Materials	73
Service Related Site Preparations and Construction	38,000
Fixed Assets and Equipment	1,000
Total Embodied Energy	**141,000**

The embodied energy of turbine foundation construction materials, cable trenches and cable construction materials, paths and road construction materials and site office construction materials were calculated using PCA. For the turbine foundations, the amounts of concrete and steel used were available from [56]. The other materials were estimated by multiplying the quantities of materials used in the wind farm in [48] by a factor of 3.063, which corresponds to the ratio of the mass of steel used per turbine foundation at White Hill wind farm, to that of the wind farm in [48]. Detailed calculations and explanations on calculations are given in Table WN6 in Appendices 3.1 and 3.2.

The materials used for cable trenches and cable construction, paths and road construction, and site office construction of the White Hill wind farm were not available. The construction materials used for cable trenches and cables, paths and roads were estimated using [48]. For cable trenches and cables, the quantities of construction materials used in [48] were multiplied by a factor of 2.64, which corresponds to the ratio of the number of turbines at White Hill wind farm to the number of turbines in [48]. The construction materials of the paths and roads of the White Hill wind farm were estimated by multiplying the quantities in [48], by a factor of 5.33, which corresponds to the ratio of the total area of White Hill wind farm to the total area of the wind farm studied in [48]. As with the cable trenches and cable construction materials, to estimate the quantities of building materials of the White Hill wind farm's site office, the construction materials from [48] were multiplied by

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the factor of 2.64. Detailed calculations and explanations on calculations are given in Tables WN6-WN9 in Appendices 3.1 and 3.2.

The energy embodied in service related site preparations and construction and fixed assets and equipment, were calculated using I/O analysis. The costs were extracted from [49] and [51]. They were adjusted to the White Hill wind farm and converted to 2004 dollars using appropriate price indices. The energy intensity coefficients for the corresponding economic sectors were extracted from [27]. Detailed calculations and explanations on calculations are given in Tables WN10 and WN11 in Appendices 3.1 and 3.2.

6.2.5 Wind Farm Operation and Maintenance

The embodied energy of wind farm operation and maintenance was calculated using I/O analysis. The total embodied energy associated with wind farm operation and maintenance was estimated to be 52,000 GJ. The costs of the White Hill wind farm operation and maintenance were estimated from [50] and [51], because the actual costs were unavailable from Meridian Energy.

The total annual operation and maintenance costs of a 24.3 MW, model New Zealand wind farm is $1,032,750 (1994 dollars) [51]. This was adjusted to the White Hill wind farm by multiplying by a factor of 2.386, which corresponds to the ratio of the total capacity of the White Hill wind farm to the total capacity of the wind farm studied in [51]. This total cost was divided among the various components of plant operation and maintenance by using the proportions set out in [50]. These costs were then converted to equivalent 2004 dollars using appropriate price indices. The energy intensity coefficients from [27] were used to calculate the embodied energy. Detailed calculations and explanations on the calculations are given in Table WN12 in Appendices 3.1 and 3.2.

6.2.6 Wind Farm Decommissioning and Land Reclamation

The energy embodied in wind farm decommissioning and land reclamation was assumed to be zero. The energy associated with wind turbine dismantling was already calculated in section 6.2.1, because Vestas provided a figure for embodied energy in turbine production and dismantling in [47]. It is also stated in [47] that the recycling and scrapping of the wind turbines has a negative embodied energy. This represents the energy gain because of the lower energy embodied in recycling the materials when compared to the extraction of the materials in it's raw state from the earth, for future use. It was assumed that the energy embodied in the other stages of plant decommissioning (e.g. plant equipment dismantling) cancels out with the energy gain in recycling of turbine materials. The land reclamation embodied energy was also assumed to be negligible, as the land a wind farm operates on can be used for other purposes, such as farming, while the wind farm is in operation [44].

6.3 Discussion

The proportions of energy embodied in the various phases of the White Hill wind farm's lifecycle are shown in Figure 6.3. The wind farm's lifecycle is divided in 4 main phases. They are turbine production, turbine transportation, site construction and fixed assets, and operation and maintenance. The wind farm decommissioning and land reclamation embodied energy was assumed to be zero, as mentioned in section 6.2.6, hence, is not included in Figure 6.3.

The highest portion of the wind farm's life cycle energy is embodied in turbine production and dismantling, accounting for nearly 43% of the wind farm's total embodied energy. Turbine transportation and site construction and fixed assets contribute significant amounts of energy, accounting for approximately 30% and 20% of the total embodied energy respectively. Wind farm operation and maintenance contribute only 7.38% of the total embodied energy. The direct energy of the wind farm corresponds to operation and maintenance, while indirect energy includes all the other phases of the life cycle.

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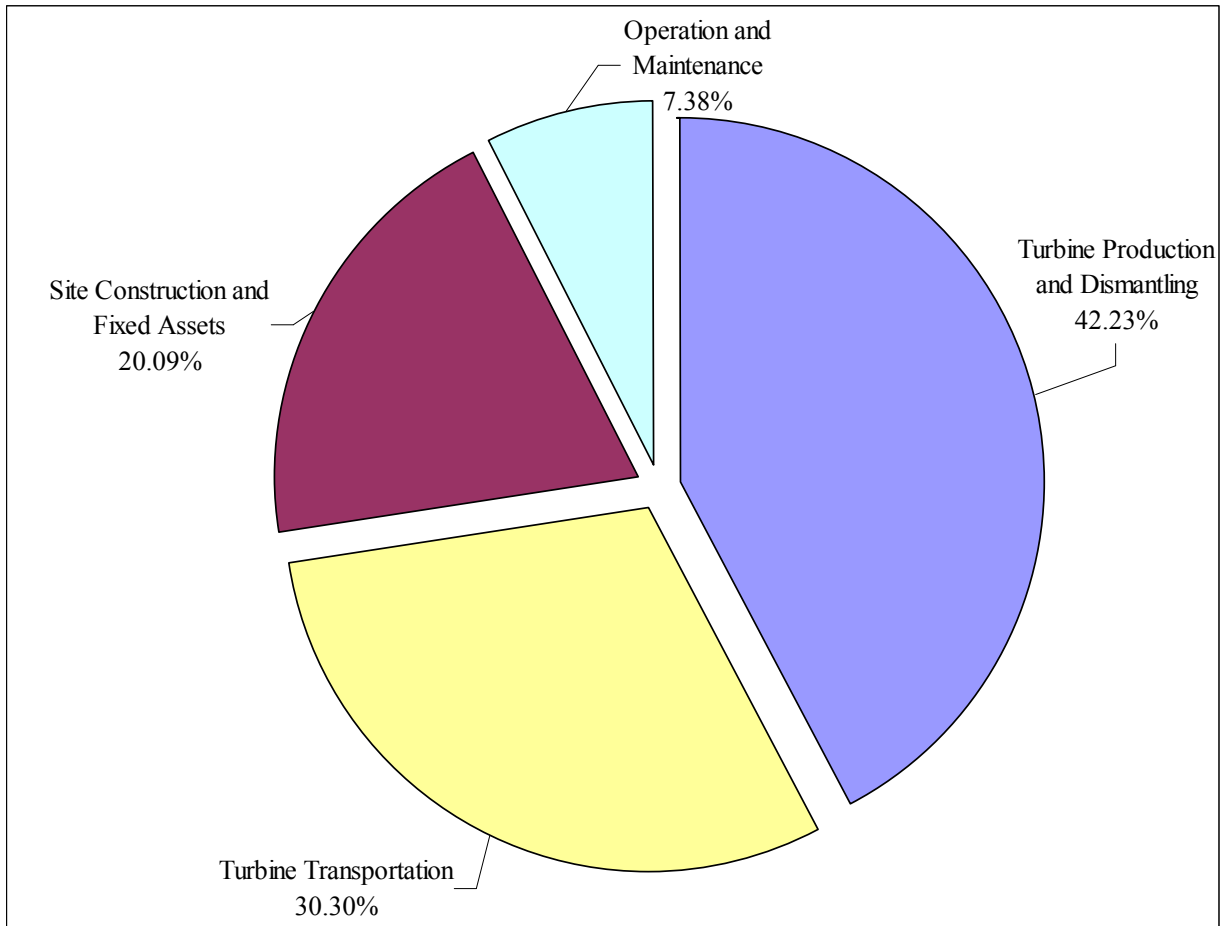
Figure 6.3. Distribution of Total Embodied Energy among the Various Phases of the Wind Farm's Lifecycle

The proportions of indirect energy embodied in the various phases of the wind farm's life cycle are illustrated in Figure 6.4. The turbine production and dismantling phase is broken down to turbine construction materials, and turbine manufacture and dismantling. The turbine construction materials account for about 46% of the indirect energy, while other turbine manufacturing processes and dismantling contribute only 0.05% of indirect energy. Figures 6.3 and 6.4 show that turbine production is the most energy intensive phase of a wind farm's life cycle. These figures also show that turbine transportation and site construction are also significant phases of the wind farm's life cycle.
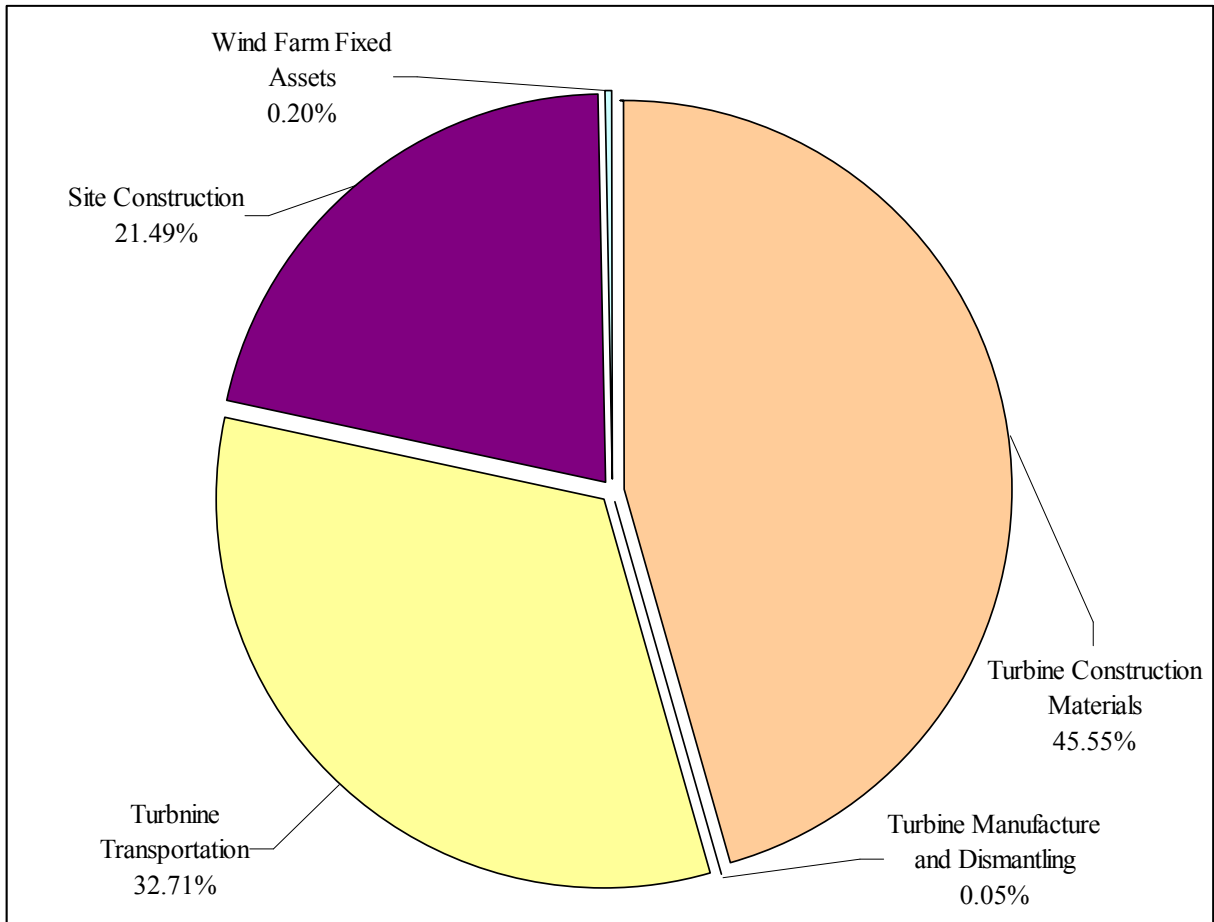
Figure 6.4. Distribution of Indirect Energy among the Various Phases of the Wind Farm's Lifecycle

The results of the embodied energy analysis of the White Hill wind farm concur with the analysis undertaken on an Italian wind farm in [48]. For the Italian wind farm, the turbine manufacturing and installation, which consists of wind turbine construction, building works and transport during manufacture, accounted for 92% of the total embodied energy. For the White Hill wind farm the proportion energy embodied in turbine manufacturing and installation, which consists of turbine production and dismantling, site construction and turbine transportation, accounts for 92.4% of the total embodied energy.

In the Italian wind farm, wind turbine construction, building works and transportation accounted for 61%, 32.5% and 6.5% of the energy embodied in turbine manufacturing and installation. For the White Hill wind farm turbine production and dismantling, site

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construction and turbine transportation accounts for 46%, 33% and 22% of the energy embodied in turbine manufacturing and installation, respectively. The proportion of energy embodied in transportation in wind turbine manufacturing and installation is significantly higher for the White Hill wind farm than the Italian wind farm. This is because the transport distance is significantly larger for the White Hill wind farm than the Italian wind farm, as the turbines for both the Italian wind farm and White Hill wind farm were shipped from European locations.

The ratios in Equations 3.1 and 3.2 for the White Hill wind farm are shown in Table 6.6. The numerical values used for calculating these ratios are given in Table WN1 in Appendix 3.1. These ratios are compared to the ratios of the other power plants analysed in this thesis in chapter 9.

Table 6.6. Ratios of the Wind Farm used for Plant Comparison

Description	Quantity	Unit	Calculation
Life Cycle Electrical Output	14,825,760	GJ	A
Life Cycle Electrical Output	4.118×10^9	kWh	B
Life Cycle Energy Input	701,190	GJ	C
LEPR	**21.1**		A/C
Life Cycle Energy Cost	**0.170**	**MJ/kWh**	C/B

The estimated LEPR of 21.1 is greater than one, because the life cycle electrical energy output is greater than the life cycle energy input to the wind farm. The life cycle energy cost of the White Hill wind farm is 170 kJ/kWh. This is much higher than that of the Te Apiti wind farm, which is estimated to be 70.2 kJ/kWh in [52]. This may be because the analysis in [52] is carried out over a normalised plant life of 100 years.

The life cycle energy cost of the White Hill wind farm normalised over a 100 year period is 44 kJ/kWh. To calculate this, it was assumed that the energy embodied in all phases of the life cycle, apart from plant operation and maintenance, remained constant. The embodied energy of operation and maintenance, and life cycle electrical output, were multiplied by a factor of 5, which corresponds to 100 years/20 years. It

can be concluded that if the wind turbines could operate for a longer period of time, then the life cycle efficiency of the plant would increase. The life cycle energy cost of the White Hill wind farm, however, is now much lower than that approximated for the Te Apiti wind farm in [52]. This may be due to the fact that White Hill wind farm was commissioned in 2007, which is 3 years later than the Te Apiti wind farm and hence has more energy efficient wind turbines. However, it should be noted the study in [52] might not have used the same methodology as explained above, when normalising the results to 100 years.

The results from a survey of energy and environmental performances of wind farms around the world, undertaken by Lenzen and Munskgaard [57], have shown that the energy intensity ranges from 0.014-1 kWh_{used}/kWh_{el}. The results from this study can be assumed as a reliable benchmark data of wind farm performances [48]. The energy intensity is defined as the ratio of embodied energy of the wind farm to that of the total life cycle electrical energy output, in [57]. For the White Hill wind farm, the energy intensity is calculated to be 0.047 kWh_{used}/kWh_{el}. This falls within the given range, hence further validating the analysis carried out in this thesis. The limitations of the embodied energy analysis undertaken on the White Hill wind farm are discussed in chapter 9.

7. Reservoir Hydro

The embodied energy analysis for a reservoir hydro power station is based on the Benmore power station. The Benmore power station is one of eight power stations of the Waitaki hydro scheme. It is owned and operated by Meridian Energy Ltd. The Benmore power station consists of six, 90 MW, 16 kV Francis turbine driven generators, making the total capacity 540 MW. It has the largest solid earth dam giving the largest man made lake, Lake Benmore, in New Zealand. The construction work for Benmore power station began in 1958 and the first electricity was generated in January 1965 [58], [59].

A reservoir hydro power station works by harnessing the energy from falling water held in the reservoir. The water held above the power station in a lake or reservoir is channelled through penstocks to the turbine. The turbine extracts the energy from the water turning it into mechanical energy that spins the generator rotor. This in turn generates electricity in the stator windings. For any given volume of water, the amount of energy that can be extracted is determined by the height from which the water falls from the reservoir. This is known as the head of the power station. After passing through the turbine, water exits through a draught tube, back to a river, canal or lake [58]. The physical structure of a reservoir hydro electric generation plant is shown Figure 7.1 [60].
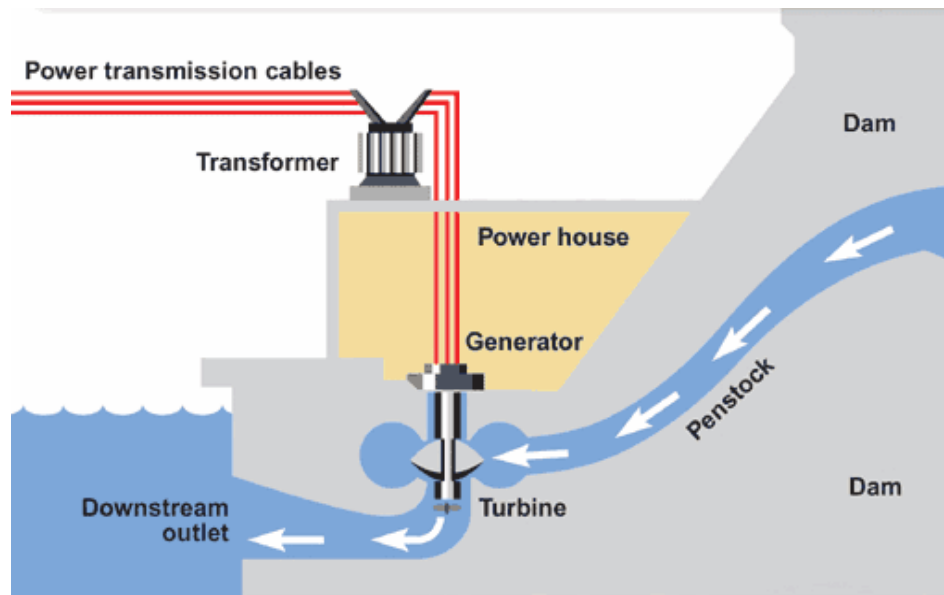
Figure 7.1. Physical Structure of a Reservoir Hydro Power Plant [60]

7.1 Embodied Energy Analysis for Reservoir Hydro Power Plant

The lifecycle of a reservoir hydro power station consists of preliminary investigations and river diversion, power plant construction and civil works, operation and maintenance, and plant decommissioning and land reclamation. For the Benmore power station, the power plant construction and civil works include the hydro dam, the spillway, the intake and penstocks, and the power house and switchyard. The life cycle of a hydro power station, with energy flows, is shown in Figure 7.2.

The framework for carrying out the analysis was based on Figure 7.2. The necessary data to carry out embodied energy analysis were extracted from construction and financial reports of the Benmore power station. Much of these are located in the Meridian Energy archives at the Twizel office. Detailed tables and calculations are presented in Appendix 4.1. The assumptions and explanations on calculations and the citations for sources of data are presented in Appendix 4.2. The references cited in Appendix 4.2 are recorded in Appendix 6.
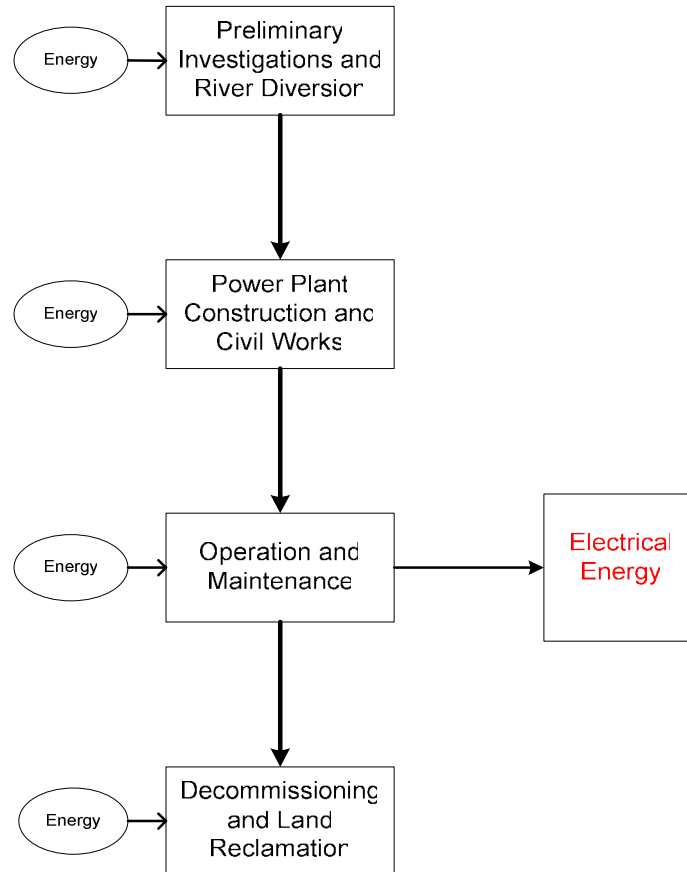
Figure 7.2. Lifecycle Energy Flow of a Hydro Power Plant

7.2 Methodology and Results

7.2.1 Electrical Energy Output

The estimated life cycle electrical energy output of the Benmore power station is presented in Table 7.1. It was estimated by multiplying the average annual energy output to the national system by the estimated life of the Benmore power station. The average annual electrical energy output of Benmore power station is 2,215 GWh [58]. The total life of the Benmore power station is assumed to be 200 years, as it has already been in operation for 45 years and Meridian Energy has predicted it will be in operation for more than another 145 years [61]. The total life cycle electrical output was estimated to be 1,595,000,000 GJ. Detailed calculations and explanations are presented in Table HD2 in Appendices 4.1 and 4.2.

Table 7.1. Useful Electrical Energy Output of Reservoir Hydro Power Plant

Description	Quantity	Unit
Annual Energy Output	2,215	GWh
Calendar Year Lifetime	200	Years
Total Life Cycle Electrical Output	443,000	GWh
Total Life Cycle Electrical Output	**1,595,000,000**	**GJ**

7.2.2 Preliminary Investigations and River Diversion

The embodied energy of the preliminary investigations was calculated using I/O analysis. The costs of preliminary investigations was in 1956 pounds [62]. This was converted to 2004 dollars using the CPI, which is the only price index available since 1956. The embodied energy of the river diversion was calculated using both PCA and I/O analysis. The energy embodied in construction materials used for the river diversion was calculated using PCA, and the energy embodied in other processes relating to river diversion was calculated using I/O analysis. Detailed calculations and explanations on calculations are presented in Tables HD3 and HD4 in Appendices 4.1 and 4.2 respectively.

Table 7.2. Energy Embodied in Preliminary Investigations and River Diversion

Description	Embodied Energy (GJ)
Preliminary Investigations	7,000
Construction Materials of River Diversion	186,000
Other Processes of River Diversion	89,000
Total Embodied Energy	**282,000**

7.2.3 Major Civil Works

The major civil works of the Benmore power station include the dam, spillway, intake and penstocks, and power house and switchyard. The embodied energy associated with the construction materials of the major civil works are presented in Table 7.3. It

was calculated using PCA. The construction materials of the dam, spillway, intake and penstocks were extracted from [62-64]. The only information available on the power house and switchyard construction materials was the amount of concrete. This amounted to 80,000 cu.yards which is approximately equivalent to 141,910 tonnes [64]. The quantities of other construction materials were estimated by multiplying the quantities of construction materials used in the NGCC power plant in [13] by a factor of 4.785, which corresponds to the ratio of the mass of concrete used in the construction of the power house and switchyard of Benmore power station to the mass of concrete used in the construction of the NGCC power plant in [13]. For detailed calculations and explanations on calculations, refer to Table HD5, HD7 and HD9 in Appendices 4.1 and 4.2, respectively.

Table 7.3. Energy Embodied in the Construction Materials of Major Civil Works

Material	Embodied Energy (GJ)	Percentage of Total (%)
Earth - Hydro Dam	21,807,000	94.77
Concrete - Spillway, Intake & Penstocks	489,000	2.12
Concrete - Power House & Switchyard	142,000	0.62
Concrete - Total	631,000	2.74
Steel - Spillway	10,000	0.04
Steel - Powerhouse & Switchyard	182,000	0.79
Steel - Total	192,000	0.83
Aluminium - Power House & Switchyard	1,000	0.01
Chromium - Power House & Switchyard	124	0.0005
Copper - Power House & Switchyard	2,000	0.008
Iron - Power House & Switchyard	8,000	0.04
Manganese - Power House & Switchyard	4,000	0.02
Molybdenum - Power House & Switchyard	300	0.001
Plastic - Power House & Switchyard	4,000	0.02
Silicon - Power House & Switchyard	3,000	0.01
Vanadium - Power House & Switchyard	9,000	0.04
Total	**22,660,000**	

Earth used in the construction of the hydro dam accounts for nearly 95% of the embodied energy of the construction materials of the major civil works in Benmore power station. Concrete and steel, which are the second and the third highest contributors, account for 2.74% and 0.83% respectively. The other construction materials only account for about 0.15% of the embodied energy.

The embodied energy associated with the construction of major civil works that are not related to construction materials were calculated using I/O analysis. This includes excavation and disposal of earth, dewatering, engineering and construction, administration, transportation of equipment and powerhouse and switchyard equipment. A summary of the calculations is presented in Table 7.4. The costs are extracted from [62] and are represented in terms of 1971 dollars. They were converted to 2004 dollars using the CPI, which was the only price index available in 1971. Detailed calculations and explanations on calculations are given in Tables HD6, HD8, HD10 and HD 11, in Appendices 4.1 and 4.2 respectively.

Table 7.4. Embodied Energy Associated with the Construction of Major Civil Works that are not related to Construction Materials

Description	Embodied Energy (GJ)
Hydro Dam Construction	296,000
Spillway, Intake and Penstocks Construction	358,000
Powerhouse and Switchyard Construction	250,000
Powerhouse and Switchyard Equipment	426,000

7.2.4 Ancillary Construction Works

The embodied energy of ancillary construction works include the permanent village and other establishments, and other miscellaneous expenses such as public relations, village maintenance and flood damage. The calculations are summarised in Table 7.5. These embodied energies were calculated using I/O analysis. The costs were extracted from [62] and converted to equivalent 2004 dollars using the CPI. Detailed

calculations and explanations on calculations are given in Tables HD13 and HD14 in Appendices 4.1 and 4.2, respectively.

Table 7.5. Embodied Energy Associated with Ancillary Construction Works

Description	Embodied Energy (GJ)
Permanent Village and Other Establishments	304,000
Other Miscellaneous Construction Works	86,000
Total Embodied Energy of Ancillary Construction Works	**390,000**

7.2.5 Plant Operation and Maintenance

The energy associated with the operation and maintenance of the Benmore power station was calculated using I/O analysis. The calculations are summarised in Table 7.6. The annual operation and maintenance costs of Benmore power station are approximately $1,000,000 (assumed to be in 2008 dollars) [61]. This was converted to equivalent 2004 dollars using the inputs PPI for electricity generation and supply.

Currently, after nearly 50 years of operation, Benmore power station is undergoing major refurbishing which will cost approximately $12,000,000 (assumed to be in 2008 dollars) per annum over 5 years. A repeat of this type of capital investment is not expected to be made for another 50 years [61]. Therefore, taking into consideration that the assumed lifetime of the Benmore power station is 200 years, it was estimated that the annual cost of refurbishing is $1,200,00 (2008 dollars). This was converted to 2004 dollars using the CGPI for plant machinery and equipment. Detailed calculations and explanations on calculations are given in Table HD12 in Appendices 4.1 and 4.2 respectively.

Table 7.6. Energy Embodied in Power Plant Operation and Maintenance

Description	Embodied Energy (GJ)
Lifetime Operation and Maintenance	85,000
Lifetime Refurbishing and Replacement	512,000
Total Lifetime Operation and Maintenance	**597,000**

7.2.6 Plant Decommissioning and Land Reclamation

The embodied energies associated with plant decommissioning and land reclamation were calculated using I/O analysis. They are presented in Table 7.7. The cost of the dam, spillway, intake and penstocks decommissioning/demolition was estimated to be 10% of the total construction costs. The powerhouse and switchyard decommissioning was estimated to be 10% of the total equipment costs.

The building demolition costs were extracted from [13] and adjusted for Benmore power station by multiplying by the factor of 4.785, which corresponds to the mass of concrete used in the construction of the power house and switchyard of the Benmore power station, to the mass of concrete used in the construction of the NGCC power plant in [13]. The dam, spillway, intake and penstocks decommissioning costs were estimated to be equivalent to 10% of their total construction costs. The cost of land reclamation was estimated to be 10% of the total decommissioning and demolition costs. Detailed calculations and explanations on calculations are given in Tables HD15 and HD16 in Appendices 4.1 and 4.2 respectively.

Table 7.7. Energy Embodied in Plant Decommissioning and Land Reclamation

Description	Embodied Energy (GJ)
Plant Decommissioning	112,000
Land Reclamation	16,000

7.3 Discussion

A graphical representation of the proportions of energy embodied in the various phases of the lifecycle of Benmore power station is shown in Figure 7.3. The lifecycle of the Benmore power station was divided into five sectors. They are preliminary investigations and river diversion, major civil works, ancillary construction works, plant operation and maintenance, and plant decommissioning and land reclamation. The direct energy of the Benmore power station is the energy embodied in plant operation and maintenance, while the indirect energy is comprised of all the other sectors illustrated in Figure 7.3.
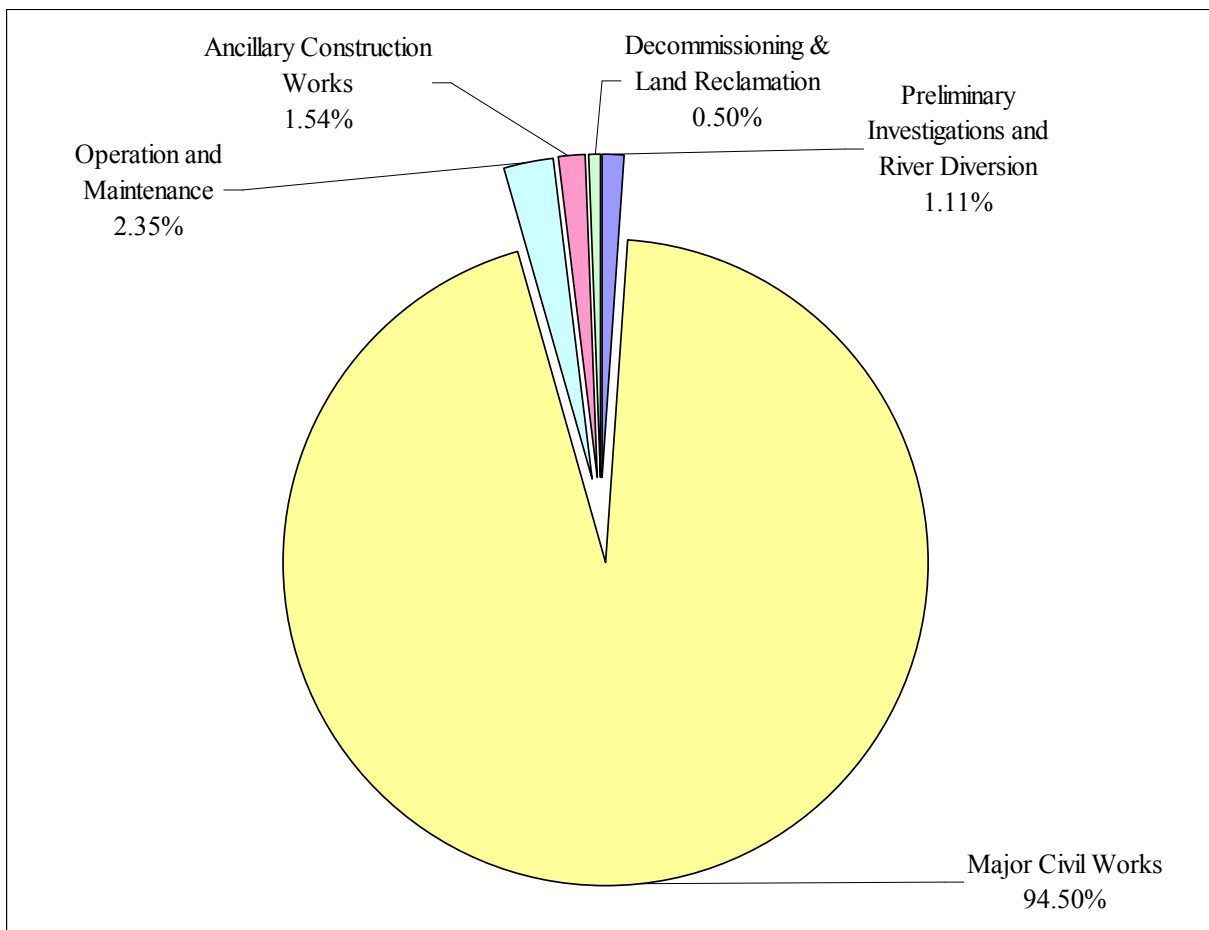
Figure 7.3. Distribution of Total Embodied Energy among the Various Phases of the Reservoir Hydro Power Plant's Lifecycle

The major civil works, which include the dam, spillway, intake and penstocks, and the power house and switchyard, accounts for 94.50% of the total embodied energy of the power plant. The total embodied energy in construction works, which includes major civil works and ancillary construction works, accounts for about 96% of the total embodied energy of the power station. Therefore, the most energy intensive phase of the Benmore power station's life cycle is the power plant construction and civil works.

The direct embodied energy accounts for about 2.5% of the total embodied energy of the Benmore power station, while the indirect energy accounts for more than 97%. Major civil works account for nearly 97% of the indirect embodied energy of the Benmore power station. The total construction works, which includes major civil works and ancillary construction works, accounts for more than 98% of the indirect embodied energy. The life cycle phases of preliminary investigations and river diversion, and plant decommissioning and land reclamation, account for only about 1.7% of the indirect embodied energy of the power plant. Hence, the indirect energy input to the Benmore power station is significantly higher than the direct energy input, in which the energy embodied in the major civil works takes a prominent place.

Figure 7.4 illustrates the distribution of energy embodied in construction works over the dam, spillway, intake and penstocks, powerhouse and switchyard, and ancillary construction works. The powerhouse and switchyard construction also includes equipment in the powerhouse and switchyard. The construction of the hydro dam embodies about 91% of the energy embodied in the construction works of the Benmore power station. Figures 7.3 and 7.4 show that the construction of the dam is the most energy intensive process for a reservoir hydro power station.
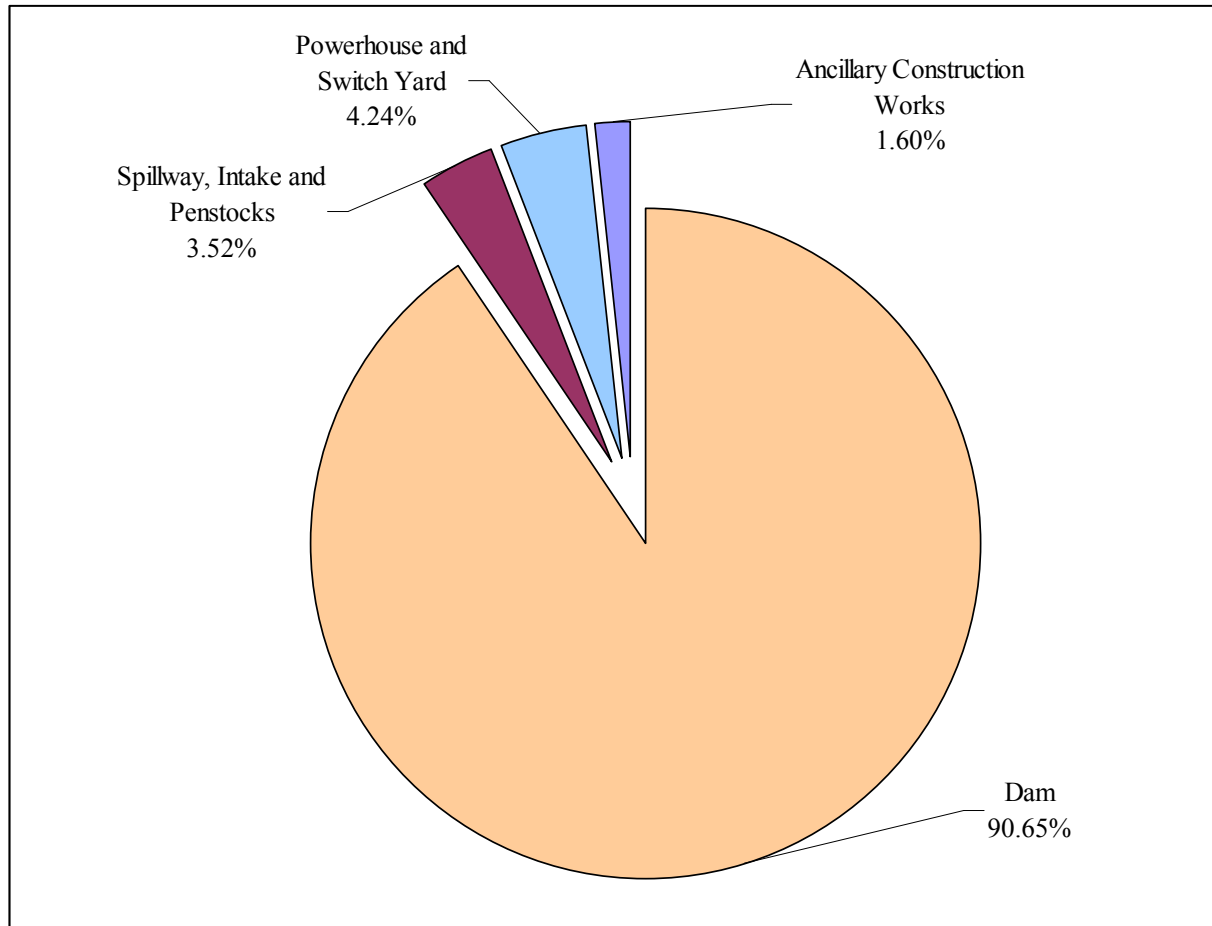
Figure 7.4. Distribution of Embodied Energy among the Various Phases of the Reservoir Hydro Power Plant's Construction Works

The ratios in Equations 3.1 and 3.2 for the Benmore power station are shown in Table 7.9. The numerical values used for calculating these ratios are given in Table HD1 in Appendix 4.1. The ratios in Table 7.9 are compared with the corresponding ratios of the other power plants studied in this thesis, in chapter 9. The estimated LEPR is 62.8, which is much higher than unity. This shows that the lifecycle electrical energy output of the power station is significantly greater than the lifecycle energy input to the power plant.

Table 7.8. Ratios of the Reservoir Hydro Power Station used for Plant Comparison

Description	Quantity	Unit	Calculation
Life Cycle Electrical Output	1,594,800,000	GJ	A
Life Cycle Electrical Output	4.430×10^{11}	kWh	B
Life Cycle Energy Input	25,388,027	GJ	C
LEPR	**62.8**		**A/C**
Life Cycle Energy Cost	**0.057**	**MJ/kWh**	**C/B**

The lifecycle energy cost of the Benmore power station is 57 kJ/kWh. This is approximately the lifecycle energy cost of the Clyde power station, which was estimated to be 55 kJ/kWh in [52]. The lifecycle energy cost for Clyde dam stated in [52], however, is for an assumed life of 100 years. For the Benmore power station, the lifecycle energy cost over 100 years was estimated to be 113kJ/kWh. To estimate this, the lifecycle electrical energy output, plant operation and maintenance embodied energy was multiplied by a factor of 0.5, while the embodied energies in the other phases of the life cycle were assumed to remain constant. The lifecycle energy cost of the Benmore power station for an assumed life of 100 years is much greater than the lifecycle energy cost estimated for Clyde power station in [52]. This may be due to the much larger civil works required to build the dam at Benmore power station.

8. Run of River Hydro

The embodied energy analysis for run of river hydro generation is based on the Aratiatia power station, owned and operated by Mighty River Power Ltd. The Aratiatia power station is one of eight power stations in the Waikato hydro scheme. It contains three 31.3 MW vertical Francis turbines and three 30MW generators. The turbines never achieve the designed total output capacity of 90 MW. The generators at Aratiatia were commissioned in 1964 [65],[66].

Run of river hydro schemes take water directly from the river to the powerhouse where the turbines are installed. They do not have dams installed but usually involve some sort of barrage [35]. At Aratiaita power plant, water from the Waikato River passes through a tunnel into a surge tank. The surge tanks ensure a steady flow of water to the turbines by diverting excess flow into the surge chambers and releasing it slowly when required. From the surge tank, water is taken to the turbines at the power house by three penstocks, where electricity is produced. The physical structure of the Aratiatia power station is illustrated in Figure 8.1 [67].
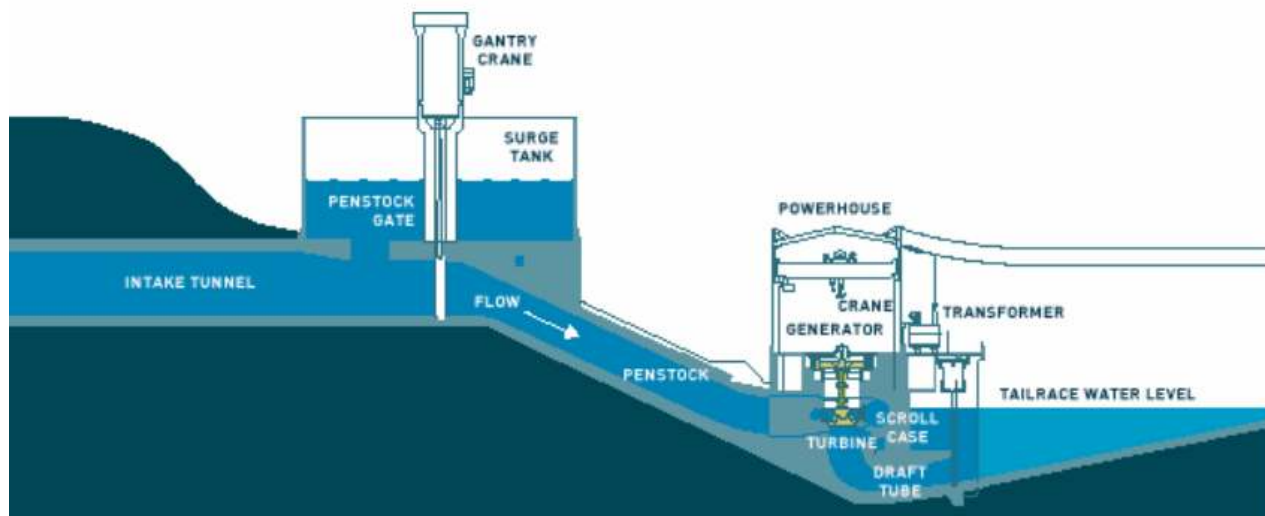
Figure 8.1. Physical Structure of Aratiatia Power Station [67]

8.1 Embodied Energy Analysis for Run of River Hydro Power Plant

The lifecycle of a run of river hydro power plant is equivalent to that of a reservoir hydro power plant. It consists of preliminary investigations and river diversion, power plant construction and civil works, operation and maintenance, and decommissioning and land reclamation. For the Aratiatia power station, power plant construction and civil works include the intake tunnel, surge tank, spillway, penstocks, powerhouse and switchyard, and the Taupo gates. The lifecycle of a hydro power station, with energy flows, is shown in Figure 7.2.The framework for undertaking embodied energy analysis on a run of river hydro power station was based on this figure.

The necessary data to carry out embodied energy analysis on Aratiatia power station were not available from Mighty River Power. Hence, most of the data were estimated from the data of Benmore power station, for which embodied energy analysis was carried out in chapter 7. Detailed tables and calculations are presented in Appendix 5.1. The assumptions, explanations on calculations, and the citations for sources of data are presented in Appendix 5.2. The references cited in Appendix 5.2 are recorded in Appendix 6.

8.2 Methodology and Results

8.2.1 Electrical Energy Output

The estimated lifecycle electrical energy output of Aratiatia power station is presented in Table 8.1. This was estimated by multiplying the annual electrical energy output to the national grid by the estimated life of the Aratiatia power station. The average annual electrical energy output of the Aratiatia power station to the national grid is 270 GWh [66]. The useful life of Aratiatia power station was not available, hence was estimated to be equal to that of the Benmore power station. The total life cycle electrical output was estimated to be 145,800,000 GJ. Detailed calculations and explanations on calculations are presented in Table HR2 in Appendices 5.1 and 5.2.

Table 8.1. Useful Electrical Energy Output of Run of River Hydro Power Plant

Description	Quantity	Unit
Annual Energy Output	270	GWh
Calendar Year Lifetime	200	Years
Total Life Cycle Electrical Output	54,000	GWh
Total Life Cycle Electrical Output	**194,400,000**	**GJ**

8.2.2 Preliminary Investigations and River Diversion

The data required in order calculate the embodied energy of the preliminary investigations and river diversion for Aratiatia power station was not available. Hence, the quantities of materials required and the monetary costs were estimated to be equivalent to the corresponding costs of Benmore power station. The embodied energy of the preliminary investigations was calculated using I/O analysis, while the embodied energy of the river diversion was calculated using a combination of both I/O analysis and PCA. The energy embodied in the preliminary investigations and river diversion are summarised in Table 8.2. Detailed calculations and explanations on calculations are presented in Tables HR3 and HR4 in Appendices 5.1 and 5.2.

Table 8.2. Energy Embodied in Preliminary Investigations and River Diversion

Description	Embodied Energy (GJ)
Preliminary Investigations	7,000
Construction Materials of River Diversion	186,000
Other Processes of River Diversion	89,000
Total Embodied Energy	**282,000**

8.2.3 Power Plant Construction and Civil Works

The embodied energy associated with the power plant construction and civil works of the Aratiatia power station are summarised in Table 8.3.   This includes the powerhouse and switchyard, and the earthworks and hydraulics. The earthworks and

hydraulics include the intake tunnel, surge tank, spillway and penstocks. The embodied energy of the construction materials of the hydraulics were calculated using PCA. The construction materials and the corresponding quantities for the tunnel, spillway and penstocks at Aratiatia power station were not available. Hence, they were estimated to be equivalent to the construction materials of intake, spillway and penstocks at Benmore power station, respectively. The construction materials of the surge tank were estimated from its dimensions given in [65]. Detailed calculations and explanations on calculations are given in Table HR5 in Appendices 5.1 and 5.2.

The energy associated with the construction of earth works and hydraulics that are not related to construction materials was calculated using I/O analysis. This includes excavation and disposal of earth, dewatering, engineering and construction, administration and transportation equipment. The costs specifically associated with these for the Aratiatia power station were not available. Therefore the construction costs of Aratiatia power station associated with construction of the intake tunnel, spillway and penstocks, which are not related to construction materials, were estimated to be equivalent to those for the intake, spillway and penstocks of the Benmore power station. The non material related construction costs of the surge tank were assumed to be negligible, because the embodied energy of the construction materials of the surge tank is significantly smaller than the embodied energy of the construction materials of other earth works and hydraulics. Detailed calculations and explanations on calculations are given in Table HR6 in Appendices 5.1 and 5.2.

The embodied energy of the powerhouse and switchyard was calculated using both I/O analysis and PCA. PCA was used to calculate the energy embodied in the construction materials of the powerhouse and switchyard. The energy embodied in the construction processes of the powerhouse and switchyard, which are not related to construction materials, and the energy embodied in powerhouse and switchyard equipment, were calculated using I/O analysis. The powerhouse and switchyard, construction materials and quantities, and construction costs for Aratiatia power station were approximated to be equal to that of the Benmore power station. The powerhouse and switchyard equipment costs at the Aratiatia power station were estimated by multiplying the Benmore powerhouse and switchyard equipment costs, by a factor of 0.167. This corresponds to the ratio of the power rating of Aratiatia

power station to that of the Benmore power station, which are 90 MW and 540 MW, respectively. Detailed calculations and explanations on calculations are given in Tables HR7-HR9 in Appendices 5.1 and 5.2.

Table 8.3. Energy Embodied in Power Plant Construction and Civil Works

Description	Embodied Energy (GJ)
Earth Works and Hydraulics Construction	858,000
Powerhouse and Switchyard	607,000
Powerhouse and Switchyard Equipment	71,000

8.2.4 Taupo Gates

The embodied energy of the Taupo gates associated with Aratiatia power station is given in Table 8.4. Lake Taupo is the source for the Waikato River, providing natural flows of water which are tapped to generate electricity in the Waikato Hydro Scheme. Resource management requires the lake to be kept above a minimum set level, with only one percent of its volume available for electricity generation. The Taupo gates provide some controllability over the water flowing down the Waikato River [68]. Data on the Taupo gates building materials and costs of Taupo gates construction were not available. Therefore, when calculating the embodied energy of the Taupo gates, the construction materials and costs were assumed to be equivalent to the construction of the spillway of Benmore power station. To estimate the embodied energy of the Taupo gates associated with Aratiatia power station, the total embodied energy of the Taupo gates was multiplied by a factor of 0.0587. This corresponds to the ratio of the average annual electrical energy output of Aratiatia power station to that of the Waikato Hydro Scheme, which are 270 GWh and 4601 GWh, respectively [66]. Detailed calculations and explanations on calculations are given in Tables HR11-HR13 in Appendices 5.1 and 5.2.

Table 8.4. Embodied Energy Associated with Taupo Gates

Description	Quantity	Unit	Calculation
Annual Electrical Energy Output Waikato Hydro Scheme	4,601	GWh	A
Annual Electrical Energy Output Aratiatia	270	GWh	B
Multiplication Factor	0.0587		C = B/A
Total Emboded Energy Taupo Gates	509,000	GJ	D
Taupo Gates Embodied Energy Associated with Aratiatia	**30,000**	**GJ**	**E = C*D**

8.2.5 Plant Operation and Maintenance

The energy embodied in power plant operation and maintenance is presented in Table 8.5. It was calculated using I/O analysis. The operation and maintenance costs of Aratiatia power station were not available. They were estimated by multiplying the operation and maintenance costs of the Benmore power station by the factor of 0.167, corresponding to the ratio of the power rating of Aratiatia power station to that of the Benmore power station, which are 90 MW and 540 MW, respectively. Detailed calculations and explanations on calculations are given in Table HR10 in Appendices 5.1 and 5.2.

Table 8.5. Energy Embodied in Power Plant Operation and Maintenance

Description	Embodied Energy (GJ)
Lifetime Operation and Maintenance	11,000
Lifetime Refurbishing and Replacement	64,000
Total Lifetime Operation and Maintenance	**75,000**

8.2.6 Plant Decommissioning and Land Reclamation

The energy embodied in plant decommissioning and land reclamation are shown in Table 8.6. They were calculated using I/O analysis. The costs of earth works and hydraulics, and powerhouse and switchyard decommissioning were estimated to be 10% of the total, earthworks and construction costs and powerhouse and switchyard equipment costs, respectively. The cost of building demolition and land reclamation were assumed to be equivalent to that of the Benmore power station. Detailed calculations and explanations on calculations are given in Tables HR14 and HR15 in Appendices 5.1 and 5.2.

Table 8.6. Energy Embodied in Plant Decommissioning and Land Reclamation

Description	Embodied Energy (GJ)
Plant Decommissioning	43,000
Land Reclamation	16,000

8.3 Discussion

A graphical representation of the proportions of energy embodied in the various phases of the lifecycle of Aratiatia power station is shown in Figure 8.2. The life cycle is divided into five phases, namely, preliminary investigations and river diversion, plant construction and civil works, operation and maintenance, Taupo gates construction, and decommissioning and land reclamation. The direct embodied energy of the Aratiatia power station is plant operation and maintenance, while the other phases of the plant life cycle account for the indirect embodied energy.
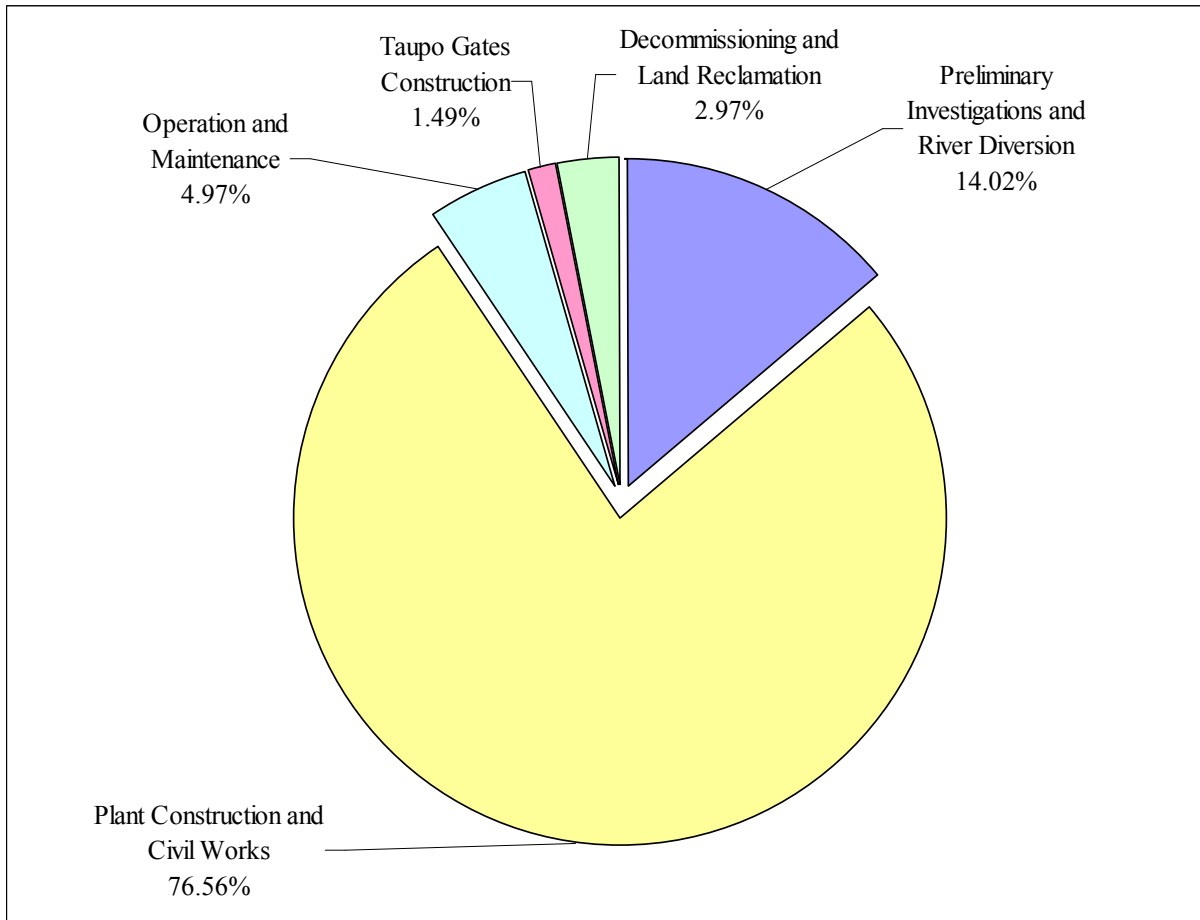
Figure 8.2. Distribution of Total Embodied Energy among the Various Phases of the Run of River Hydro Power Plant's Lifecycle

The direct embodied energy accounts about 5% of the total embodied energy while the indirect embodied energy accounts for more than 95% of the total embodied energy of the plant. Therefore, in a run of river hydro power plant the indirect embodied energy is significantly higher than the direct embodied energy. The plant construction and civil works, which include the earthworks and hydraulics, and powerhouse and switch yard, contributes nearly 77% of the total embodied energy of the power plant. Hence, the most energy intensive phase of the life cycle of a run of river hydro power plant is the power plant construction and civil works. Preliminary investigations and river diversion is also a significant phase of the lifecycle, as it constitutes about 14% of the total embodied energy of the power plant.

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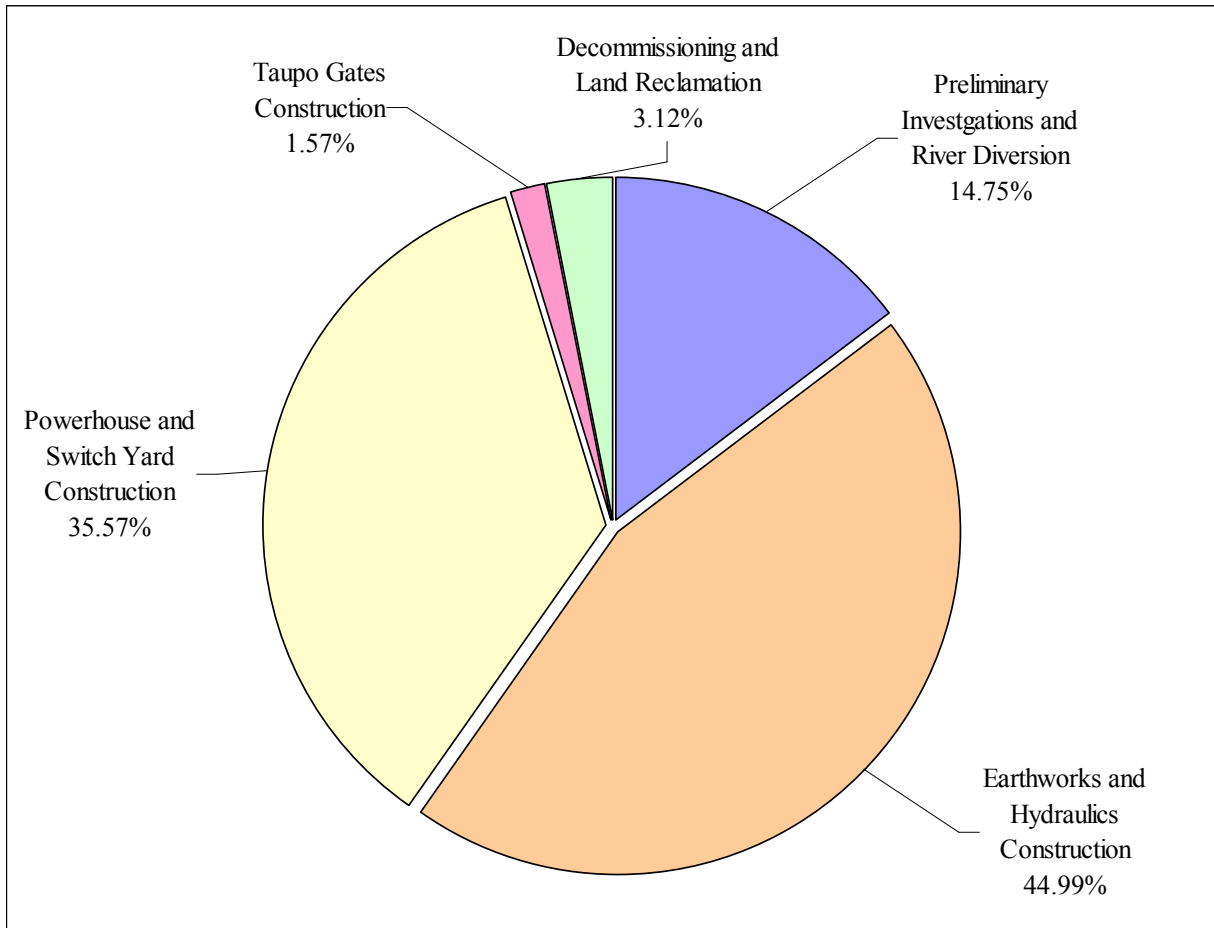
Figure 8.3. Distribution of Indirect Energy among the Various Phases of the Run of River Hydro Plant's Lifecycle

Figure 8.3 illustrates how the indirect embodied energy is distributed amongst the various phases of the lifecycle of the run of river hydro power plant. The earthworks and hydraulics account for about 45%, while powerhouse and switchyard construction accounts for nearly 36%, of the indirect embodied energy of the plant. Preliminary investigations and river diversion contributes about 15% of the indirect embodied energy. This further shows that the plant construction and civil works is the most energy intensive phase of the life cycle of a run of river hydro plant. This also shows that both the powerhouse and switchyard construction, and earthworks and hydraulics construction, are significant processes of power plant construction and civil works.

The ratios given in Equations 3.1 and 3.2 for the Aratiatia power station are shown in Table 8.7. The numerical values used for calculating these ratios are given in Table HR1 in Appendix 5.1. The ratios in Table 8.7 are compared with the corresponding ratios of the other power plants studied in this thesis, in chapter 9. The estimated LEPR is 96.9. This shows that the lifecycle electrical energy output is nearly 100 times as much as the lifecycle energy input to the power plant.

Table 8.7. Ratios of the Reservoir Hydro Power Plant used for Plant Comparison

Description	Quantity	Unit	Calculation
Life Cycle Electrical Output	194,400,000	GJ	A
Life Cycle Electrical Output	5.400×10^{10}	kWh	B
Life Cycle Energy Input	2,006,464	GJ	C
LEPR	**96.9**		**A/C**
Life Cycle Energy Cost	**0.037**	**MJ/kWh**	**C/B**

The lifecycle energy cost of the Aratiaita power station is 37 kJ/kWh over a useful life of 200 years. The lifecycle energy cost over a useful life of 100 years is 72 kJ/kWh. This is higher than the Clyde power station which has a lifecycle energy cost of 55 kJ/kWh over a useful life of 100 years [52]. Hence, this shows that the lifecycle energy input to the Aratiatia power station may have been over estimated in this thesis, because it would be expected that constructing the reservoir at Clyde would mean it's life cycle efficiency is smaller than that of the Aratiatia power station. However, it should be noted that the Clyde power station operates as a run of river hydro power plant as well as a reservoir hydro power plant and that the dam at Clyde power station is significantly smaller in size than that of Benmore power station. This means, if the lifecycle of the Aratiatia power station was, in fact, over estimated it would have been by a very small margin.

The embodied energy of much of the earthworks and hydraulics of Aratiatia power station were estimated to be equivalent to the major civil works of the Benmore power station. The scale of construction of the Benmore power station would have been significantly greater than that of Aratiatia power station, which accounts for the possible over estimation of the lifecycle energy input to the Aratiatia power station.

9. Discussion

The results from the embodied energy analysis of the different types of generation stations are compared and discussed in this section. The limitations in the analysis carried out for the different generation methods and the limitations in embodied energy analysis, or lifecycle energy analysis, as a means of evaluating the environmental impacts of the electricity generation industry are also discussed in this section. In order to compare the embodied energies of the various lifecycle phases among the different generation methods, the lifecycle is divided into three main sections. They are exploration and plant construction, plant operation and maintenance, and plant decommissioning and land reclamation.

9.1 Exploration and Plant Construction

The embodied energy normalised as the per unit of lifecycle electrical energy output, the functional unit, and the proportions of the total embodied energy in the exploration and plant construction phase of the lifecycle, for the different types of generation stations are shown in Figures 9.1 and 9.2, respectively. For the NGCC and NGOC power plants, exploration and plant construction consist of power plant construction and equipment, natural gas transmission pipeline construction, and compressor station construction and equipment. For the wind farm, exploration and plant construction consists of wind turbine construction and transportation, site construction and wind farm fixed assets. For the hydro power plants, exploration and plant construction consists of preliminary investigations and river diversion, major civil works and plant construction, power plant equipment, and other construction works. Other construction works for the reservoir hydro power plant are the permanent village and other miscellaneous expenses such as public relations, village maintenance and flood control. For the run of river hydro power station, other construction works includes the construction of Taupo gates.

Figure 9.1. Normalised Embodied Energies of Exploration and Plant Construction for the Different Generation Methodologies
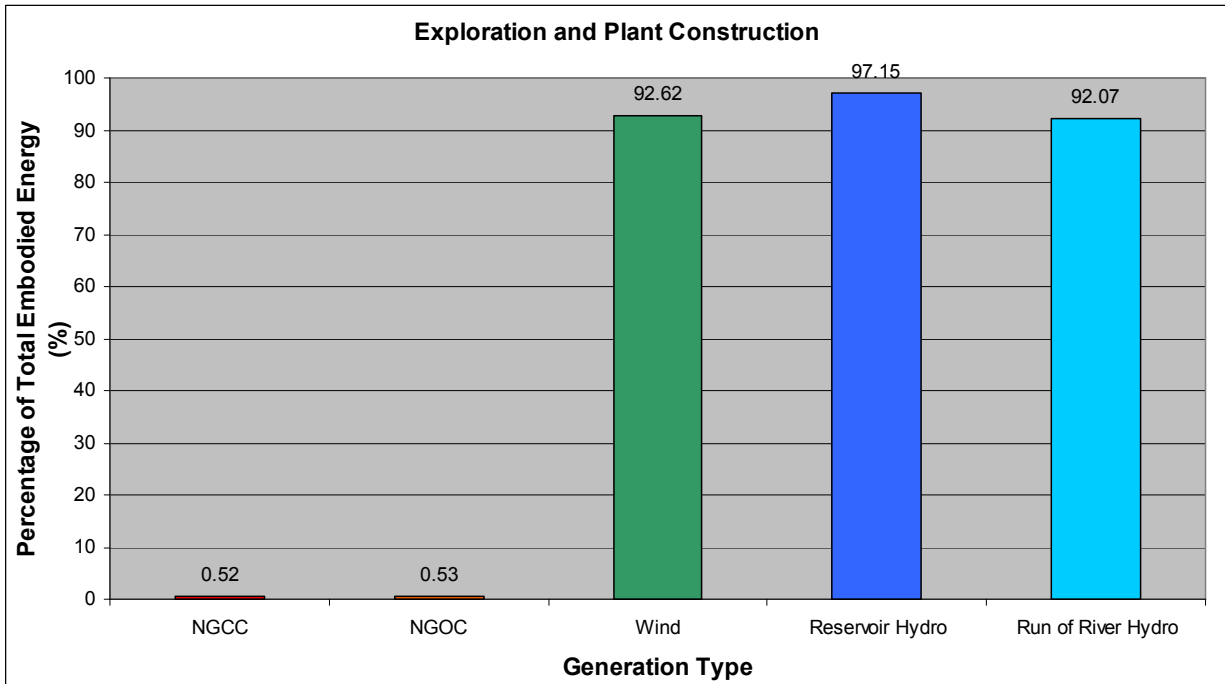
Figure 9.2. Proportion of Total Embodied Energy in Exploration and Plant Construction for the Different Generation Methodologies

The wind farm has the highest amount of normalised energy embodied in exploration and plant construction, being 158 kJ/kWh, followed by that for reservoir hydro and NGOC power plants at 56 kJ/kWh and 54 kJ/kWh respectively. The significant difference between the normalised exploration and construction embodied energy of the wind farm to the other power plants can be attributed to the lower power rating and smaller life of the wind farm when compared to the high measures of energy embodied in constructing and transporting the wind turbines. The normalised exploration and plant construction embodied energy of the reservoir hydro power plant is ranked second. It is significantly lower than the wind farm because of it's longer useful life and the higher rating of the power plant. However, the normalised exploration and plant construction embodied energy of the reservoir hydro power plant was larger than the non renewable power plants due to the large quantity of energy embodied in the construction of the hydro dam. The normalised exploration and plant construction embodied energy of the NGCC power plant is lower than that of the NGOC power plant because of the higher thermal efficiency of the NGCC power plant. The run of river hydro power plant has the lowest normalised exploration and plant construction embodied energy, even though its power rating is much lower than the reservoir hydro and the NGCC power plants. This is because it's useful life is equivalent to that of the reservoir hydro power plant, and because a major energy expenditure is avoided by not constructing a hydro dam.

The energy embodied in exploration and plant construction accounted for 92.62% of the total embodied energy, for wind generation. For the hydro power stations, the proportions were very high at 97.15% and 92.07% for the reservoir and run of river hydro power stations, respectively. For the NGCC and NGOC power plants the proportion are 0.52% and 0.53%. Therefore, exploration and construction accounts for a large portion of the total embodied energy in renewable generation, whereas in non renewable generation it is insignificant.

9.2 Plant Operation and Maintenance

The embodied energy normalised per unit of lifecycle electrical output and the proportions of the total embodied energy, in plant operation and maintenance, for the different types of generation stations, are shown in Figures 9.3 and 9.4, respectively. For the NGCC and NGOC power plants, plant operation and maintenance consists of natural gas exploration and production losses, natural gas transmission losses and transmission system operation, fuel input to the plant and power plant operation and maintenance. For the wind and hydro power stations, plant operation and maintenance only includes the embodied energy of plant operation and maintenance.
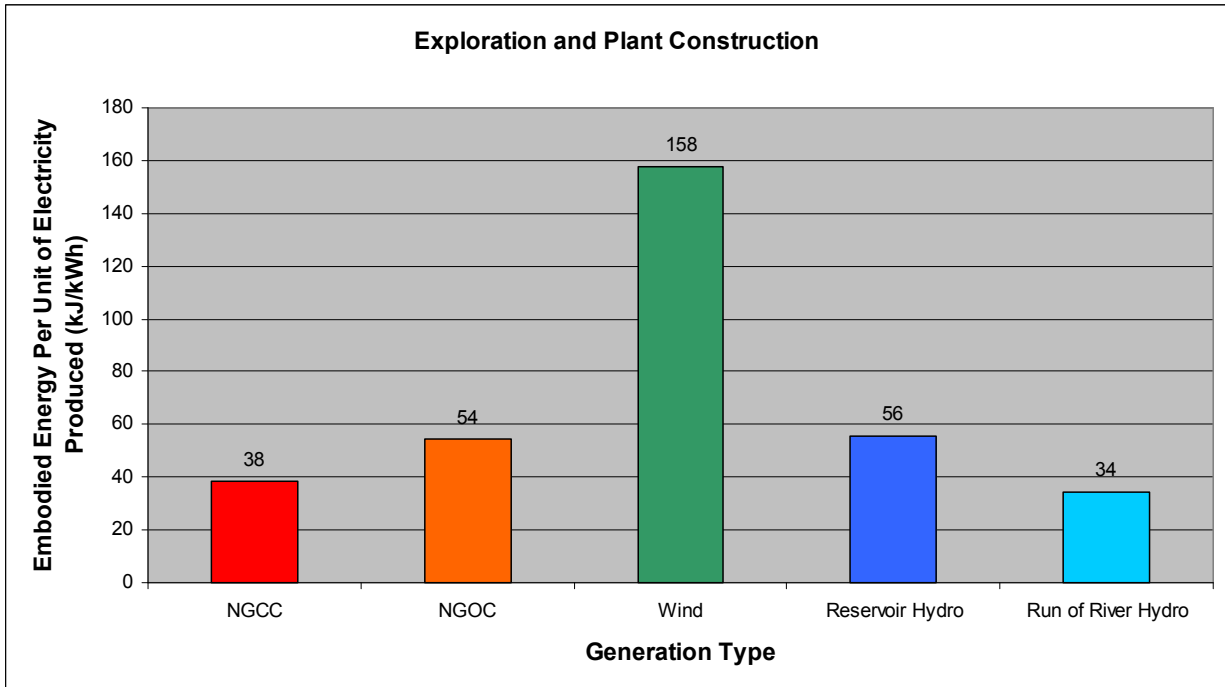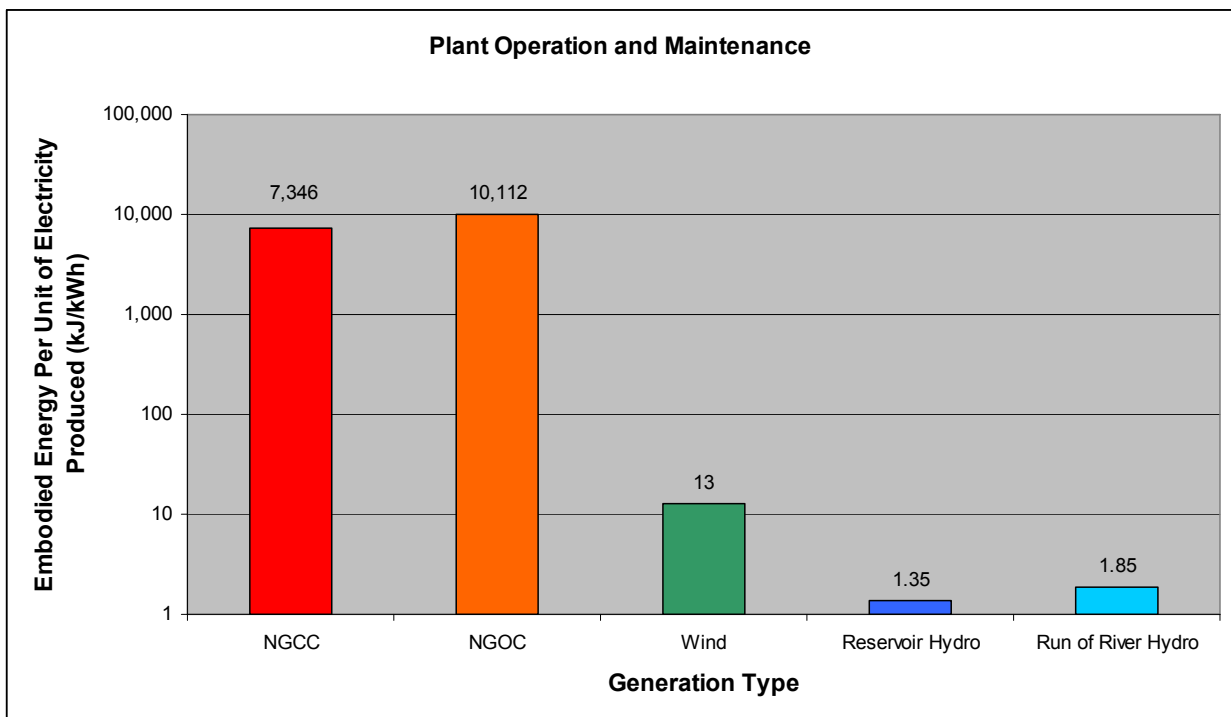

Figure 9.3. Normalised Embodied Energies of Plant Operation and Maintenance for the Different Generation Methodologies
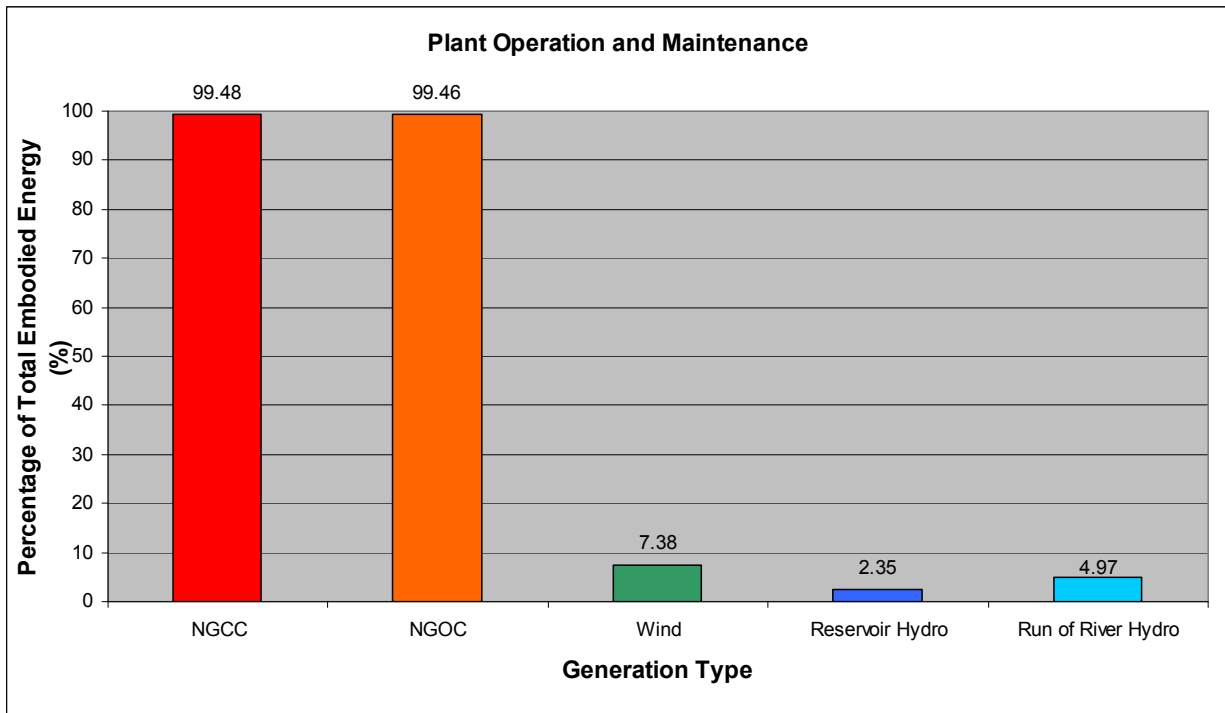
Figure 9.4. Proportion of Total Embodied Energy in Plant Operation and Maintenance for the Different Generation Methodologies

The NGOC power plant has the highest normalised plant operation and maintenance embodied energy of 10,112 kJ/kWh, followed by that for the NGCC power plant at 7,346 kJ/kWh. The normalised plant operation and maintenance embodied energy of the NGOC plant is higher than that of the NGCC plant, because the NGOC power plant has a lower thermal efficiency than the NGCC plant. The normalised plant operation and maintenance embodied energy for the wind farm, at 13 kJ/kWh, followed the non-renewable power plants. It is notably higher than that of the hydro power plants due to the lower power rating and shorter life of the wind farm, compared to the hydro power plants. This could also be due to the high maintenance cost of the wind turbines due to their low reliability.

Plant operation and maintenance accounted for nearly 99.5% of the total embodied energy for both the non renewable plants. For the renewable power plants, however, plant operation and maintenance accounted for very small proportions of the plants' total embodied energy, the highest being 7.38% for the wind farm. The normalised plant operation and maintenance embodied energy and the proportion of total embodied energy in plant operation and maintenance are much larger in non-

renewable power plants due to the large measures of energy embodied in their fuel input.

9.3. Plant Decommissioning and Land Reclamation

The embodied energy normalised per unit of lifecycle electrical output and the proportions of the total embodied energy in plant decommissioning and land reclamation, for the different types of generation stations, are shown in Figures 9.5 and 9.6, respectively. Both the normalised embodied energy and the proportion of total embodied energy in plant decommissioning and land reclamation were larger for the hydro power stations. This is because of the larger scale of construction involved in the hydro plants, which means that decommissioning would require more energy than the other power plants.
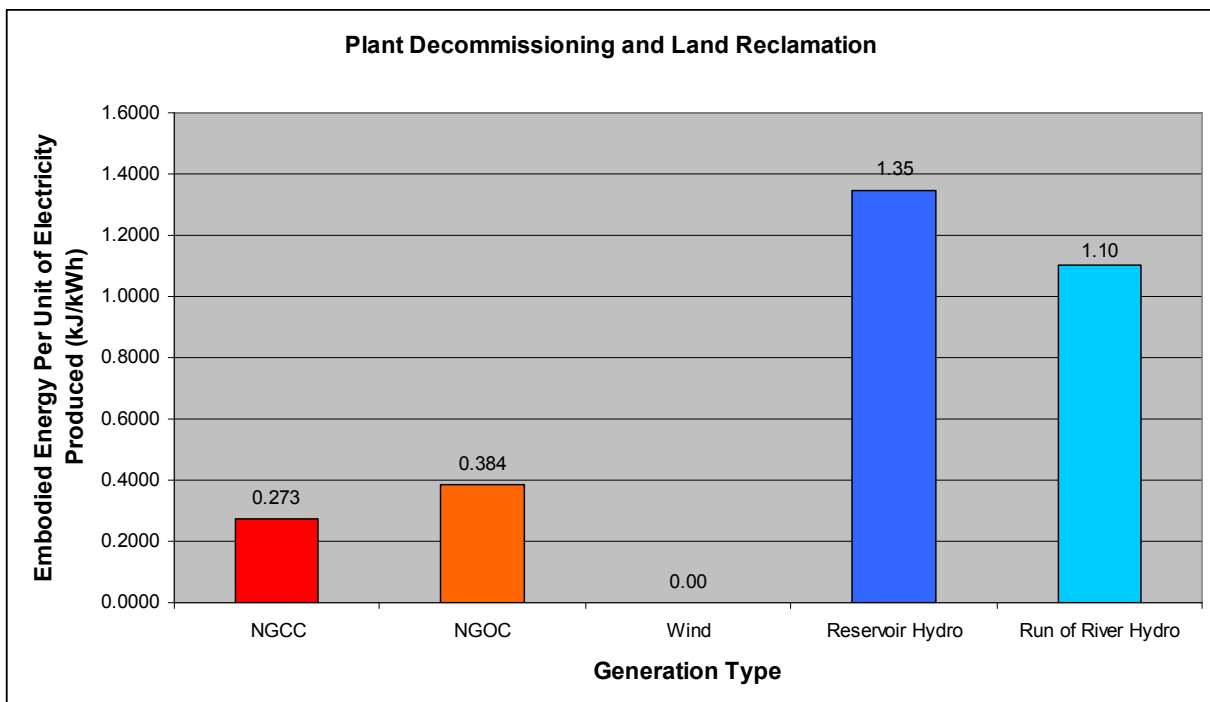
Figure 9.5. Normalised Embodied Energies of Plant Decommissioning and Land Reclamation for the Different Generation Methodologies
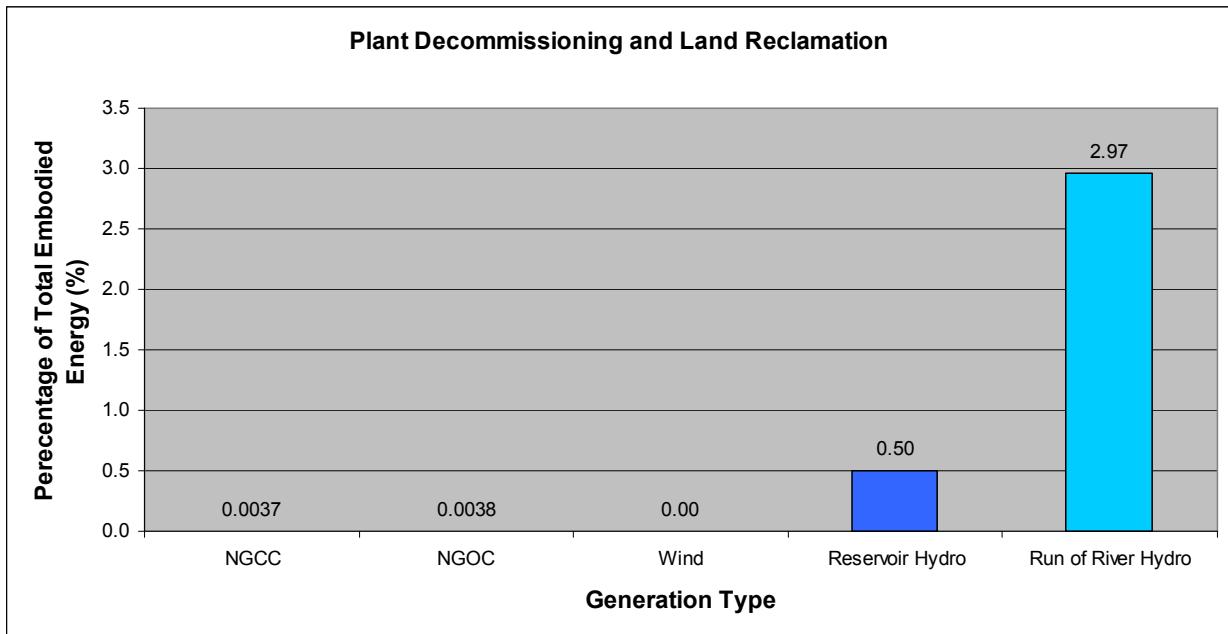
Figure 9.6. Proportion of Total Embodied Energy in Plant Decommissioning and
Land Reclamation for Different Types of Generation

9.4 Performance Comparison

The lifecycle electrical outputs normalised over the plant power rating for the
different power plants are shown in Figure 9.7. The normalised electrical output of the
power plants are 820 GWh/MW, 600 GWh/MW, 302 GWh/MW, 273 GWh/MW and
71GWh/MW, for reservoir hydro, run of river hydro, NGCC, NGOC and Wind power
plants respectively. Generally the longer the useful life of the plant, the higher the
electrical output of the plant normalised over its power rating. The normalised
electrical energy of the run of river hydro power plant is lower than the reservoir
hydro power plants, even though they have equivalent useful lives. This is due to the
fact that the run of river hydro plant could never operate at full capacity, because of
environmental factors such as droughts and low water levels at Lake Taupo. Though
the above environmental factors would influence the operation the reservoir hydro
power plant, it would not be affected as severely as the run of river hydro power plant
because of the large capacity of water stored in the reservoir. The normalised

electrical output of the NGCC plant is higher than the NGOC plant because the NGCC plant has a higher thermal efficiency.

Lifecycle Electrical Energy Output
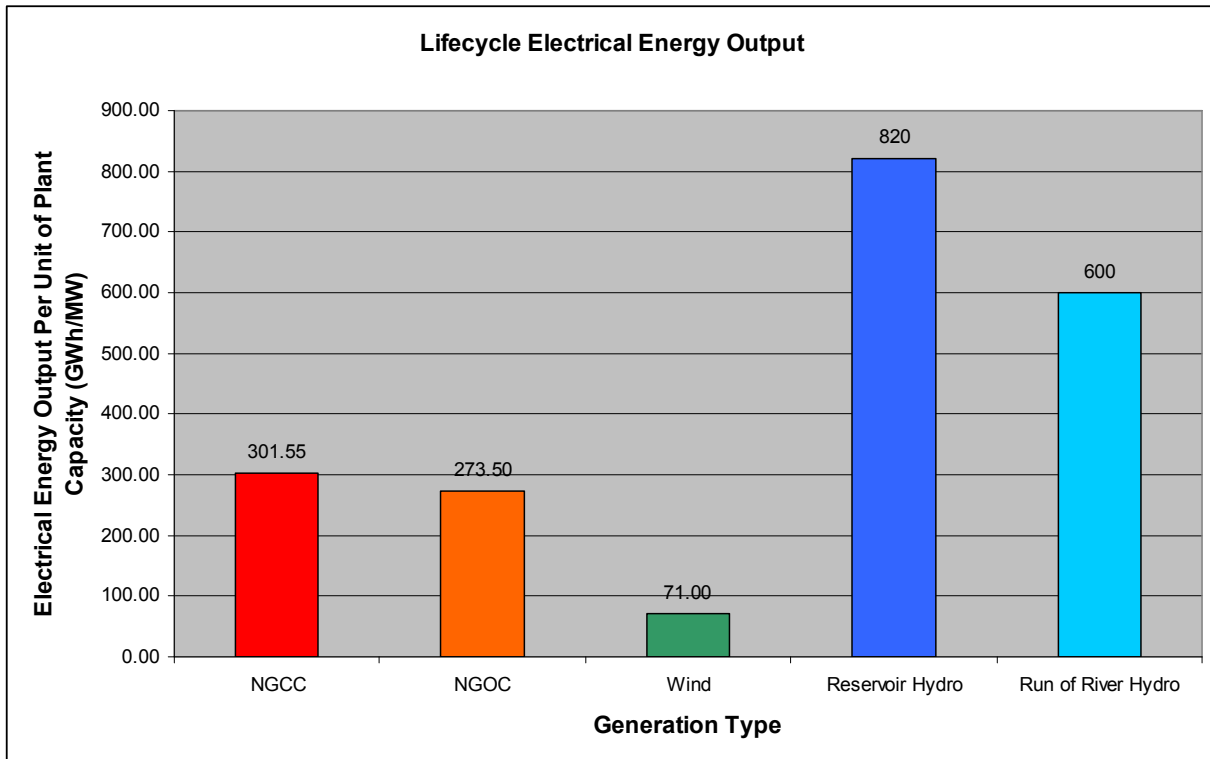
Figure 9.7. Lifecycle Electrical Energy Outputs of the Power Plants Normalised Over their Power Ratings

The LEPR and the lifecycle energy cost, defined in Equations 3.1 and 3.2, for the different power plants are shown in Table 9.1. The non-renewable power plants have LEPRs less than unity, whereas the renewable power plants have LEPRs much greater than unity. This is because of the large amount of energy embodied in the fuel input to the non-renewable power plants, without which it would not be possible to produce electricity, whereas in the renewable power plants, electrical energy is produced from flux sources for which there are no energy costs.

Table 9.1. LEPRs and Lifecycle Energy Costs of the Different Power Plants

	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

The run of river hydro power plant has the highest LEPR of 96.9, followed by the reservoir hydro power plant, which has a LEPR of 62.8. The hydro power plants have very high LEPRs due to their inherently long useful lives of 200 years, and low energy costs in plant operation and maintenance. The LEPR of the wind power plant of 21.1 is significantly lower than the hydro power plants, because of its lower power rating and very short useful life of just 20 years. The lifecycle efficiency in the NGOC plant is significantly lower than that of the NGCC plant. This is due to the lower thermal operational efficiency of the NGOC plant, as the proportions of total embodied energy in the corresponding lifecycle phases are almost identical in these plants, as illustrated in Figures 9.2, 9.4 and 9.6.

The lifecycle energy costs of the power plants are inversely proportional to the corresponding LEPRs. Hence, the renewable power plants have much lower lifecycle energy costs than the non renewable power plants. These were used to compare the lifecycle performances of the power stations studied in this thesis to power stations analysed in other studies, with the same generation methods. The LEPRs and energy costs for the power plants studied in this thesis are in close proximity to the power plants analysed in other studied, hence, proving the validity of the analysis in this thesis.

9.5 Limitations

The major limitation when carrying out the analysis was the lack of availability of data. Apart from the Benmore power station, most of the required data for the other power stations were not available. Hence, data from previous studies, most of which are overseas power plants, had to be adjusted to the relevant power stations accordingly. Therefore, some of the data extracted from the overseas power plants might not represent the New Zealand power plants well. For example, the construction data of the wind turbines for White Hill wind farm were extracted from a Danish wind farm which had the same model of wind turbines. Though the wind turbines are of the same model, the wind turbines are constructed slightly differently depending on the location of the wind farm. Also, the New Zealand embodied energy coefficients for some construction materials were not available. These were either approximated to be equivalent to the New Zealand embodied energy coefficient of a material with similar physical characteristics, or to an overseas embodied energy coefficient for that material.

The New Zealand energy intensity coefficients of only 42 sectors were available when carrying out the I/O analysis in this thesis. For all the other sectors, the energy intensity coefficients were estimated from the closest related sectors. This might have given an inaccurate approximation of embodied energy for some processes or equipment because, even though the items might have similar economic characteristics, this does not necessarily mean that their embodied energies per dollar are similar. For example, when calculating the embodied energy of generators and turbines using I/O analysis, the energy intensity coefficient for machinery and equipment manufacturing was used because the energy intensity coefficient for imported machinery was not available.

One of the main advantages of embodied energy analysis is that it is a crude method of evaluating the total environmental impacts due to a process. However it does not provide a complete understanding on the specific environmental impacts of a process. For example, even though a higher embodied energy would suggest a higher amount of greenhouse gas emissions, it does not provide a quantitative value on of how much

more greenhouse gases are emitted to the atmosphere. As mentioned in the introduction, there are many aspects of a process which affect the environment in a negative manner of which GHG emissions, ozone depletion, acidification and human toxicity are a few examples. Embodied energy analysis does not give a clear indication as to which aspects of a process affect the environment more severely.

Many of the benefits of embodied energy analysis as a method to evaluate the total environmental impacts due to a process stems from it's quantitative nature [6]. Therefore embodied energy analysis does not account for qualitative factors such as social impacts due to a process. This is true especially for renewable energy generation. For example, reservoir hydro generation has many advantages such as flood control and provision for recreational activities, and disadvantages such as habitat destruction and population displacement, which are not accounted for in the embodied energy analysis. In the case of wind farms, the land occupied could be used for other economic activities such as sheep farming, whereas in all the other power stations the land cannot be put into other uses.

10. Conclusion

Embodied energy is the energy consumed in all activities necessary to support a process in its entire life cycle. For power generation systems, this includes the energy cost of raw material extraction, transportation, plant construction, energy generation, and the recycling and disposal stages following actual use. Embodied energy analysis is a crude method of estimating the environmental impacts and depletion of natural resources due to a certain process, essentially, the higher the embodied energy of a process, the greater the environmental impacts and the depletion of natural resources.

This thesis presents the embodied energy analysis undertaken on some New Zealand power plants belonging to various methods of generation, namely, NGCC, NGOC, wind, reservoir hydro and run of river hydro power plants. The analyses for NGCC and NGOC power plants were based on the Huntly power station. For the wind, reservoir hydro and run of river hydro power, stations were based on White Hill wind farm, Benmore power station and Aratiatia power station, respectively.

The two fundamental methodologies for embodied energy analysis are PCA and I/O analysis. PCA calculates the energy embodied in each material that makes up the final system, tracing back through each manufacturing process to it's initial extraction. The I/O analysis method estimates the embodied energy by correlating the dollar cost to the energy consumption, by tracing the energy flows within the national economy and equating the dollar output of each sector with it's energy usage. In this thesis, embodied energy analysis is carried out using a combination of both PCA and I/O analysis. The methodology for the analysis follows the standard set out by the ISO 14040 series, whilst using some useful guidelines given in the IFIAS workshop on energy analysis methodology and conventions.

From the analysis, it was found that for renewable generation power plants, the exploration and plant construction phase of the lifecycle accounts for the largest proportion of embodied energy. For the three renewable power plants studied in this thesis, wind, reservoir hydro and run of river hydro, exploration and plant construction accounted for more than 90% of the total embodied energy of the power

plants. For non renewable power plants, the lifecycle phase that accounts for the largest proportion of embodied energy is plant operation and maintenance. For the NGCC and NGOC power plant studied in this thesis, plant operation and maintenance accounted for more than 99% of the total embodied energy of the power plants. Also, the lifecycle energy costs of the non renewable power plants were higher than the renewable power plants. This is due to the large measures of energy embodied in the fuel input to the non renewable power plants. Hence, in order to improve the lifecycle energy performance of non renewable energy generation, particular attention has to be given to the plant operation and maintenance phase of the life cycle, i.e. using generators with a higher thermal efficiency. To improve the lifecycle energy performance of renewable power plants, attention has to be given to the exploration and plant construction phases of the lifecycle.

The LEPRs of the power plants are 96.9, 62.8, 21.1, 0.487 and 0.354, which correspond to run of river hydro, reservoir hydro, wind, NGCC and NGOC, respectively. The LEPRs of the renewable power plants are greater than unity, whereas the LEPRs of the non renewable power plants are less than unity. Therefore, in terms of lifecycle energy performance, renewable electricity generation is superior to non renewable electricity generation. The diverse range of construction methods of hydro power plants, due to environmental and geological aspects, means that these values are not representative of all other hydro power plants. However, the much larger LEPRs of the hydro power plants studied in this thesis suggest that the performance of hydro electricity generation is exceptionally higher to other methods of electricity generation. In conclusion, the environmental impacts and depletion of natural resources from renewable electricity generation is lower than that of non-renewable electricity generation.

For future research, embodied energy analysis could be undertaken on power systems, which include electricity transmission and distribution. This would provide a better representation of the environmental impacts of the electricity industry in New Zealand. Also, the methodology used in this thesis could be used to undertake embodied energy analysis on other NGCC, NGOC, wind and hydro power plants in New Zealand, so as to make comparisons between different plants belonging to the same generation method. This can be used to make observations to determine the

processes that would yield a higher LEPR, in the various lifecycle phases of an electrical generation system. Further, embodied energy analysis could be undertaken on other existing generation methods in New Zealand, such as geothermal, bio energy and solar energy. The performance of these generation methods could be compared to the performance of the generation methods evaluated in this thesis.

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Appendices

Appendix 1: Embodied Energy Analysis for NGCC Power Plant

Appendix 1.1: Data and Calculations

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Appendix 1.2: Detailed Assumptions

Table GC2: Plant Operation Characteristic and Useful Electrical Energy Output

- Gross Power Output - 385 MW [1]
- Net Thermal Efficiency - 57% [1]
- The Annual Capacity Factor was extracted from [2] and was estimated to be 86%
- Plant Natural Gas consumed per Calendar Year = Estimated Lifetime Gas Input / Assumed Lifetime.
- The annual average gas consumption is estimated from dividing the lifetime natural gas input estimate by the assumed a 40 year annual life span.
- Annual NZ Natural Gas Consumption year was the 2000-2007 average and was extracted from [3].

Table GC3: Natural Gas Exploration

- Data for estimating average cost of adding proved reserves are extracted from [4]. The cost of adding proved reserves for the years 2001-2007 was calculated by dividing the National Summary of Activity and Expenditure (all petroleum exploration and mining permits/ licences) by the sum of Total Oil and Gas Production for the corresponding year.
- The petroleum costs were converted to equivalent 2004$ using the inputs (PPI) for mining [5].
- The average cost of adding proved reserves was calculated by averaging the costs of adding proved reserves for year 2001-2007.
- Energy Cost of Natural Gas Exploration - 0.0045319 GJ/$ [6] in 2004$.
- NZ Natural Gas production/ Delivery Ratio was estimated by averaging the ratio of Total Gross Natural Gas Production from [7] over the Natural Gas Delivered to End User from [3] for the years 2000-2007. This is calculated to be 1.15.

Table GC4: Material Embodied Energy of NZ Transmission Pipelines Related to Plant

- The NZ transmission pipelines lifetime was not available, hence was estimated by the US pipeline lifetime [8].

Table GC5: NZ Transmission Pipelines' Material Embodied Energy

- There are over 3400km of high pressure and more than 11600km or medium and low pressure gas transmission and distribution pipelines. This brings the total length to over 15000km of transmission and distribution pipelines[9].

- This was the only information available on NZ gas transmission pipelines. Therefore the US gas distribution system from [8] is adapted to NZ when calculating the embodied energy of transmission pipelines.

- The NZ length is estimated by multiplying the length of US pipelines by the factor 15,000/47,3429 = 0.0317. This corresponds to the ratio of total length of NZ transmission pipelines to the total length of US transmission pipelines.

- The embodied energy of GJ/Km is calculated by dividing the embodied energy (GJ/mile) by 1.609 (Km/mile).

Table GC6: Construction, Engineering and Administration Energy for Transmission Pipelines

- Calculations were carried out in a similar manner to Table GC4.

Table GC7: Pipeline Construction Energy

- Calculations were carried out in a similar manner to Table GC5

Table GC8: Pipeline Engineering and Administration Energy

- Calculations were carried out in a similar manner to Table GC5.

Table GC9: NZ Natural Gas Production Losses

- Total Gas production per year is the average of years 2000-2007 extracted from [7].
- Net Gas production per year is the average of years 2000-2007 extracted from [10].

Table GC10: NZ Natural Gas Transmission Losses

- Transmission Losses is the 2000-2007 average [11].

Table GC11: Energy Requirements for Compressor Stations and Miscellaneous Equipment

- The required data for New Zealand gas transmission was not available. Therefore the costs from [8] were converted to New Zealand dollars and adjusted to New

Zealand by multiplying by a factor of 0.0317. This corresponds to the ratio of total length of New Zealand transmission pipelines to the total length of US transmission pipelines 15000/473429. Hence it was assumed that the costs have a direct linear correlation with the length of transmission pipelines.

- The exchange rate used to convert from US$ to NZ$ is from [12]. This was calculated by taking the average of monthly exchange rates for 1997. This is 1/0.6630 = 1.508

- The 1997 NZ$ were converted to equivalent 2004 NZ$ using the CGPI for other non residential buildings, for compressor station, and structures and improvements.

- For measuring and regulating, communication and other the CGPI for pumping and compressing equipment was used [13].

- The IO coefficients are from [6]. The assumed industry when choosing the coefficients for different equipment types are mentioned below.

Compressor station - Gas Supply

Structures and Improvements - Construction

Measuring and Regulation - Gas Supply

Communication - Communication Services

Other - Gas Supply

- The plant energy requirement = Book Value * Energy Intensity * 0.0987

(where 0.0987 is the plant percentage of NZ natural gas consumption).

Table GC12: Energy Requirements for Transmission System Operation and Maintenance

- As for Table GC11 the data from [8] were adjusted for New Zealand using the same methods.

- The 1997 exchange rate was 1/0.6630 = 1.508 [12]. The costs were converted to equivalent 1997 NZ$ as per Table GC11.

- The costs were converted to equivalent 2004 NZ$ using the inputs PPI for Gas Supply [13].

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories in the table are listed below.

Operation Supervision and Engineering - Gas Supply

System Control and Load Dispatching - Gas Supply

Communication System Expenses - Communication Services

Mains Expenses - Gas Supply

Measuring and Regulating Station Expenses - Gas Supply

Transmission and Compression of Gas by Others - Gas Supply

Other Expenses - Gas Supply

Supervision and Engineering - Gas Supply

Structures and Improvements - Construction

Mains Expenses - Gas Supply

Compressor Station Equipment - Gas Supply

Measuring and Regulating Station Equipment - Gas Supply

Communication Equipment - Communication Services

Other Equipment - Gas Supply

- Plant Energy Requirement = Book Value * Energy Intensity * 0.0987 * 40 years

Table GC13: Energy Embodied in Plant Building Materials

- The plant building materials for Huntly power station were not available. It was estimated to be equivalent to the NGCC plants' building material in [8].

- The embodied energy coefficients of concrete, aluminium and structural steel are from [14]. For concrete the embodied energy coefficient of 40MPa concrete was used.

- The embodied energy coefficients of copper and plastic are from [15].

- The embodied energy coefficient of iron, chromium, manganese, molybdenum, silicon and vanadium are from [8], as New Zealand coefficients could not be found.

Table GC14: Energy Associated with Non-Material Related Plant Construction Processes

- As with the tables above the costs for plant construction were not available hence were estimated from the NGCC plant in [8]. The costs were readjusted by converting them to NZ$ and then multiplying by the factor of 385MW/620MW = 0.621

- In 1999 the average NZ$ = 0.5296US$ [16]. Therefore to convert prices to NZ$ the US costs were multiplied by 1.888.

- The costs were converted to equivalent 2004$ using the following inputs PPI for Construction [5].

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories in the table are listed below:

Engineering and Administration - Construction

Plant Construction & Equipment Assembly - Construction

Facility Testing & Completion - Construction

Site Assessment & Permitting - Construction

Business Administration - Construction

Table GC15: Energy associated with Plant Equipment

- The costs of plant equipment were not available. Therefore the costs were estimated from [8]. They were converted to equivalent NZ\$ and then readjusted to the plant by multiplying the factor 385MW/620MW = 0.621. This is assuming that the cost of plant equipment correlates with its net output capacity.

- In 99 the average NZ\$ = 0.5296US\$ [16]. Therefore to convert prices to NZ\$ the US costs were multiplied by 1.888.

- The costs were converted to equivalent 2004\$ using the following CGPI and PPI Indices [13] [5].

Combustion Turbines - CGPI for Engines and Turbines

Transformers - CGPI for Electric Motors, Generators and Transformers

Steam Generator - CGPI for Steam Generators

Pumps - CGPI for Pumping and Compressing Equipment

Condensers - CGPI for Pumping and Compressing Equipment

Electrical Equipment - CGPI for Other Electrical Equipment

Noise Attenuation - CGPI for Other Electrical Equipment

Road upgrades - Inputs PPI for Road Transport

Pipeline & Header Interconnect - CGPI for Other Fabricated Metal Products

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories in the table are listed below:

Combustion Turbines - Machinery and Equipment Manufacturing

Transformers - Machinery and Equipment Manufacturing

Steam Generator - Machinery and Equipment Manufacturing

Pumps - Machinery and Equipment Manufacturing

Condensers - Machinery and Equipment Manufacturing

Electrical Equipment - Machinery and Equipment Manufacturing

Noise Attenuation - Machinery and Equipment Manufacturing

Road upgrades - Road Transport

Pipeline & Header Interconnect - Structural, sheet, and fabricated metal product manufacturing

Table GC16: Energy Associated with Plant Operation and Maintenance

- As with the tables above the costs for plant operation and maintenance were not available hence were estimated from [8]. The costs were adjusted to Huntly NGCC

power plant by converting them to NZ$ and then multiplying by the factor of 385MW/620MW = 0.621

- In 1999 the average NZ$ = 0.5296US$ [16]. Therefore to convert prices to NZ$ the US costs were multiplied by 1.888.

- The costs were converted to equivalent 2004$ using the inputs PPI for Electricity generation and supply.

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories in the table are listed below:

Water Supply & Treatment - Water Supply

Major Maintenance - Electricity Generation and Supply

Routine Maintenance - Electricity Generation and Supply

Materials & Supplies - Electricity Generation and Supply

Contract Services - Electricity Generation and Supply

Administrative Overhead - Electricity Generation and Supply

Other Expenses - Electricity Generation and Supply

Start up Costs - Electricity Generation and Supply

Replacement Parts - Machinery and Equipment Manufacturing

Repair Parts - Machinery and Equipment Manufacturing

- The life cycle plant energy requirement was calculated by Energy = Cost(2004$) * Energy Intensity(GJ/2004$) * Plant Life(Years)

Table GC17: Energy Associated with Plant Decommissioning

- Decommissioning was estimated to be 10% of equipment costs.

- The building demolition costs were estimated to be equivalent to that of [8].

- In 1999 the average NZ$ = 0.5296US$ [16]. Therefore to convert the building demolition cost to NZ$ the US cost was multiplied by 1.888.

- The cost for building demolition was converted to equivalent 2004$ using the inputs PPI for construction

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories in the table are listed below:

Dismantling - Construction

Building Demolition - Construction

Table GC18: Costs Associated with Land Reclamation

- The area of land for New Zealand transmission pipelines was not available. This was estimated from [8], by multiplying by the factor of (116,219/7,979,266) where

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116,219 and 7,979,266 correspond to area of New Zealand North Island and area of contiguous US [17], [18].

- The plant area was estimated to be equivalent to that of [8].
- Plant fraction is equal to 0.0987 which is the proportion of NZ natural gas consumed by plant.
- Seeding costs were extracted from [8].
- The life of New Zealand transmission pipelines was not available, hence estimated to be equivalent to the life of US pipelines from [8].
- Cost = Plant Applied Acres * Seeding Cost * (Plant Lifetime/ Pipeline Lifetime)

Table GC19: Energy Associated with Land Reclamation

- The energy intensity coefficients are from [6]. The assumed industries land reclamation is forestry and logging (It was assumed that reclaimed land will be converted to forests).

Appendix 2: Embodied Energy Analysis for NGOC Power Plant

Appendix 2.1: Data and Calculations

Appendix 2.2: Detailed Assumptions

Table GO2: Plant Operation Characteristics and Useful Electrical Energy Output

- Gross Power Output - 48MW [19]
- Net Thermal Efficiency - 41% [20]
- Calendar year lifetime was assumed to be 40 from [8]
- Annual capacity factor was assumed to be the 2007 figure from [21]
- The annual average gas consumption was estimated by dividing the lifetime natural gas input estimate by the assumed 40 year annual life span.
- Annual NZ Natural Gas Consumption was the average for years 2000-2007 from [3].

Table GO3: Natural Gas Exploration

- Data for estimating average cost of adding proved reserves was extracted from [4]. The cost of adding proved reserves for years 2001-2007 was calculated by dividing the National Summary of Activity and Expenditure (all petroleum exploration and mining permits/ licences) by the sum of Total Oil and Gas Production for the corresponding year.
- The petroleum costs were converted to equivalent 2004$ using the inputs Producers Price Index (PPI) for mining [5].
- The average cost of adding proved reserves was calculated by averaging the costs of adding proved reserves for year 2001-2007.
- Energy Cost of Natural Gas Exploration - 0.0045319 GJ/$ [6] in 2004$.
- NZ Natural Gas production/ Delivery Ratio was estimated by averaging the ratio of Total Gross Natural Gas Production from [7] over the Natural Gas Delivered to End User from [3] for the years 2000-2007. This is calculated to be 1.15.

Table GO4: Material Embodied Energy for Production and Transmission Pipeline Related to Plant

- The NZ transmission pipelines' lifetime was not available, hence was estimated by the US pipeline lifetime [8].

Table GO5: NZ Transmission Pipelines' Material Embodied Energy

- There are over 3400km of high pressure and more than 11600km or medium and low pressure gas transmission and distribution pipelines. This brings the total length to over 15000km of transmission and distribution pipelines[9].

- This was the only information available on NZ gas transmission pipelines. Therefore the US gas distribution system from [8] was adopted to NZ when calculating the embodied energy of transmission pipelines.

- The NZ length was estimated by multiplying the length of US pipelines by the factor 15,000/473,429. This corresponds to the ratio of total length of NZ transmission pipelines to the total length of US transmission pipelines

- The embodied energy of GJ/Km was calculated by dividing the embodied energy (GJ/mile) by 1.609 (Km/mile).

Table GO6: Construction, Engineering and Administration Energy for Transmission Pipeline

- Calculations were carried out in a similar manner to Table GO4.

Table GO7: Pipeline Construction Energy

- Calculations were carried out in a similar manner to Table GO5

Table GO8: Pipeline Engineering and Administration Energy

- Calculations were carried out in a similar manner to Table GO5.

Table GO9: NZ Natural Gas Production Losses

- Total Gas production per year is the average of years 2000-2007 extracted from [7]
- Net Gas production per year is the average of years 2000-2007 extracted from [10]

Table GO10: New Zealand Natural Gas Transmission Losses

- Transmission Losses is the 2000-2007 average [11]

Table GO11: Energy Requirements for Compressor Stations and Miscellaneous Equipment

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- The require data for the New Zealand gas transmission was not available. Therefore the values from [8] were converted to New Zealand dollars and adjusted to New Zealand by multiplying by a factor of 0.0317. This corresponds to the ratio of total length of New Zealand transmission pipelines to the total length of US transmission pipelines 15000/473429. Hence it was assumed that the costs have a direct linear correlation with the length of transmission pipelines.

- The exchange rate used to convert from US$ to NZ$ is from [12]. This was calculated by taking the average of monthly exchange rates for 1997. This works out to be 1/0.6630 = 1.508

- The 1997 NZ$ were converted to equivalent 2004 NZ$ using the CGPI for other non residential buildings for compressor station, and structures and improvements.

- For measuring and regulating, communication and other the CGPI for pumping and compressing equipment was used [13]. The costs were converted to equivalent 2004$ as the IO coefficients are in 2004$.

- The IO coefficients are from [6]. The assumed industry when choosing the coefficients for different equipment types are mentioned below.

Compressor station - Gas Supply

Structures and Improvements - Construction

Measuring and Regulation - Gas Supply

Communication - Communication Services

Other - Gas Supply

- The plant energy requirement = Book Value * Energy Intensity * 0.0155

(where 0.0155 is the plant percentage of NZ natural gas consumption).

Table GO12: Energy Requirements for Transmission System Operation and Maintenance

- As for Table GO11 the data from [8] were adjusted for New Zealand using the same methods.

- The 1997 exchange rate was 1/0.6630 = 1.508 [12]. The costs were converted to equivalent 1997 NZ$ as per Table GO11.

- The costs were converted to equivalent 2004 NZ$ using the inputs PPI for Gas Supply [13].

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories in the table are listed below:

Operation Supervision and Engineering - Gas Supply

System Control and Load Dispatching - Gas Supply

Communication System Expenses - Communication Services

Mains Expenses - Gas Supply

Measuring and Regulating Station Expenses - Gas Supply

Transmission and Compression of Gas by Others - Gas Supply

Other Expenses - Gas Supply

Supervision and Engineering - Gas Supply

Structures and Improvements - Construction

Mains Expenses - Gas Supply

Compressor Station Equipment - Gas Supply

Measuring and Regulating Station Equipment - Gas Supply

Communication Equipment - Communication Services

Other Equipment - Gas Supply

- Plant Energy Requirement = Book Value * Energy Intensity * 0.0987 * 40 years

Table GO13: Energy Embodied in Plant Building Materials

- The plant building materials for Huntly power station were not available. It is estimated to be equivalent to the NGCC plants' building material in [8].

- The embodied energy coefficients of concrete, aluminium and structural steel are from [14]. For concrete the embodied energy coefficient of 40MPa concrete is used.

- The embodied energy coefficients of copper and plastic are from [15].

- The embodied energy coefficient of iron, chromium, manganese, molybdenum, silicon and vanadium are from [8], as New Zealand coefficients could not be found.

Table GO14: Energy Associated with Non-Material Related Plant Construction Processes

- As with the tables above the costs for plant construction were not available hence were estimated from NGCC plant in [8]. The costs were adjusted by converting them to NZ$ and then multiplying by the factor of 48MW/620MW = 0.0774

- In 1999 the average NZ$ = 0.5296US$ [16]. Therefore to convert prices to NZ$ the US costs were multiplied by 1.888.

- The costs were converted to equivalent 2004$ using the following inputs PPI for Construction [5].

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories in the table are listed below:

Engineering and Administration - Construction

Plant Construction & Equipment Assembly - Construction

Facility Testing & Completion - Construction

Site Assessment & Permitting - Construction

Business Administration - Construction

Table GO15: Energy associated with Plant Equipment

- The costs of plant equipment for Huntly NGOC power plant were not available. Therefore, the costs were estimated from the NGCC plant in [8]. The costs were converted to equivalent NZ$ and then readjusted to the plant by multiplying the factor 48MW/620MW = 0.0774. This is assuming that the cost of plant equipment correlates with its net output capacity.

- In 1999 the average NZ$ = 0.5296US$ [16]. Therefore to convert prices to NZ$ the US costs were multiplied by 1.888.

- The costs were converted to equivalent 2004$ using the following CGPI and PPI Indices [13] [5].

Combustion Turbines - CGPI for Engines and Turbines

Transformers - CGPI for Electric Motors, Generators and Transformers

Steam Generator - CGPI for Steam Generators

Pumps - CGPI for Pumping and Compressing Equipment

Condensers - CGPI for Pumping and Compressing Equipment

Electrical Equipment - CGPI for Other Electrical Equipment

Noise Attenuation - CGPI for Other Electrical Equipment

Road upgrades - Inputs PPI for Road Transport

Pipeline & Header Interconnect - CGPI for Other Fabricated Metal Products

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories in the table are listed below:

Combustion Turbines - Machinery and Equipment Manufacturing

Transformers - Machinery and Equipment Manufacturing

Steam Generator - Machinery and Equipment Manufacturing

Pumps - Machinery and Equipment Manufacturing

Condensers - Machinery and Equipment Manufacturing

Electrical Equipment - Machinery and Equipment Manufacturing

Noise Attenuation - Machinery and Equipment Manufacturing

Road upgrades - Road Transport

Pipeline & Header Interconnect - Structural, sheet, and fabricated metal product manufacturing

Table GO16: Energy Associated with Plant Operation and Maintenance

- As with the tables above the costs for plant operation and maintenance were not available hence were estimated from [8]. The costs were adjusted to Huntly NGOC power plant by converting them to NZ$ and then multiplying by the factor of 48MW/620MW = 0.0774

- In 1999 the average NZ$ = 0.5296US$ [16]. Therefore to convert prices to NZ$ the US costs were multiplied by 1.888.

- The costs were converted to equivalent 2004$ using the inputs PPI for Electricity generation and supply.

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories in the table are listed below:

Water Supply & Treatment - Water Supply

Major Maintenance - Electricity Generation and Supply

Routine Maintenance - Electricity Generation and Supply

Materials & Supplies - Electricity Generation and Supply

Contract Services - Electricity Generation and Supply

Administrative Overhead - Electricity Generation and Supply

Other Expenses - Electricity Generation and Supply

Start up Costs - Electricity Generation and Supply

Replacement Parts - Machinery and Equipment Manufacturing

Repair Parts - Machinery and Equipment Manufacturing

- The life cycle plant energy requirement was calculated by Energy = Cost(2004$) * Energy Intensity(GJ/2004$) * Plant Life(Years)

Table GO17: Energy Associated with Plant Decommissioning

- Plant decommissioning was estimated to be 10% of equipment costs.

- The building demolition cost was estimated to be equivalent to that of [8].

- In 1999 the average NZ$ = 0.5296US$ [16]. Therefore to convert prices to NZ$ the US cost was multiplied by 1.888.

- The cost for building demolition was converted to equivalent 2004$ using the inputs PPI for construction

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories in the table are listed below:

Dismantling - Construction

Building Demolition - Construction

Table GO18: Costs Associated with Land Reclamation

- The area of land for New Zealand transmission pipelines was not available. This was estimated from [8] by multiplying the US transmission pipeline area by the factor of (116,219/7,979,266) where 116,219 and 7,979,266 correspond to area of New Zealand North Island and area of contiguous US [17], [22].

- The plant area was estimated to be equivalent to that of [8].

- Plant fraction is equal to 0.0155 which is the proportion of NZ natural gas consumed by plant.

- Seeding costs were extracted from [8].

- The life of New Zealand transmission pipeline was not available, hence estimated to be equivalent to that of the US pipelines from [8].

- Cost = Plant Applied Acres * Seeding Cost * (Plant Lifetime/ Pipeline Lifetime)

Table 19: Energy Associated with Land Reclamation

- The energy intensity coefficients are from [6]. The assumed industries land reclamation is forestry and logging (It was assumed that reclaimed land will be converted to forests).

Appendix 3: Embodied Energy Analysis for Wind Farm

Appendix 3.1: Data and Calculations

Appendix 3.2: Detailed Assumptions

Table WN2: Useful Electrical Output

- There are 29, 2MW wind turbines hence making the total net power output of 58MW [23].

- The useful life of White Hill wind farm is not available. It is assumed to be 20 years which is also the life of the Vestas V80 - 2 MW wind turbine [24]

- It is assumed that the turbines will generate electricity for 90% of the year which takes into consideration the appropriate wind conditions for the operation of wind turbines (typically 4-24m/s) [25].

- Within this range turbines can only deliver their full generation capacity at a speed of approximately 15 m/s. This is accounted for by applying an annual load factor of 45%, this being generally accepted as the ratio of actual generation to that the turbine would produce at full capacity during a given year, under New Zealand conditions [25].

Table WN3: Energy Associated with Wind Turbine Materials

- The embodied materials, of the wind turbines, apart from concrete, are extracted from [26].

- For the embodied energy coefficients of materials, ideally the Danish coefficients should be used. As these were not available, the New Zealand coefficients were used.

- The embodied energy coefficients of steel, concrete, glass fibre and aluminium were extracted from [14]. The steel used is assumed to be steel sheet and coefficient for glass fibre insulation is used as the coefficient for glass fibre. For Aluminium the embodied energy coefficient of extruded aluminium is used.

- The embodied energy coefficients of high strength steel, plastic and copper are from [15]. Plastic is assumed to be PVC, copper is assumed to be virgin sheet and aluminium is assumed to be extruded and anodized when choosing the embodied energy coefficients.

- The embodied Energy coefficient of zinc is from [27].

- The New Zealand embodied energy coefficient for cast iron was not available. Hence, the US coefficient for iron was used [8]

Table WN4: Energy Associated with Turbine Manufacturing and Dismantling

- As stated in [26] a V80 turbine for an on shore wind farm requires 3,282,723 kWh or energy per turbine for manufacturing/ dismantling.
- If this information was not available IO analysis would have been used.

Table WN5: Energy Associated with Wind Turbine Transportation

- It was assumed that the wind turbines were transported from the Copenhagen harbour in Denmark to Lyttelton port in New Zealand (It was also assumed that the turbine components are manufactured in Copenhagen)
- It was assumed the Lyttelton port the turbines were carried by rigid plus articulated trucks to Mossburn.
- The total weight of a turbine includes the tower, nacelle, blades and hub. This amounts to a total weight of 230.4 tonnes.
- The sailing distance between Copenhagen port and Lyttelton port is 21,852km [28].
- The driving distance from Lyttelton port to Mossburn is about 600 km. This was calculated using Google Maps [29].
- The energy coefficients for coastal shipping and rigid plus articulated trucks were extracted from [30].

Table WN6: Energy Associated with Foundation Building Materials

- The amount of concrete in foundation of a turbine is 364 m^3. It was assumed that this is 40MPa concrete and it has a density of 2400kg/m^3 [31]. Therefore the mass of concrete for each foundation was worked out to be 873.6 tonnes.
- The amount of reinforcing (steel) is 34 tonnes per turbine [32]
- The other materials in foundation are estimated from [24]. In that study a turbine foundation contains 11.1 tonnes of steel. Therefore, the quantities of other materials in a turbine foundation in [24] were multiplied by a factor of 34/11.1 = 3.063, to estimate the amount of other materials in a turbine foundation at White Hill wind farm.
- The embodied energy coefficients of concrete and reinforcing steel were extracted from [14].
- The embodied energy coefficient of PVC was extracted from [15].
- The embodied energy coefficient of HDPE was extracted from [27].

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Table WN7: Energy Associated with Cable Trenches and Cable Materials

- The quantities of materials for cable trenches and cables were estimated from [24].

- The wind farm in [24] only contains 11 wind turbines where as the White Hill wind farm contains 29 wind turbines. Therefore, the amount of materials required for cable and cable trenches from [24] were multiplied by a factor of 29/11 = 2.64, to estimate the quantities of materials for cable trenches and cable material at White Hill wind farm.

- The embodied energy coefficient of concrete (assumed to be 40MPa) and aluminium were extracted from [14].

- The embodied energy coefficients of PVC, sand and copper (assumed to be virgin, rod, wire) were extracted from [15].

- The embodied energy coefficient of soils and stones were estimated by the embodied energy coefficient of local stone [27].

- The embodied energy coefficient of poly butadiene is estimated by the embodied energy coefficient of synthetic rubber (as poly butadiene is a synthetic rubber), from [27].

Table WN8: Energy Associated with Paths and Roads Building Materials

- The materials used in paths and roads construction were estimated from [24].

- It was assumed that amount of material used for road construction is correlated with the area of the wind farm. Hence materials used in paths and roads construction in [24] was multiplied by the factor of 24 km^2/4.5 km^2 = 5.33, which are the areas of the White Hill wind farm [23] and the Italian wind farm in [24], respectively.

- The embodied energy coefficient of steel (assumed to be reinforcing steel) was extracted from [14].

- The embodied energy coefficient of aggregate quarrying (assumed to be aggregate, general) was extracted from [15].

- The embodied energy coefficients of soils and stones (assumed to be local stones), poly propylene and HDPE were extracted from [27].

Table WN9: Energy with Site Office Building Materials

- The materials used in construction of site office at White Hill wind farm were not available. This was estimated by the materials used in main transformer room of the study in [24].
- The materials in [24] were multiplied by a factor of 29/11 when estimating the materials used in site office construction at White Hill wind farm.
- The embodied energy coefficient of concrete (assumed to be 40MPa) and steel were extracted from [14].

Table WN10: Energy Associated with Non-Material Related Site Preparation and Construction Processes

- The costs of site preparation and construction were extracted from [33], which has given typical investment cost structure for per MW installed in a wind farm for a wind farm with 2MW turbines. It is stated in [33] that capital costs of wind energy projects are dominated by the cost of the wind turbine itself.
- It has been assumed that these costs are representative of New Zealand costs. The costs given in [33] are as follows.

Description	Investments (€1000/MW)
Turbine	928
Foundation	80
Electric Installation	18
Gird Connection	109
Consultancy	15
Financial Costs	15
Road	11
Total	1127

- The turbine costs were ignored as the embodied energy in turbine materials and manufacturing/dismantling has already been calculated from data in [26].
- The costs above were multiplied by capacity of White Hill wind farm (58MW) to find out the costs associated with White Hill Wind Farm.
- For foundation and road it is assumed that 40% of the above costs are associated with materials and 60% with engineering and construction. Hence, only 60% of the cost given above was used in calculating energy associated with road and

foundation construction, as the energy embodied in the materials of foundation and roads has already been calculated in Table WN8.

- The costs in [33] are given in 2006 euros. The exchange rate used to convert from 2006 € to 2006 NZ$ is from [12]. This was calculated by taking the average of monthly exchange rates for 2006. This works out to be 1/0.6495 = 1.540

- These costs were converted to 2004NZ$ using the inputs PPI for construction, apart from financial costs, which is 1211 and 1428 for 2004 and 2006 respectively [5].

- The financial costs were converted to 2004 NZ$ using the inputs PPI for finance which is 1185 and1126 for 2004 and 2006 respectively [5].

- Land Licenses/Rights/Consents cost is NZ$50,000 (1994$) in [34], which has an area of 1km^2. This was multiplied by 24 (24km^2/1km^2) to estimate the land licenses/ rights/ consents costs for White Hill wind farm. This was converted to 2004NZ$ using the inputs PPI for other property services which is 948 and 1173 for 1994 and 2004 respectively [5].

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories are shown below.

Land Licenses/ Right/ Consents - Real Estate

Foundations Engineering and Construction - Construction

Electric Installation - Construction

Grid Connection - Construction

Consultancy - Construction

Financial Costs - Finance

Road Engineering and Construction - Construction

Table WN11: Energy Associated with Other Equipment and Fixed Assets

- The equipment in plant were assumed to be control system equipment, the value of which is extracted from [33].

- The cost was converted to 2004 NZ$ using CGPI for Electrical Distribution and Control Apparatus, which is 1046 and 1088 for 2004 and 2006 respectively [13].

- The fixed assets in plant (which hasn't been considered above) is assumed to be the transmission vehicle, the value of which was extracted from [34].

- This was converted to 2004NZ$ with the same methodology as above table, using outputs PPI for transport equipment manufacturing, which is 1020 and 1100 for 1994 and 2004 respectively [5].

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories are shown below:

Control Systems - Machinery and Equipment Manufacture

Transmission Vehicle - Transport Equipment Manufacture

- **Table WN12: Energy Associated with Operation and Maintenance of Wind Farm**

- The total annual cost of a New Zealand wind farm operation is $1,032,750 (1994$) [34]. The wind farm in [34]only has a capacity of 24.3MW. Therefore the total annual operation and maintenance cost of white hill wind farm was estimated by multiplying the above cost by a factor of 58/24.3.

- This was converted to 2004$ by using the inputs PPI for Electricity generation and distribution, which is 994 and 1174 for 1994 and 2004 respectively.

- The average proportions, over the time period of 1197-2001, for different categories associated operation and maintenance of German turbines are given in [35]. Assume that this holds for the Danish Vestas turbines and is representative of the time period for which the White Hill wind farm will be in operation.

- The proportions are:

Category	Proportion (%)
Administration	21
Insurance	13
Land Rent	18
Miscellaneous	17
Power from Grid	5
Service and Spare Parts	26

- The total cost from [34] was divided into the above categories according to the given proportion in [35] when calculating the embodied energy for wind farm operation and maintenance.

- It was assumed that land rent does not consume energy hence is ignored in this analysis

- The energy intensity coefficients are from [6]. The assumed industry for each of the categories is mentioned below.

Administration - Electricity Generation and Distribution

Insurance - Insurance

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Miscellaneous - Electricity Generation and Distribution

Power from Grid - Electricity Generation and Distribution

Service and Spare Parts - Machinery and Equipment Manufacture

- Life Cycle O&M costs = Cost (2004$) * Energy Intensity (GJ/2004$) * Plant Life (20years).

Table WN13: Energy Associated with Plant Decommissioning

- It was assumed that land reclamation energy required is negligible, as the land a wind farm operates on can be used for other activities while it is in operation.

- In [26] it is stated that dismantling and scrapping has a negative embodied energy value (e.g. energy gain), as most of the materials in the turbines can be recycled. It was assumed this energy gain cancels out with the energy embodied in the other stages of plant decommissioning. Hence, the embodied energy in plant decommissioning was assumed to be zero.

Appendix 4: Embodied Energy Analysis for Reservoir Hydro Power Plant

Appendix 4.1: Data and Calculations

Appendix 4.2: Detailed Assumptions

Table HD2: Useful Electrical Energy Output

- Annual Energy Output into National System - 2215GWh [36]

- The life time of 200 years is an assumption as Meridian energy predicts that it will be in operation for greater than 144 years from today, and it is really 45 years old [37].

Table HD3: Energy Embodied in River Diversion Building Materials

- The structure contains a total of 100,000 cu. yards of reinforced concrete [38]

- The density of concrete was assumed to be 2320 kg/m^3 [31].

- Mass of Concrete = 100000 cu. yards * 0.7646 m^3/cu.yard *2.32 tonnes/m^3 = 177387 tonnes

- For the embodied energy of concrete the value of 40MPa concrete from [14] was used, as this had the highest embodied energy coefficient of the two reinforced concrete types. Embodied energy coefficient is 1.003GJ/tonne.

- There are two 155-ton steel diversion gates [38].

- The embodied Energy coefficient of structural steel is 25.04 GJ/tonne [14].

Table HD4: Energy Associated with Preliminary Investigations and Non-Material Related River Diversion Processes

- Cost of preliminary investigations was extracted from [39] and was in 1956 pounds. This was converted to 2004$ using the CPI, which was the only price index existent in 1956.

- The costs for non-material related river diversion processes were extracted from [39] and are in 1971 $. They were converted 2004$ using the CPI as this is the only price index available in 1971[40].

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories in the table are listed below:

Preliminary Investigations - Construction

Common Excavation & Transport to Tip (River Diversion) - Mining and Quarrying

Engineering and Construction (River Diversion) - Construction

Diversion of River (Dewatering & crib wall) - Construction

Table HD5: Energy Embodied in Hydro Dam Construction Materials

- The content of the earth dam is 15.6 million cu. yards, involving the cartage and compaction of 27.6 million tons of material [38]. Therefore the density of the material of earth dam is 27.6/15.6 = 1.77 tons/ cu. yard.

- The dam is divided into three main zones - an impervious core of clayey gravel, supported on each side by a massive shoulder of river gravel [38].

- Mass of Dam core = 3,800,000*1.77 = 6,726,000 [41]

- Mass of Upstream Shoulder = 5,700,000 * 1.77 = 10,089,000 [41]

- Mass of Downstream Shoulder = 5,900,000 * 1.77 = 10,443,000 [41]

- For the embodied energy coefficient of dam material, the rammed soil cement embodied energy coefficient from [27] was used.

HD6: Energy Associated with Non-Material Related Dam Construction Processes

- The rock excavation and transportation to dam site was not included, because the energy cost of this was already calculated in Table HD5 from embodied energy in the material of the dam.

- The costs are extracted from [39] and are in 1971 $. They were converted 2004$ using [40].

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories are shown below.

Engineering and Construction Expenses - Construction

Dewatering - Construction

Other Expenses including Administration - Construction

Table HD7: Energy Embodied in Spillway, Intake and Penstocks Construction Materials

- Mass concrete for spill way = 73,848 cu. yards [39]. The density of concrete was assumed to be 2320 kg/m^3 [31]. The mass of concrete was calculated as in Table HD3.

- For mass concrete the embodied energy coefficient of block fill concrete was used, which is 1.2 GJ/tonne [15].

- Reinforced concrete for spillway = 90,032 cu. yards [39]. The density of concrete is assumed to $2320 kg/m^3$ and the mass was calculated as above.

- For the embodied energy of concrete the value of 40Mpa concrete from [14] was used, as this was the higher embodied energy coefficient of the two reinforced concrete types. Embodied energy coefficient is 1.003 GJ/tonne.

- Steel gates and equipment had an estimated weight of approximately 400tons [38].

- The embodied Energy coefficient of structural steel is 25.04 GJ/tonne [14].

- 80,000 cu.yards of precast prestressed concrete was used for intake and penstocks [41]. It is assumed that the density of $2320 kg/m^3$ and the mass was calculated as above.

- The embodied energy coefficient of pre-cast concrete, which is 1.208GJ/tonne, from [14] was used as the embodied energy coefficient of pre-cast, pre-stressed concrete was not available.

HD8: Energy Associated with Non-Material Related Spillway, Intake and Penstock Construction Processes

- The rock excavation and transportation to dam site was not included, because the energy cost of this was already calculated in Table HD5 from embodied energy in the material of the dam.

- The costs were extracted from [39] and are in 1971 $. They were converted 2004$ using [40].

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories are shown below:

Common Excavation & Disposal (Spillway) - Mining and Quarrying

Engineering and Construction (Spillway) - Construction

Dewatering (Spillway) - Construction

Other Expenses including Administration (Spillway) - Construction

Cranes used in Spillway, Intake and Penstock - Transport Equipment Manufacturing

Common Excavation & Disposal (Intake & Penstocks) - Mining and Quarrying

Engineering and Construction (Intake & Penstocks) - Construction

Dewatering (Intake & Penstocks) - Construction

Other Expenses including Administration (Intake & Penstocks) - Construction

Table HD9: Energy Embodied in Power House and Switchyard Construction Materials

- The only information available on Powerhouse and Switchyard Material was the amount of concrete, which was 80,000 cu.yards [41]. This is equal to 141,910 tonnes, using the same assumption as used in Table HD3.

- The amounts of other construction materials were estimated using [8]. It is estimated by multiplying by the factor of (141,910/29,660) where 29,660 refers to the mass of concrete used for the plant concerned in [8].

- The embodied energy coefficients of concrete, aluminium and structural steel were extracted from [14].

- The embodied energy coefficients of copper and plastic were extracted from [15].

- The embodied energy coefficient of iron, chromium, manganese, molybdenum, silicon and vanadium were extracted from [8], as a New Zealand coefficients could not be found.

Table HD10: Energy Associated with Powerhouse and Switchyard Construction

- The rock excavation and transportation to dam site is not included, because the energy cost of this is already calculated in table 5 from embodied energy in the material of the dam.

- The costs are extracted from [39] and are in 1971 $. They are converted 2004$ using [40].

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories are shown below:

Common Excavation & Disposal - Mining and Quarrying

Engineering and Construction - Construction

Technical Supervision - Construction

Dewatering - Construction

Cranes used in Powerhouse Construction - Transport Equipment Manufacturing

Transport - Road Transport

Special Testing - Construction

Maintenance of Tools - Construction

Other Expenses including Administration - Construction

Table HD11: Energy Associated with Powerhouse and Switchyard Equipment

- The costs were extracted from [39] and are in 1971 $. They were converted 2004$ using [40].

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories are shown below:

Main Turbines - Machinery and equipment manufacturing

Auxiliary Turbines - Machinery and equipment manufacturing

Main Generators - Machinery and equipment manufacturing

Transformers - Machinery and equipment manufacturing

Communication Equipment - Machinery and equipment manufacturing

Miscellaneous P.H. Electrical Equipment - Machinery and equipment manufacturing

Cooling and Drainage Water Systems - Water Supply

Busworks and Switch Gear - Machinery and equipment manufacturing

Transmission Lines - Machinery and equipment manufacturing

Other Miscellaneous Equipments - Machinery and equipment manufacturing

Table HD12: Energy Associated with Power Station Operation & Maintenance

- "O&M costs for BEN are approximately $1,000k per annum. After about 45 years of operation we have implemented quite a large capital works program that is currently underway. This involves generator refurbishment along with runner replacement. Also we are reconfiguring the BEN GIP, replacing power transformers and IPB. The cost for this is approximately $12,000k over 5 years. This type of capital work is not expected to be undertaken for another 50 years." [37]

- For operation and Maintenance only the above information was available. It was assumed that these costs are in 2008$. They were converted to 2004$ using the inputs producer price index (PPI) for electricity generation and supply.

- The PPI 2008 = 1639 and PPI 2004 = 1174 [5]

- Therefore the Annual cost in 2004$ = (1174/1639)*1,000,000 = $716,290

- From the above statement it could be assumed that the power station undergoes major refurbishments of $60,000,000 every 50 years. Therefore the annual cost of Refurbishments = $60,000,000/50 = $1,200,000. This was converted to 2004$ this using the capital goods price index (CGPI) for plant, machinery and equipment.

- The CGPI for 2008 = 1056 and CGPI for 2004 = 1005 [13].

- Therefore the Annual cost of refurbishment in 2004$ = (1005/1056)*1,200,000 = $1,142,045.

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories are as mentioned below.

Annual Operation and Maintenance Costs - Electricity Generation and Supply

Annual Refurbishing and Replacement Costs - Machinery and Equipment Manufacturing

- The total plant energy requirement = Cost ($) * Energy Coefficient (GJ/$) * Plant Life (Years)

Table HD13: Energy Associated with Permanent Village and Other Establishments

- The costs were extracted from [39] and are in 1973$. They were converted to 2004$ using the CPI as this is the only price index existent since 1973 [40].
- The energy intensity coefficient are extracted from [6] and the assumed industries for the cost categories are listed below:

Permanent Village "60 man size" - Construction

A.C. Outdoor Station - Construction

Permanent Roads and Bridges - Construction

Land Compensation - Real Estate

Investigations - Construction

Road Construction - Construction

Communications - Communication Servies

Works Buildings - Construction

Works Services (Air, Power Water) - Construction

Construction Village - Construction

Central Facilities - Construction

Temporary Bridges - Construction

Table HD14: Energy Associated with Other Miscellaneous Construction Expenses

- The costs were extracted from [39] and are in 1973$. They were converted to 2004$ using the CPI as this is the only price index existent since 1973 [40].
- The energy intensity coefficient were extracted from [6] and the assumed industries for the cost categories are listed below:

Lake Filling Preparations - Construction

Making Good - Machinery and Equipment Manufacturing

Public Relations - Printing, Publishing & Recorded Media

Village Maintenance - Accommodation, Restaurants and Bars

Recovered Debt & Indirect Charges - Finance

Powerhouse gallery fire - Construction

Flood damage - Construction

P.R.D. and Mechanical Store Fire - Construction

Stocks and Equipment losses (P.R.D Fire) - Machinery and Equipment Manufacture

Canteen Fire Damage - Construction

Fire Damage to Project Plant - Construction

Shot Blast Shed Fire - Construction

Passenger Lift and Shafts - Construction

Timaru Transit Shed - Construction

Table HD15: Energy Associated with Power Station Decommissioning

- The power house and switch yard decommissioning was estimated to be 10% of equipment costs.

- The cost of building demolition was estimated using [8]. It was estimated by multiplying by the cost of building demolition of [8] by the factor of (141,910/29,660) where 141,910 and 29,660 refers to the masses of concrete used for the power house in Benmore and the NGCC plant in [8], respectively.

- The cost of building demolition in [8] is US$107,016 in 1999$. This was converted to NZ$ using an exchange rate of 1US$ = 1.888NZ$ [16].

- The cost of building demolition was converted to Equivalent 2004$ using CGPI for other non residential buildings. These are 999 and 1177 for 1999 and 2004 respectively.

- Therefore Building Demolition costs = 107,016 * 4.785 * 1.888 * (1177/999) = $1,099,773.

- The dam, spillway, intake and penstocks decommissioning costs were estimated to be 10% of their total construction costs.

- The energy coefficients are from [6]. The assumed industry for each of the categories is as shown below.

Dam, Intake & Penstocks Decommissioning - Construction

Power House & S.Y. Decommissioning - Construction

Building Demolition - Construction

Table HD16: Energy Associated with Land Reclamation

- The cost of Land reclamation was estimated at 10% of the total decommissioning/ demolition.

- The energy intensity coefficients are from [6]. The assumed industries land reclamation is forestry and logging (It is assumed that reclaimed land will be converted to forests).

Appendix 5: Embodied Energy Analysis for Run of River Hydro Power Plant

Appendix 5.1: Data and Calculations

Appendix 5.2: Detailed Assumptions

Table HR2: Useful Electrical Energy Output

- Annual Energy Output into National System - 270GWh [42].
- The life of the power station was assumed to be 200 years.

Table HR3: Energy Embodied in River Diversion Building Materials

- The construction materials and their quantities of the diversion culvert used, when building the Aratiatia power station, were not available. It was estimated to be equivalent to the diversion culvert used in Benmore power station. (Refer to Table HD3 in Appendices 4.1 and 4.2)

Table HR4: Energy Associated with Preliminary Investigations and Non-Material Related River Diversion Processes

- The specific costs for preliminary investigations and non-material related river diversion processes for Aratiatia power station were not available. These were estimated to be equivalent to that of the Benmore power station. (Refer to Tables HD4 in Appendices 4.1 and 4.2)
- The energy intensity coefficients were extracted from [6]. The assumed industries for each of the categories in the table are listed below:

Preliminary Investigations - Construction
Common Excavation & Transport to Tip (River Diversion) - Mining and Quarrying
Engineering and Construction (River Diversion) - Construction
Diversion of River (Dewatering & crib wall) - Construction

Table HR5: Energy Embodied in Spillway, Penstocks, Intake Tunnel and Surge Tank Construction Materials

- The details of materials used in the construction of Aratiaita spillway, penstocks and intake tunnel were not available. These were estimated to be equivalent to the construction material used in the spillway, penstocks and intake of the Benmore power station. (Refer to Table HD7)
- The embodied energy coefficients are extracted from the same sources as table HD 7.

- The Surge tank has a height of 17m, a diameter of 37m and a capacity of 18 million litres. It is made of high strength concrete [43].

- The amount of concrete used in surge tank is calculated from the above dimensions. It is assumed that it is made of 40Mpa concrete. The embodied energy coefficient was extracted from [14].

Table HR6: Energy Associated with Non-Materials Related Earthworks/Hydraulics Construction Processes

- The Specific costs for the construction of spillway, intake tunnel, and penstocks of the Aratiatia Power Station were not available. These were estimated to be equivalent to the construction costs of spillway, intake and penstocks of the Benmore Power Station. (Refer to Table HD 8 in Appendices 4.1 and 4.2)

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories are shown below:

Common Excavation & Disposal (Spillway) - Mining and Quarrying

Engineering and Construction (Spillway) - Construction

Dewatering (Spillway) - Construction

Other Expenses including Administration (Spillway) - Construction

Cranes used in Spillway, Intake and Penstock - Transport Equipment Manufacturing

Common Excavation & Disposal (Intake & Penstocks) - Mining and Quarrying

Engineering and Construction (Intake & Penstocks) - Construction

Dewatering (Intake & Penstocks) - Construction

Other Expenses including Administration (Intake & Penstocks) - Construction

- The engineering and construction costs of the surge tank were not available and are assumed to be negligible, because the embodied energy of the construction materials is insignificant comparing to the embodied energy of the construction materials of other earth works and hydraulics.

Table HR7: Energy Embodied in Power House and Switchyard Construction Materials

- The building materials and quantities required to construct the powerhouse and switchyard for Aratiatia power station were not available. They were assumed to be the equivalent to that if Benmore power station. (Refer to Table HD 9 in Appendices 4.1 and 4.2)

Table HR8: Energy Associated with Powerhouse and Switchyard Construction

- The specific powerhouse and switch yard construction costs of Aratiatia Power Station were not available. These were approximated to be equivalent to powerhouse and switchyard construction costs of Benmore power station (Refer to Table HD10 in Appendices 4.1 and 4.2).

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories are shown below:

Common Excavation & Disposal - Mining and Quarrying

Engineering and Construction - Construction

Technical Supervision - Construction

Dewatering - Construction

Cranes used in Powerhouse Construction - Transport Equipment Manufacturing

Transport - Road Transport

Special Testing - Construction

Maintenance of Tools - Construction

Other Expenses including Administration - Construction

Table HR9: Energy Associated with Powerhouse and Switchyard Equipment

- The costs of powerhouse and switchyard equipment at Aratiatia were not available. They were estimated by multiplying the costs of equipment in Benmore power station (Refer to Table HD 11) by a factor of 90/540 = 0.167, which are the capacities of Aratiatia and Benmore power stations in MW, respectively. It was assumed that the cost of powerhouse and switchyard equipment is directly correlated to the capacity of the plant.

- The energy intensity coefficients are from [6]. The assumed industries for each of the categories are shown below:

Main Turbines - Machinery and equipment manufacturing

Auxiliary Turbines - Machinery and equipment manufacturing

Main Generators - Machinery and equipment manufacturing

Transformers - Machinery and equipment manufacturing

Communication Equipment - Machinery and equipment manufacturing

Miscellaneous P.H. Electrical Equipment - Machinery and equipment manufacturing

Cooling and Drainage Water Systems - Water Supply

Busworks and Switch Gear - Machinery and equipment manufacturing

Transmission Lines - Machinery and equipment manufacturing

Other Miscellaneous Equipments - Machinery and equipment manufacturing

Table HR10: Energy Associated with Power Station Operation and Maintenance

- As above the specific operation and maintenance costs for Aratiatia power station were not available. These were estimated by multiplying the Benmore power station operation and maintenance costs by a factor of $90/540 = 0.167$.
- The energy intensity coefficients are from [6]. The assumed industries for each of the categories are as mentioned below.

Annual Operation and Maintenance Costs - Electricity Generation and Supply

Annual Refurbishing and Replacement Costs - Machinery and Equipment Manufacturing

- The total plant energy requirement = Cost ($) * Energy Coefficient (GJ/$) * Plant Life (Years).

Table HR11: Material Embodied Energy Taupo Gates

- Data on construction materials of the Taupo gates were not available. These were estimated to be equivalent to the construction materials of the spillway in Benmore power station. (Refer to Table HD7 in Appendices 4.1 and 4.2)

Table HR12: Energy Associated with Non-Material Related Taupo Gates Construction Processes

- The costs of Engineering and Construction of Taupo gates were not available. They were estimated to be equivalent to the cost of engineering and construction of spillway of the Benomre power station (Refer to Table HD8 in Appendices 4.1 and 4.2)
- The energy intensity coefficients are from [6]. The assumed industries for each of the categories are shown below:

Common Excavation & Disposal - Mining and Quarrying

Engineering and Construction - Construction

Dewatering - Construction

Other Expenses including Administration - Construction

- It was assumed that the embodied energy associated with operation and maintenance of Taupo gates is negligible.
- It was assumed that the gates decommissioning and demolition embodied energy of Taupo gates is also negligible, as they can be used for flood control and will have a much longer life time than the Aratiatia power station.

Table HR13: Proportion of Taupo Gates Embodied Energy Associated with Aratiatia Power Station

- In 1992 the Waikato Hydro scheme generated about 4,601GWh [42]. Assume this is the annual average electricity produced by the Waikato Hydro scheme.

- Annual Energy output of Aratiatia power station is 270GWh [42].

- To estimate the embodied energy of the control centre associated with Benmore power station the total embodied energy of the control station was multiplied by (270/4601). It was assumed that all other power stations of the Waikato scheme have an operating lifecycle equivalent to that of Aratiatia power station (i.e. 200 years).

Table HR14: Energy Associated with Power Plant Decommissioning

- The earth works and hydraulics decommissioning was estimated to be 10% of their total construction costs.

- The power house and switch yard decommissioning was estimated to be 10% of equipment costs.

- The cost of building demolition was assumed to be equivalent to that of Benmore power station (refer to Table HD18 in Appendices 4.1 and 4.2).

- The energy coefficients are from [6]. The assumed industries for each of the categories are as shown below.

Hydraulic Works Decommissioning/Demolition - Construction

Power House & S.Y. Decommissioning - Construction

Building Demolition - Construction

Table HR15: Energy Associated with Land Reclamation

- The cost of Land reclamation was estimated to be equivalent to that of Benmore power station (Refer to Table HD16).

- The energy intensity coefficients are from [6]. The assumed industry for land reclamation is forestry and logging (It was assumed that reclaimed land will be converted to forests).

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