Net Energy Payback and CO_2 Emissions from Helium-3 Fusion and Wind Electrical Power Plants

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by

Scott W. White

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Abstract

A net energy analysis and life cycle CO_2 emission analysis is performed on a D^3He-fusion power plant using lunar helium-3 and five other electricity-generating power plant technologies, including a wind, conventional coal, PWR and two DT-fusion tokamak (UWMAK-I and ARIES-RS) power plants. The energy payback ratio is the amount of electrical energy produced over the lifetime of the power plant divided by the total amount of energy required to procure the fuel, build, operate, and decommission the power plants. The analysis focused on D^3He-fusion and particularly the acquisition of the helium-3 fuel from the Moon.

The energy payback ratio varies widely for the six power plants with a low of 11 for a conventional coal plant to a high of 31 for a D^3He-fusion power plant. Energy payback ratios for wind (23), nuclear fission (16), ARIES-RS DT-fusion (24) and UWMAK-I DT-fusion (27) power plants all fall in between.

The CO_2 emissions for each power plant were calculated from the life-cycle energy requirements data. The coal plant was responsible for the greatest emissions with 974 tonnes CO_2/GW_eh, followed by fission and wind (15), ARIES-RS DT-fusion (11), ARIES-III D^3He-fusion (10) and UWMAK-I DT-fusion power plant (9).

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Table of Contents

Table of Figures

Table of Tables

1 Introduction

The Energy Information Administration[1] forecasts that by 2020 world energy consumption will have grown from 1996 levels by between 38% to 108%, assuming an annual growth rate of 1.4% and 3.1%, respectively. As long as the world depends on energy technologies with finite fuelstocks, the need to find new forms of energy will persist. Between the growing energy needs in developing countries and increased use of electricity, which is forecast to increase by an average of 1.8% to 3.4% annually through 2020, there will continue to be the need for new energy producing technologies. The uncertainty surrounding the global climate effects of increased concentrations of carbon dioxide and subsequent international efforts to reduce carbon emissions, such as those discussed at the Third Convention of Parties to the Framework Convention on Climate Change in Kyoto, Japan[2], will require nations to find less carbon-intensive energy sources to meet future increasing demands.

The coal and fission industry may see their share of the electricity market grow in the near term, although environmental concerns about both fuels will likely spur on the search for energy options that are abundant, clean, safe and economically viable. Nuclear fusion may be one of these options.

It is likely that of the two fusion fuel cycles analyzed in this thesis, the deuterium-tritium (DT) fuel cycle will be the first to become economically viable due to more favorable physics and availability of the fuel. Deuterium and helium-3 (D^3He) will likely be the fuel for the second generation fusion plants. The main advantage of D^3He-fusion plants comes from the reduction by a factor of 50-100 of the number of neutrons emitted per kWh. This advantage will greatly reduce the radiation damage in the D^3He system and result in much smaller amounts of radioactive waste generated when compared to fission and DT-fusion. The main drawback to D^3He-fusion is that there are no abundant terrestrial sources of ^3He. Wittenberg et al.[3] first proposed that the Moon, discovered to have trapped at least one million tonnes of ^3He in its regolith, could supply the necessary ^3He for a D^3He -fusion economy.

The most successful electrical energy sources must excel in many areas: economics, safety, reliability, and environmental impact. It is the purpose of this thesis to address two issues that feed into the economic and environmental impact assessments of these energy sources. First, the energy payback ratio (i. e., the total amount of useful energy derived from a power plant divided by the total amount of energy invested in the power plant) should be as large as possible to generate favorable economics. Secondly, the amount of pollutants emitted per kWh of electricity generated should be as low as possible to reduce the environmental impact of future power plants.

This thesis will concentrate on one pollutant that is currently in the public's view, carbon dioxide gas. One may be tempted to invoke the popular, but mistaken view that nuclear and renewable energy sources do not emit greenhouse gases. Proponents of both nuclear and renewable energy have made many claims, a few of which are repeated here:

- "Nuclear power is a zero-carbon energy source"[4],
- "Nuclear power produces electricity without emitting any greenhouse gases."[5],
- "Wind, photovoltaics, and improved energy efficiency produce no carbon at all."[6],
- and "Additional government support of clean, carbon-free wind energy is an ideal few would disagree with..."[7].

Though these are nearly true statements when considering the electricity generation process only, they all fail to address the larger picture. All the energy (much of it fossil energy) required to mine, transport, fabricate materials of construction, as well as to build and decommission the plants must be included. When the total "cradle to grave" energy invested in nuclear and renewable facilities is amortized over the useful lifetime of the plant, there will be a finite, though smaller greenhouse gas emission rate compared to coal fired plants.

Though this thesis focuses on D^3He-fusion, five other power plants will be analyzed as well. Two DT-fusion power plants are included to provide a basis for comparison to the helium-3 fuel cycle. The comparisons of the three fusion power plants will be a main element of the overall analysis. A coal power plant and nuclear fission pressurized water reactor (PWR) are also included in this analysis to both serve as a basis to compare the fusion results to well known and understood electricity generating technologies and to serve as a barometer to compare the methodology used here with results from other energy payback studies. The sixth power plant analyzed in this thesis is a wind power plant, which is a technology that may be competitive in the future.

It is recognized that there are many other issues that will influence future debates on which of the electrical energy sources should be emphasized. These include, but are not limited to, the rate at which the world energy demand expands, the geographic distribution of fuels or materials of construction, and scale of economy (e. g., MW_e vs. GW_e). These issues will certainly play an important role in the final decisions, as will the issues of energy payback ratio and CO_2 gas emission discussed in this thesis.

Chapter 1 References

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2 Background and Literature Review

2.1 Energy Analysis

2.1.1 History of Net Energy Analyses

The use of net energy analyses (NEA) as a tool for evaluating government projects and policy originated in the 1970's. The interest in where and how energy was used seems to have paralleled the growing awareness of environmental issues and hit full stride with the Middle Eastern oil embargo of the early-1970's.

The origins of energy analysis go back many years. Reviews about the history of energy analyses by both Daniel Spreng[1] and M.C. Duffy[2, 3] point to W.S. Jevons' study of a proposal to use electric batteries charged by tidal mills in 1865 as one of the earliest energy analyses[4]. An editorial in *Energy Policy*[5] points to Nobel Prize winner, Sir Frederick Soddy, who in the 1930's suggested that energy is a more fundamental accounting unit than money, as an early precursor to NEA's. Soddy's ideas were not well received at the time.

The use of energy has been analyzed in other ways, ranging from the study of a system's thermodynamics to energy forecasting. However, it is the net energy analyses of electricity producing technologies that emerged from the early 1970's and are the most relevant to the work performed here.

It is unclear who or what initiated the "modern" net energy analysis, since several early works were published at about the same time in the early '70's. Spreng[1] suggests that Howard Odum's 1971 book, *Energy, Power, and Society*[6] stimulated the NEA concept. Soon after this, there were several papers, which analyzed the energy requirements of manufactured materials. In 1972, Makhijani and Lichtenberg[7] analyzed the energy consumed in the production of various materials, Hannon[8] focused on beverage containers and

Bravard[9] looked at the production and recycling of different metals. In 1974, Chapman[10, 11] compared the energy costs of primary and secondary copper and aluminum.

In 1973, the first energy input/output (I/O) matrix was produced in a report by R.A. Herendeen[12] of the Center for Advanced Computation (CAC) at the University of Illinois. This matrix linked the energy flows of U.S. economic sectors in a manner similar to that of economic I/O matrices and became one of several methods of performing I/O analyses (see Section 2.1.2 below).

Peter Chapman and the Energy Research Group at Open University, in the UK published the first study of the energy inputs of an energy systems in their 1974 paper, "The Energy Cost of Fuels"[13]. This was followed up the same year with an analysis of the British nuclear power program along with various nuclear power technologies[14, 15].

As energy research groups sprung up at institutions such as the Open University, the University of Illinois, Oak Ridge National Laboratory, and others, a number of analytical approaches were adopted. These methods broadly fall into two categories, the input/output analysis (I/O) and the process chain analysis (PCA).

2.1.2 Input/Output Approach

Before the energy input/output matrices were developed by Herendeen[12] in 1973, the I/O method had long been used as an economics analysis tool. The I/O approach was first introduced as an economics modeling technique by Wassily Leontief[16] in 1936. The original model divided the U.S. economy into 43 economic sectors and measured the flow of money between each sector. The model which was expanded and improved in later years[17, 18] was designed to interconnect the industries of an individual nation to account for all flows of money.

With the first energy I/O matrix[12], the flows of goods and services were expressed in energy terms rather than money. This energy I/O matrix was based on the 1963 economy of the United States and was updated later[19, 20]. The first paper in which the I/O method was applied to energy analysis was by Bullard and Herendeen[21] of the CAC. This work also coincided with Herendeen's I/O matrix.

The main advantage to using the I/O method in net energy analyses is that it uses the most thorough and readily available information, monetary costs of products, and services which can be translated into units of energy. The energy analysis, therefore, also tends to be very thorough. It eliminates the complicated process of identifying all relevant inputs and outputs of process steps.

There are some disadvantages to using the I/O approach. The matrices can only analyze industries as a whole, and they can not take into account different methods of production, varying energy efficiencies, individual firms or different technologies. The data is always several years old since it uses census data, which takes up to eight years to analyze[1]. Another disadvantage is that all transactions are dealt with in financial terms and not physical quantities. Errors can occur if commodities are liable to large price fluctuations or if some purchasers are able to get special prices for the commodity[22]. Another disadvantage is that with inflation, price levels of a commodity can change, but the energy cost may not[23]. Finally, new technologies or economic sectors, such as nuclear fusion, do not fall into the sectors defined in the matrix.

2.1.3. Process Chain Analysis

The Process Chain Analysis (PCA), or Process Analysis as it is often referred to, addresses an actual production process and tries to establish its energy and material inputs and outputs. It requires defining the specific processes involved in the production of a product, analyzing each process individually and summing the energy expended for each process. In relation to energy accounting, it involves identifying all of the energy-consuming processes and defining the boundaries of each. Figure 2.1 shows the process chain of a coal-fired electrical power plant. This figure shows the individual processes included in the analysis of energy requirements for the conventional coal plant included in this thesis. The energy requirements of each process are

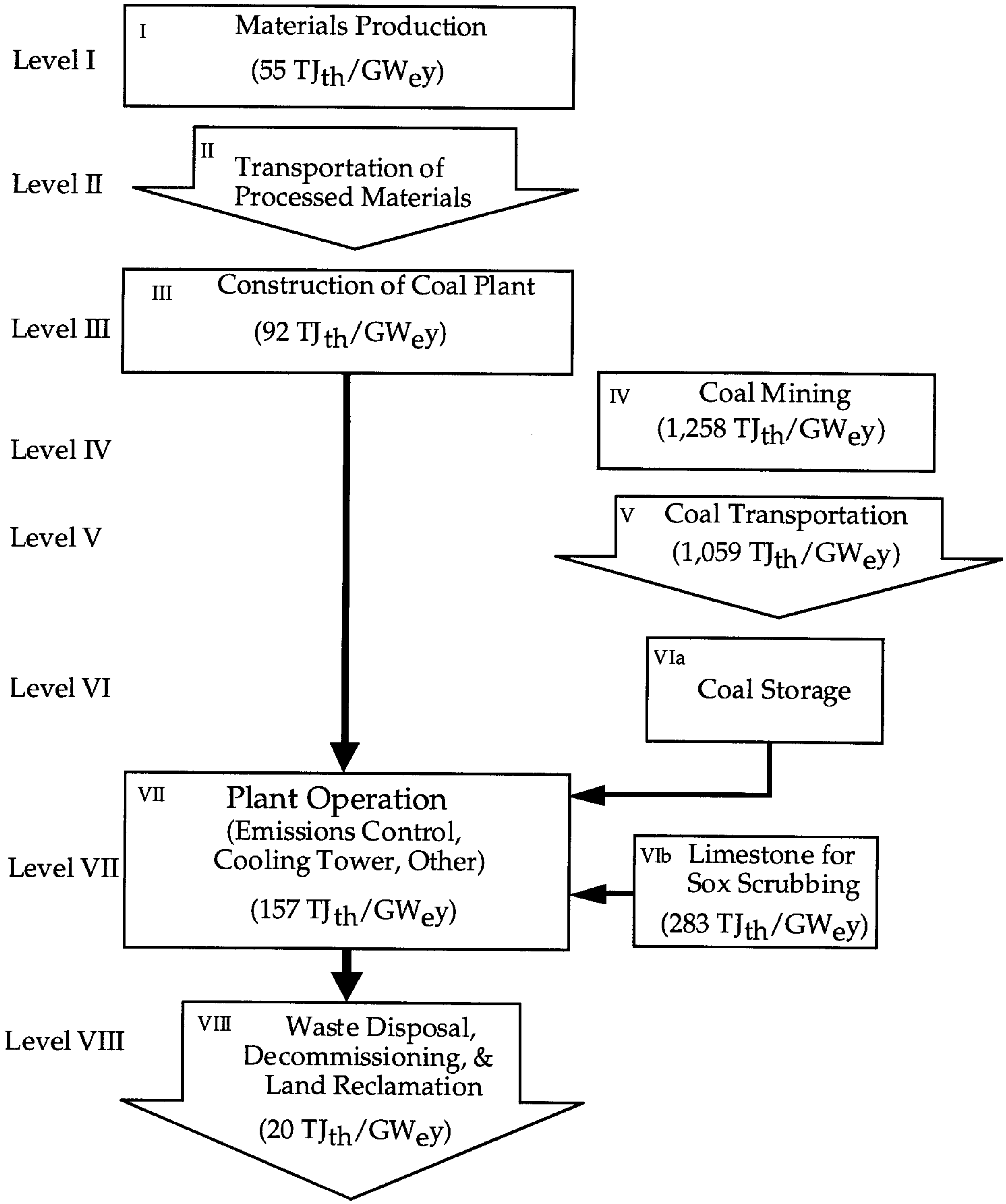

Figure 2.1: Graphical Representation of the Process Chain for a Coal Plant

shown within each box and again in Figure 2.2, which is an example of the energy payback ratio (EPR). The EPR is the ratio of energy produced over the lifetime of a power plant over

$$1\ GW_e \times \frac{8760\ hrs}{year} \times \frac{3.6\ TJ}{GW_e h} = 31{,}536\ TJ_e/GW_e y$$

$$\mathbf{EPR} = \frac{\mathbf{Energy\ Output}}{\mathbf{Energy\ Input}} = \frac{31{,}536}{2{,}925} = \mathbf{10.8}$$

$TJ_{th}/GW_e y$

Materials = 55

Construction = 92

Coal Mining = 1,258

Coal Transportation = 1,059

Limestone = 283

Plant Operation = 157

Waste Disposal, Decommissioning, & Land Reclamation = 20

Total = 2,925

Figure 2.2: An Example of the Energy Payback Ratio Equation.

the energy requirements over the plants life. The coal plant in Figure 2.1 has an EPR of nearly 11. The EPR will be explained and discussed more thoroughly in Section 3.1.

References to the PCA method of energy analysis have been traced to Chapman[22] in 1974, but the technique is likely to have been used long before this without being formally defined or necessarily applied to the analysis of energy. For example, in 1972 Bravard[9] used the PCA to determine the energy requirements to produce several types of metals without actually referring to it as such.

There are several advantages to using the PCA method. It is best suited for analyzing specific processes or power plant in which the flows of materials and energy are well understood. It is more flexible than the I/O method in that the author can clearly define the boundaries of the analysis and the modularity of the analysis allows for changes to individual processes to be readily incorporated into the model. The level of detail of the PCA method aids in the measurement of emissions, such as CO_2, from the very same data that measures the energy requirements.

There are several disadvantages to using the PCA method. Though this method works well with direct energy inputs, it becomes increasingly more complicated when analyzing the indirect energy inputs associated with equipment, materials and services. Chapman[22] points out that it is difficult to choose an appropriate subsystem and to attach the appropriate energy value to inputs that partially rely on the outputs of the given process. As an example, he states that to determine the input energy value for steel machinery that is used to manufacture steel first requires an energy value of steel. Another disadvantage to the PCA method as noted by Spreng[1] is that estimates of inputs and outputs may be inaccurate for new processes that have not passed the "acid test of routine application".

It is expected that the I/O method slightly overestimates the energy intensity because some of the cost is needed for profit, bank interest, and so forth. On the other hand, the PCA approach probably underestimates the energy investment because it does not include all the auxiliary energy requirements associated with individual processes. In this study both the I/O and PCA techniques have been used. The PCA method is used when possible and the I/O method was employed mainly to assess non-materials related processes. It is thought that the combination of the two will result in a reasonable, but not perfect, assessment of the energy inputs.

2.1.4 Key Institutes in Net Energy Analysis

There are three major groups that have been influential in the field of net energy analysis; the Energy Research Group of the Open University (UK), the Institute for Energy Studies at the

Oak Ridge Associated Universities and the Energy Research Group of the University of Illinois. All of these groups had their start in the mid-1970's and were responsible for net energy analyses of numerous technologies as well as key papers on the application of NEA's. Spreng[1] summarizes the works of each of these institutes.

2.1.4.1 Energy Research Group, The Open University, UK

Led by Peter Chapman, the Energy Research Group was one of the early leaders in the field of net energy analysis in the 1970's and 1980's. Chapman's 1974 paper, "Energy Costs: A Review of Methods"[22] is an important document in the field and is frequently referenced.

Some of the earliest net energy analyses came out of the Open University including Mortimer's 1973 analysis of the energy cost of transport in the UK[24]. In the next year, Chapman was quite prolific publishing a review of methods for net energy analysis[22], a paper on nuclear power[25], two papers on the energy requirements for copper and aluminum production[10, 11], and a net energy analysis of fuels[13]. In 1975 a third and more comprehensive NEA on nuclear power stations was published in the journal *Energy Policy*[15].

Chapman's papers on nuclear power plants introduced the "dynamic analysis", which focused on whether a rapidly growing energy program in general (a nuclear program in particular) is overall a net-energy producer or consumer. In the 1980's, two more energy analyses of metals production were published by Boustead[26] and Hancock[27].

2.1.4.2 Institute for Energy Studies, Oak Ridge Associated Universities

A large number of studies on a variety of power plant technologies came out of this institute. One of the earliest studies on the energy requirements of processes was published by Bravard in 1972[9], which analyzed the energy expenditures associated with the production and recycle of metals. Guidelines on net energy analysis were published by Perry et al.[28] in 1977. Net energy analyses focused on primary sources of electricity such as coal[29] and fission[30, 31], as well as alternative fuels such as in-situ oil shale processing[32], ocean thermal energy conversion[33], and municipal solid waste[34]. Other studies focused on the energy cost of freight transport[35], energy used in construction of energy facilities[36], and various goods[37]. One of the key books on net energy analysis, by Spreng[1], was also a product of this institute. The Institute for Energy Analysis no longer exists.

2.1.4.3 Energy Research Group, Center for Advanced Computation - University of Illinois

The Center for Advanced Computation (CAC) utilized input/output matrices to analyze power plants and technologies. The key papers to come out of this institute include Herenedeen's original I/O matrix[12] and Bullard, et al.'s "Handbook for Combining Process and Input-Output Analysis"[23, 38]. Though many of the analyses that came from this institute relied heavily on the I/O method (see also [19, 20, 39-41]), there were a number of studies that came from this institute that focused on power plants, such as the solar power satellite[42] and geothermal technologies[43]. A report that was heavily used in this thesis for calculating both the energy requirements and CO_2 emissions of materials production was by Penner et al.[44], which relied heavily on the process analysis method.

2.1.5 Applications to Power Plants

There have been numerous net energy analyses performed on a variety of electricity generation technologies. It was found that there is no single way to perform a net energy analysis nor is there one type of result that can be generated from such studies. Some studies have analyzed an individual power plant, while others analyzed an entire system of similar power plants. The goal of some studies is to generate an energy payback ratio, while others calculate the net energy balance, payback time, harvest ratio, or the energy requirements of individual processes.

2.1.5.1 Coal

Net energy analyses of coal have been included in many of the studies performed. As the primary source of electricity in much of the world, coal plants are included in most studies of new technologies for comparison purposes. Two energy analyses of coal plants were performed by the Institute of Energy Analysis (IEA) at Oak Ridge Associated Universities (ORAU) in 1977. Whittle and Cameron[29] calculated the energy requirements for several fluidized-bed and conventional coal power plants which were later included in a net energy analysis of five technologies by Perry et al.[45].

Coal technologies were included in broader studies by the Institute for Energy Policy[46], Cirillo[47], Tsoulfanidis[48], and Uchiyama[49, 50]. A coal plant was compared to a fission power plant in an energy requirement analysis by Rombough and Koen[51]. The energy requirements of transporting coal via various methods were analyzed by Szabo[52].

2.1.5.2 Wind

There have been several papers which have included net energy analyses of wind-generated power. The earliest two were in the United States by Perry et al. [45] and Devine [53] in 1977. More recently the NEA's involving wind have been performed outside of the United States. There have been three German NEA's involving wind [54-56], two Danish reports[57, 58] and two reports by Uchiyama of Japan[49, 50]. The most recent NEA of wind was published in the U.S. by White and Kulcinski[59].

2.1.5.3 Fission (Light Water Reactors)

The primary focus of NEA's in the 1970's was nuclear fission. Several independent studies focused solely on Light Water Reactors (LWR), while a number of others also included other technologies, such as coal, for comparison. Chapman[15] analyzed six different fission technologies, while Rotty et al.[30] analyzed pressurized water reactors (PWR) and boiling water reactors (BWR) with varying qualities of uranium ore. Rombough and Koen's analyzed the energy requirements of both PWR's and BWR's[51]. The analysis of nuclear (fission) power by Tyner, et al.[60] focused on an entire generation and transmission system and not just an individual power plant. Held et al.[61] performed an energy analysis of nuclear power and its fuel cycle.

NEA's of fission power plants were also included in studies that focused on other technologies as authored by Bünde [62], Tokimatsu[63], and Uchiyama[50]. Hohenwarter and Heindler determined the net energy output of the German LWR program[64], while Weis et al.[65], Kolb[66], Moraw[67] and Walford[68] determined the energy requirements of the nuclear fuel cycle.

2.1.5.4 DT Fusion

Only a handful of NEA's have been performed on deuterium-tritium fusion. The earliest was performed by Fillo et al.[69] in the late 1970's. There were two more complete NEA's that focused on DT fusion in the 1980's by Tsoulfanidis[48] and Bünde [62]. The most recent NEA studies were published in 1995 by White[70], and 1998 by White and Kulcinski[71], and Tokimatsu[72].

2.1.5.5 D^3He Fusion

There has been but one other published report involving a NEA of D-^3He fusion. This was performed by Fillo et al.[69] and involved the bumpy torus (a plasma confinement design) satellite reactor design with terrestrial derived ^3He.

2.1.5.6 Other

There have been several NEA's of other types of electricity generating technologies. Cirillo et al.[47] performed a net energy analysis of Satellite Power Systems (SPS), which included similar analyses of nuclear LWR, two coal-fired technologies (atmospheric fluidized bed combustion and coal-gasification/ combined cycle), two terrestrial solar technologies (thermal and PV) and two space solar technologies (SPS - Silicon, SPS-GaAlAs)[47]. Satellite Power Systems have also been studied by Herendeen et al.[42] and Frantz and Cambel[73].

Other technologies on which NEA's have been performed include solar district heating[74], geothermal technologies[43], ocean thermal energy conversion[33], municipal solid waste[34], in-situ oil shale processing[32], and biomass[75, 76]. Energy payback times were calculated in an analysis of solar photovoltaics by Palz and Zibetta[77], Aulich et al.[78] and Hagedorn[56].

2.2 CO_2 Emissions

2.2.1 Emissions Analyses of Power Plants

A number of papers have determined the emissions of carbon dioxide associated with the life-cycles of various electrical power generation technologies. A report published in 1994 by the International Atomic Energy Agency (IAEA), "Comparison of Energy Sources in Terms of Their Full-Energy-Chain Emission Factors of Greenhouse Gases"[79], is one of the most comprehensive collections of papers on this topic. In particular, the paper by J. F. Van de Vate provides an overview of published reports on this topic[80].

A big difference between net energy analyses and life-cycle CO_2-emission analyses is that virtually none of the CO_2-emission analyses focus on one technology. Many are comprehensive analyses including three or more technologies.

2.2.1.1. Coal

Analyses on the life-cycle output of CO_2 associated with coal-fired power plants have been performed by Dones[81], Friedrich and Marheineke[82], Fritsche[55], Lewin[83], Meridian Corporation[84], San Martin[85], Science Concepts, Inc.[86], Sullivan[87], Uchiyama[50], Van de Vate[88], White[70], and Yasukawa[89].

2.2.1.2. Wind

Analyses of the life-cycle emissions of CO_2 associated with wind generated electricity were included in the following papers: Friedrich[82], Lewin[83], San Martin[85], Uchiyama[90], Van de Vate[88], White and Kulcinski[59], and Yasukawa[89].

2.2.1.3. LWR

Analyses of the life-cycle emissions of CO_2 associated with wind generated electricity were included in the following papers: Dones[81], Friedrich and Marheineke[82], Fritsche[55], Lewin[83], Meridian Corporation[84], Uchiyama[50], White[70], and Yasukawa[89].

2.2.1.4. DT Fusion

Analyses of the life-cycle emissions of CO_2 associated with DT-Fusion have been the subject in papers by White[70] and Tokimatsu[63].

2.2.1.5. D^3He Fusion

There no known studies on the CO_2 emissions associated with the production of electricity from D^3He Fusion.

2.2.1.6. Other

Other electricity generating technologies have also been subject to life-cycle CO_2 emissions analyses. Solar photovoltaics[49, 81, 83-85, 88, 89, 91, 92], hydropower[50, 81, 85, 88, 89, 91, 93], oil-fired plants[50, 81, 85-89], natural gas-fired units[50, 55, 81, 83, 85-89], biomass-fueled plants[76, 85, 88, 94], geothermal[85], and solar thermal[85] technologies have all been included in these analyses.

2.3 Power Plant and Infrastructure Designs

2.3.1 Power Plants

Several different designs for each type of power plant used in this analysis were reviewed, before a reference plant was chosen. The bill of materials for the coal plant was from El-Bassioni[95]. There were several light water reactor designs to choose from including those by El-Bassioni[95], Bryan[96], Inhaber[97] and Bünde[62]. Bryan's design was selected for this work because of its level of detail.

There were a number of DT-Fusion designs to choose from though many were slight variations of earlier models. The UWMAK-I[98] design was the most detailed ever published while the ARIES-RS[99] design was one of the most recent designs using advanced materials. Both are included here.

There were two D^3He fusion designs to choose from, the ARIES-III[100] and the APOLLO[101, 102] design. It was opted to use the ARIES-III design to be consistent with the use of the ARIES-RS, although the APOLLO plants were more efficient. Both designs were limited to the nuclear island (the structure where the plasma is confined, including the magnets) and each required some assumptions and scaling to fill out the balance of plant.

Three independent wind projects were analyzed for a previous project, including the two-turbine DePere wind project, 73-turbine Buffalo Ridge Phase-I[103] and the 143-turbine Buffalo Ridge Phase-II[104]. The Buffalo Ridge Phase-I project, which utilized Kenetech wind-turbines was used for the primary comparison due to the 3 years of production history. The other two projects will not be completed until after this thesis is finished.

2.3.2 Lunar Base for Helium-3 Procurement

Data on a complete lunar base is scarce. While there are designs of different types of habitats, only Koelle[105-109] has designed a lunar base that has a complete timetable of development. The costs and material requirements of a lunar base are both included in these reports.

However, energy inputs and gaseous emissions data surrounding the infrastructure was not included.

2.3.3 Rockets

Complete data on the bill of materials of a functioning large rocket is scarce. Koelle has designed the NEPTUNE[110, 111] heavy lift launch vehicle (HLLV) which is assumed to carry the crew and habitat infrastructure to the lunar base. Unfortunately, detailed data on the material for the Saturn V, a logical choice for this analysis, was not found. Energy and CO_2 emissions analyses of rockets were also not located. Rice performed an energy impact assessment of the space shuttle and various launch vehicles[112, 113].

2.4 Studies that cover both energy requirements and CO_2 emissions

There have been few papers that have coupled energy analysis and a life-cycle analysis of CO_2 emissions associated with power plants. Hagedorn[56] coupled the energy requirements and CO_2 emissions of solar photovoltaics, Weis et al.[65] did the same for the uranium fuel cycle, Born[76] analyzed biomass, while Uchiyama[50] recently analyzed twelve different technologies including coal, fission and wind.

Chapter 2 References

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3 Methods

One of the main purpose of this thesis is to couple the net energy analysis of electricity producing technologies with a life-cycle analysis of the CO_2 emissions. The two primary products of this analysis are the energy payback ratio (EPR) and the CO_2 emission factor of each technology. The methods used to determine these results are explained below.

3.1 Calculation of Energy Payback Ratio

The concept is straight forward. First, all the useful energy produced by an electrical power plant over its lifetime is determined. Second, the total amount of energy needed to gather all the fuel and construction materials, and the energy needed to construct, operate, and decommission the plant is calculated. Third, the energy payback ratio (EPR) is determined by the relationship in equation 3-1.

$$\boldsymbol{EPR} = \frac{\boldsymbol{E}_{n,L}}{\left(\boldsymbol{E}_{mat,L} + \boldsymbol{E}_{con,L} + \boldsymbol{E}_{op,L} + \boldsymbol{E}_{dec,L}\right)} \tag{3-1}$$

where, $\boldsymbol{E}_{n,L}$ = the net electrical energy produced over a given plant lifetime, L.

$\boldsymbol{E}_{mat,L}$ = total energy invested in materials used over a plant lifetime L.

$\boldsymbol{E}_{con,L}$ = total energy invested in construction for a plant with lifetime L.

$\boldsymbol{E}_{op,L}$ = total energy invested in operating the plant over the lifetime L.

$\boldsymbol{E}_{dec,L}$ = total energy invested in decommissioning a plant after it has operated for a lifetime L.

In practice, the calculation of the output energy is easy but the determination of the input energy is not. Two approaches to calculate the input energy have been used in the past. As described in section 2.1.2, the Input/Output method relies on the simple concept that to a large degree, the more expensive an item or service, the larger the energy content of that item or service. With the use of an energy I/O matrix, this approach allows one to calculate the energy input of a process once the cost of goods and service inputs are known.

The second approach is the Process Chain Analysis (PCA), as described in section 2.1.3, which addresses each process contributing to the useful lifetime of the power plant. The PCA method measures the flows of materials and energy for each process, it translates material flows into energy via an embodied energy factor, and sums the total energy requirements. Because this approach is very specific to the types of fuels used in each process, it greatly aids the calculation of CO_2 emission rates.

Figure 3.1 illustrates, schematically, the general approach taken to calculate the denominator of Equation 3-1. Note that the energy input can also be considered to be made up of two components: a capital investment in the power plant (including construction and decommissioning), as well as an operating component that includes the fuel and processes needed to operate the plant. Certain assumptions have to be made about the capacity factor (the fraction of time the plant is actually making electricity), the maintenance and repair during the operation period, and the expected lifetime of the plant. The end result is reported in units of gigajoules (GJ, or 10^9 joules) per net gigawatt electric year (GW_ey, or 10^9 watts for one year) which, when multiplied by the total net electricity generated, gives the total energy invested in the plant over its lifetime. The net energy produced is just the total net electrical energy generated converted to GJ for consistency.

The data for individual processes associated with coal, fission, DT fusion and wind plants were gathered from various sources and are discussed further in sections 3.4.1 - 3.4.4.

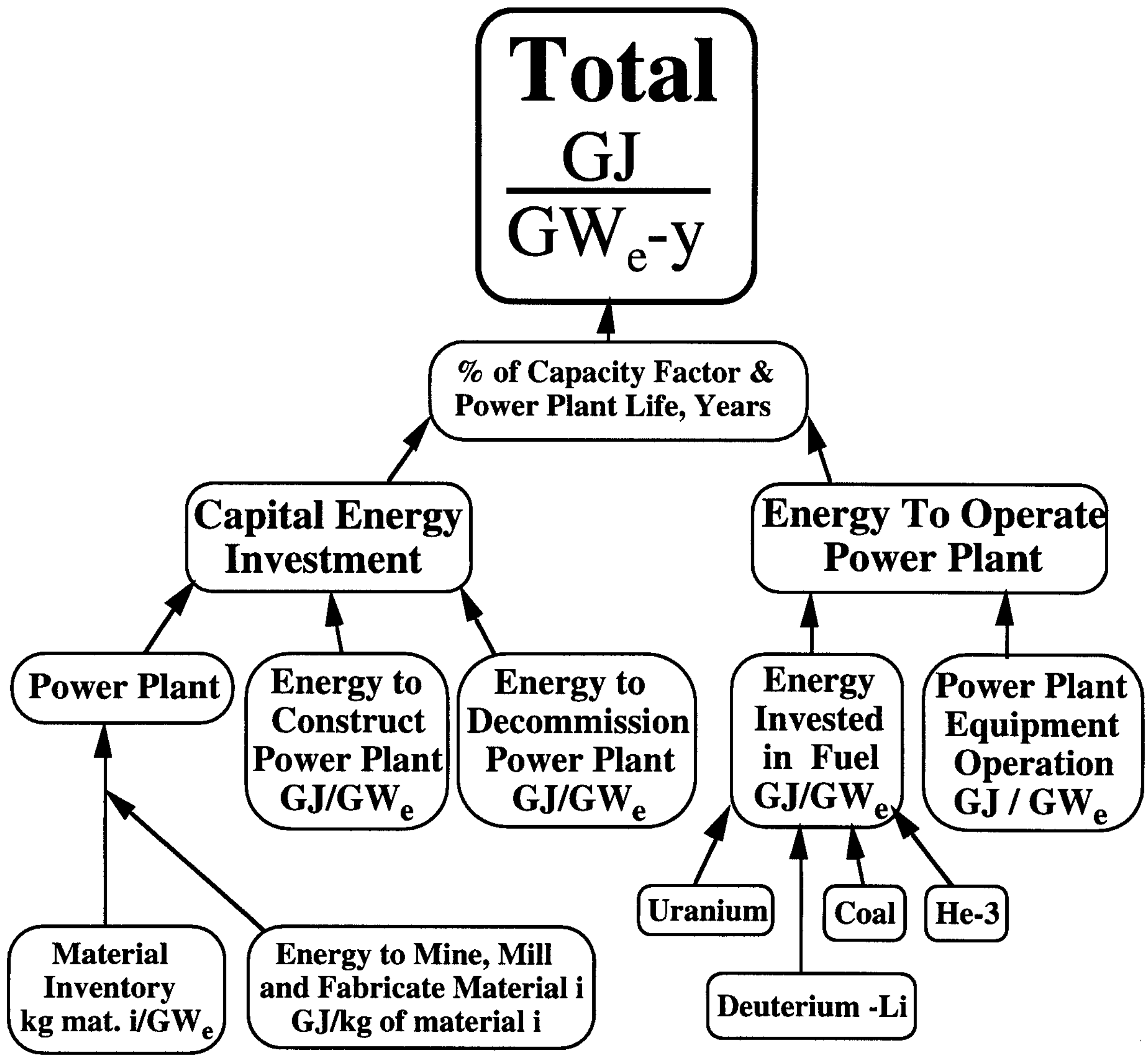

Figure 3.1: Schematic of the Method Used to Calculate the Energy Inputs to Various Electrical Power Plants.

Data for D^3He fusion is discussed in detail in section 3.3. All data was compiled on Microsoft® Excel spreadsheets and linked to databases of material inventories, the embodied energy of materials and CO_2 emission factors. The thermal energy value for electricity was based on the standard U.S. mix of electricity for 1996. Complete details for this distribution and other energy requirements can be found in Appendix A.

3.2 Calculation of the CO_2 Emission Factor

Every time energy (thermal or electrical) is used to make a product, some waste products are released to the environment. In the best case, this waste product is just heat. In most cases, the waste products include greenhouse gases such as CO_2, NO_x, CH_4, etc. The pollutants emitted during the generation of electricity depend on whether the power plant is fueled by coal, uranium, deuterium and tritium (DT), wind, or D^3He. In this thesis, the CO_2 emission factor for electricity was based on the average of the U.S. electrical mix of 1996, as shown in Appendix A.

Once the EPR is determined, one can use the components of energy input to calculate the emission of a specific pollutant (i. e., CO_2 per kg of fuel, metal, or concrete for each GW_ey of net electricity sent to consumers). This is stated mathematically, for CO_2 in Equation 3-2;

$$\frac{kg.CO_2}{GW_ey} = \frac{\sum_i \left(\frac{kg.CO_2}{kg.M_i}\right) \bullet kg.M_i}{E_{n,L}} \qquad (3\text{-}2)$$

where $E_{n,L}$ = the net electrical energy produced over a given plant lifetime, L.

$\frac{kg.CO_2}{kg.M_i}$ = kg of CO_2 emitted per kg of material i produced

$kg.M_i$ = kg of material i needed to construct and/or operate the plant for life L

Where applicable, the energy inputs are broken down into both thermal (TJ_{th}, GJ_{th}) or electrical (TJ_e, GJ_e, GW_eh) energy. This was done to account for the different emission factors for thermal fuels, such as diesel, gasoline, or coal and electricity. The total energy is accounted for in terms of thermal energy and is the sum of the electrical energy divided by the electricity efficiency (36.9%, see Appendix A) and the thermal energy.

3.3 D^3He Fusion Power Plant

Since one of the unique features of this thesis is the complete analysis of the helium-3 fuel cycle, this topic will be examined first. Later (section 3.4), other technologies will be discussed, based on open literature results.

3.3.1 Power Plant

The analysis of D^3He fusion was based on a 1000 MW_e D^3He fusion power plant. It was assumed that the power plant would operate for 40 years with a 75% capacity factor. This means that for nine months of the year, the plant produces electricity, with the balance of the year it is down for repairs and/or maintenance. With a design capacity of 1000 MW_e, the plant would produce a net 8,766 GWh of electricity per full-power year and 263 TWh of electricity over it's 30 full-power year lifetime. This number serves as the numerator in equation 3.1.

The specific design used in this study is the ARIES-III[1] tokamak power plant. The ARIES-III design only included the nuclear island. The material requirements were calculated using the raw data for materials as given by the volume fraction of various materials in each component. The product of the volume and density of each material (mass) is shown in Table 3.1.

The ARIES-III balance of plant (BOP) was based on that of the more detailed UWMAK-I design with some modifications. ARIES-III is designed to be steady-state, which UWMAK-I was not. This difference led to several design features of UWMAK-I which would not be used in the ARIES-III reactor. Such omissions include, thermal flywheels, energy storage unit, building liner and revolving door. The rest of the BOP mass of the ARIES-III was scaled from UWMAK-I data by the ratio [$MW(th)_{ARIES\text{-}III}/MW(th)_{UWMAK\text{-}}$

$_I]^{0.8}$. The results of this analysis can also be seen in Table 3.1. The ARIES-III total mass (~550 million tonnes), which is the sum of the nuclear island and BOP mass is found in Table 3.2.

In calculating the energy requirements and CO_2 emissions associated with plant materials, the mass of each material was multiplied by the corresponding multiplier for each. The energy and CO_2 emission factors for materials from ARIES-III as well as the other power plants analyzed in this study are listed in Table 3.3 and detailed in Appendix B.

Table 3.1 Summary of ARIES-III Nuclear Island and Balance of Plant Materials

Nuclear Island[1]	**(Tonnes/GW$_e$-installed)**
Copper	1,078
Helium	3
Carbon Steel	5,763
Stainless Steel	3,387
Nickel	2,064
Nb_3Sn	215
Insulator	35
Subtotal	**12,544**
Balance of Plant	
Concrete	490,050
Copper	298
Carbon Steel	46,790
Stainless Steel	9,490
Subtotal	**546,629**

Table 3.2 Summary of ARIES-III Power Plant Materials

Element or Alloy	**(Tonnes/GW$_e$-installed)**
Concrete	490,050
Copper	1,377
Helium	3
Carbon Steel	52,553
Stainless Steel	12,877
Nickel	2,064
Nb_3Sn	215
Insulator	35
Total	**559,173**

Table 3.3: Summary of Energy and CO_2 Emission Factors for Power Plant Materials

Element or Alloy	Energy (GJ/tonne)	CO_2[a] (kg CO_2/tonne material)
Aluminum[b]	208	13,738
B_4C[c]	211	13,193
Chromium[d]	83	5,393
Concrete[e]	1.4	520
Copper[b]	131	7,446
Fiber Glass[f]	13	804
Helium[g]	536	33,649
Insulation Materials[c]	95	5,680
Insulator (ARIES-III)[j]	54	6,388
Lead[d]	35	2,498
Lithium[c]	853	53,021
Manganese[h]	52	3,502
Mercury[d]	87	4,941
Molybdenum[d]	378	20,298
Nickel[d]	184	9,828
NbTi/Nb_3Sn[c]	211	13,193
Silver[d]	16,809	1,055,934
Sodium Metal[h]	124	7,727
Steel - Carbon/Low Alloy[c]	34	2,473
Steel - Stainless[c]	53	3,275
Titanium[h]	444	27,582
Tungsten[j]	418	25,797
Vanadium[d]	3,711	229,596
Yttrium[j]	1,471	84,065
Zirconium[j]	1,612	97,150

[a] All CO2 emissions were calculated from energy data.
[b] ref. [2]
[c] ref. [3]
[d] ref. [4], chromium data based on high-chromium FeCr; Molybdenum based on FeMo; nickel based on electrolytic Ni; lead data is from Penner with different fuel energy factors; vanadium data based on FeV.
[e] ref. [5]
[f] ref. [6]
[g] ref. [7]
[j] from ref. [8]
[h] from ref. [9]

The ARIES-III construction data comes from work performed by the ARIES team, provided by Ron Miller[1]. The construction energy requirements were determined by using the I/O method based on the costs of plant construction. Table 3.4 shows the cost information of ARIES-III construction as used in this study. The costs of materials were removed from the original table, since they were analyzed separately (as mentioned above). The I/O energy table

Table 3.4: Summary of Energy Required for the Construction of ARIES-III - Does Not Include Materials

Account number	Account Description	Cost (1990 M$)[1]	Inflation index to 1967	Cost (1967 M$)	I/O Sector Number
21	Structures & Improvements	Included in Materials	4.59	Included in Materials	1103
22	Reactor Plant Equipment				
22.1.04	supplemental-heat./CD system[1]	273	3.95	69	AV7
22.1.0.5	primary structure & support	Included in Materials	3.95	Included in Materials	1103
22.1.0.7	power supply, switching, energy storage	47	3.95	12	AV8
22.1.0.8	impurity control	8	3.95	2	AV9
22.1.0.10	ecrh breakdown equip.	4	3.95	1	AV7
22.1	Reactor Equipment				
22.2	2 main heat transfer. & transport.	Included in Materials	3.95	Included in Materials	AV11
23	Turbine Plant Equipment	Included in Materials	3.95	Included in Materials	AV2
24	Electric Plant Equipment	96	3.35	29	AV12
25	Misc. Plant Equipment	52	3.47	15	AV13
26	Special Materials	1	4.59	0.1	2704
90	Direct Cost (not incl. contingency)	1897			
91	Construction Services	214	4.36	49	AV14
92	Home Office Engineering	99	4.13	24	7301
93	Field Office Engineering	99	4.13	24	7301
	Total	2,791		225	
	Total per 1000 MW_e[2]	2,791		225	

1 Scaled from ARIES-RS value, accounting for price index and CD heater power ratio (160 MWe:81 MWe)
2 Totals may not equal columns due to independent rounding.

for each sector is listed in Table 3.5. The construction energy requirements were calculated by multiplying the cost of each construction element in Table 3.4 by the corresponding energy intensity listed in Table 3.5. The results can be found in section 4.1.2.

Table 3.5: Energy Intensity's Used for his Study with Thermal and Electric Components Separated[10]

Sector Number	Name	Thermal (MJ_{th}/ 1967$)	Electric (MJ_e/ 1967$)	Total (MJ_{th}/ 1967$)
1103	New Construction, public utilities	67.27	6.91	76.27
1105	New Construction, other	77.22	6.26	98.19
1202	Maintenance Construction, other	51.69	3.88	64.69
2704	Miscellaneous Chemical Products	156.75	12.75	199.46
4003	Heating Equipment	53.84	7.66	79.51
4806	Special Industrial Machinery	45.09	6.36	66.40
4901	Pumps, compressors	42.25	5.90	62.02
4907	General Industrial Machinery	49.47	6.81	72.28
5301	Electric Measuring Equipment	27.31	3.56	39.24
5404	Electric Hardware	53.85	7.24	78.11
5503	Wiring Devices	54.07	8.01	80.90
5805	Electrical Equipment	51.19	6.02	71.36
6107	Transportation Equipment	71.23	10.92	107.81
7301	Miscellaneous Business Service	24.63	2.32	32.40
AV1	(4003,4806,4907)average	49.47	6.94	72.73
AV2	(4806,4901,4907)avg.	45.60	6.36	66.90
AV3	(5301,5404,5805)avg.	44.12	5.61	62.90
AV4	(4806,4907)avg.	47.28	6.59	69.34
AV5	(1202,7301)avg.	38.16	3.60	48.55
AV6	(1105,7301)avg.	50.93	4.79	65.30
AV7	(5805, 5404)avg.[1]	52.52	6.63	74.74
AV8	(5303,5404,5805)avg.	46.95	6.05	67.23
AV9	(4806,4901)avg.	43.67	6.13	64.21
AV10	(5303,5805)avg.	43.50	5.46	61.79
AV11	(1105,4901)avg.	59.74	6.08	80.11
AV12	(5301,5303,5404,5503,5805)avg	44.44	5.95	64.37
AV13	(2704,4806,4907,6107)avg.	80.64	9.21	111.49
AV14	(1102,7301)avg.	40.67	4.08	54.34
	Auto Repair[2]			23.27

[1] AV7 - AV14 were determined by author.
[2] based on 1977$, from Spreng [11]

The CO_2 emissions were calculated by multiplying the total thermal energy by the emission factor of fuel oil and the total electrical energy by standard U.S. electrical mix emission factor. These results are listed in section 4.2.2.

The energy requirements for operations and maintenance (O&M) are defined in this study as any energy consumed by the power plant that is purchased or supplied from an outside source. This means that energy produced by the power plant for its own consumption, called station use, is not included here because it is already accounted for in the power plant design and shows up in the analysis as a larger plant (more materials) and greater fuel usage. Only the energy required to keep vital equipment operating during the 25% of the time the plant is not producing electricity is included, since this energy will have to be produced elsewhere or on site by other means.

The O&M energy data for the ARIES-III D^3He-fusion power plant data was based on information in the UWMAK-I report[12]. The equipment that will require energy during downtime includes, the cryogenics plant, after-heat cooling and the HVAC (including pumps, fans and miscellaneous equipment). This data was calculated from the UWMAK-I report. Processes used by UWMAK-I that are excluded here include, liquid metal heating and tritium separation neither of which will be used in the D^3He ARIES-III plant. There was also a difference in heat exchanger coolants in the two plants with the UWMAK-I using a lithium/sodium combination and ARIES-III an organic coolant.

It should be noted that the UWMAK-I DT-fusion power plant was designed to generate 1.475 GW_e of electricity. For all comparisons, UWMAK-I data was first scaled to 1 GW_e. The ARIES-III and ARIES-RS energy use for the cryogenics plant was scaled linearly from the normalized UWMAK-I data (GJ/GW_e) based on the ratio of each designs' magnet mass per GW_e-installed power. The mass of magnets are 13,078 tonnes for UWMAK-I, 4,588 tonnes for ARIES-RS, and 3,018 tonnes for ARIES-III. The energy data for cryogenics cooling from the UWMAK-I report is listed in Table 3.6. The totals do not include the nuclear heating load losses and divertor/transformer coil losses, which will not draw power during maintenance downtime[13]. The energy requirements for after-heat cooling were assumed to be the same as the percentage of full power as determined in UWMAK-I.

The HVAC energy use in the UWMAK-I report included fans, vacuum pumps, miscellaneous, and "other" systems. “Miscellaneous” was based on 5% of the total auxiliary power. HVAC thermal energy data was scaled linearly from UWMAK-I (5000/1.475 = 3,390 MW_{th}) based on thermal power of the plants. The salaries for ARIES-III personnel were scaled from UWMAK-I based on the thermal energy ratio. The embodied energy of the salaries was calculated using the “miscellaneous business service” sector energy intensity, listed in Table 3.5, and the I/O method and adjusted for inflation.

For the energy analysis, all operational energy was converted to thermal energy. To determine the CO_2 emissions the electrical energy was multiplied by the emission factor of the standard United States’ electrical mix in 1996.

The energy requirements for decommissioning the ARIES-III power plant was normalized from data on PWR decommissioning by the ratio of each plant’s mass. Radioactive

Table 3.6: Cryogenics Cooling - from UWMAK-1[12]

	Watts (W_e)
Radiation Loss	433
Conductive Loss	1,734
Resistive Losses	376
Lead Losses	1,200
Transfer Line Losses	786
Total (less Nuclear heat loss)	**4,529**
Multiplier (W/W)	300
Power Needs - W_e	1,358,700
Hours Used over 30 FPY	87,600
Energy Requirements - MW_eh	119,022
Energy Requirements - GJ_e	428,480

waste disposal for ARIES-III was normalized by the mass of the nuclear island from the energy requirements to dispose of waste for UWMAK-I.

3.3.2 Fuel Acquisition

Because of the lack of a sufficient terrestrial source of helium-3, it has been proposed that the Moon is the nearest and best source for the fuel[14]. There is a small amount of terrestrial ^{3}He available for experimental use, which is procured as a byproduct of tritium decay in nuclear weapons. The total amount of terrestrial-based helium-3 that would be available by the year 2010 is ~180 kg[15]. The ARIES-III 1000 MW_e D^3He power plant would require 89 kg of ^{3}He per year.

It was assumed that all ^{3}He for the ARIES-III power plant would be supplied from the Moon. Because commercially viable fusion power plants are still 20 or more years away from market reality, the time-frame for the D^3He fusion power plant analyzed in this study is assumed to be between the years 2025 and 2075.

Going to the Moon for helium-3 will be a major endeavor, requiring a colony of mining crew and various support staff. It is necessary to include the energy requirements of manufacturing and transporting the infrastructure for both the mining operation and crew habitat for all employees of some Lunar Mining Corporation. Due to the economies of scale, the helium-3 that is mined in later years will require less energy per kg then that mined earlier. To get an accurate idea of the energy needed to retrieve helium-3, a period of 50 years was analyzed starting in 2025, amortizing all energy expenditures to the mass of mined ^{3}He over that 50 year period.

Table 3.7 lists the parameters used in this forecast. The amount of ^{3}He that would be needed over this period was calculated by working backwards. The total electrical production in the U.S. in 1996 was 3.078 TWh. The U.S. Energy Information Administration used two growth rates, 0.9% and 1.9%[16], to forecast the U.S. energy use from 1996 to 2015. These same growth rates were used to forecast low and high electricity production between the years 1996 and 2075 in this study. The results, given in Table 3.8, show that by 2075 the electrical production will be between two and four times higher than current production.

It was assumed that D^3He fusion power would enter the U.S. energy market with a 0% share in 2025, and peak at 33% in 2075. This growth rate is reasonable in comparison to the penetration rate of nuclear fission in both Japan and the United States as seen in Figure 3.2 below.

Table 3.7: Parameters of D^3He Fusion Penetration Scenario and Energy Forecast

Parameter	
U.S. Electricity Low Growth Rate[a]	0.9%
U.S. Electricity High Growth Rate[a]	1.9%
% of US electricity from D^3He fusion in 2025	0%
% of US electricity from D^3He fusion in 2075	33%
D^3He Net Efficiency	60%
^3He Mass per reaction	3
D Mass per reaction	2
Energy per reaction	18.35 MeV
Area Mined per Tonne of ^3He[b]	11 km^2
Depth of Mining[b]	3 m
Regolith Density[b]	1.5 g/cm^3
Usable regolith	50%
Recoverable Grade	45 ppb
Lunar ^3He concentrations[c]	9 ppb
D^3He Power Plant Availability	75%
Mining Capability/yr./miner	1 km^2
Mass of Miner	18 tonne

[a] ref. [16]
[b] ref. [17]
[c] ref. [18]

Table 3.8: U.S. Electrical Production Growth Comparison (TWh/year)			
United States	**1996**	**2025**	**2075**
Low growth (0.9%)	3,078	3,991	6,246
High growth (1.9%)	3,078	5,312	13,614
U.S. D³He Fusion			
Low growth	-	0.0	2,078
High growth	-	0.0	4,530

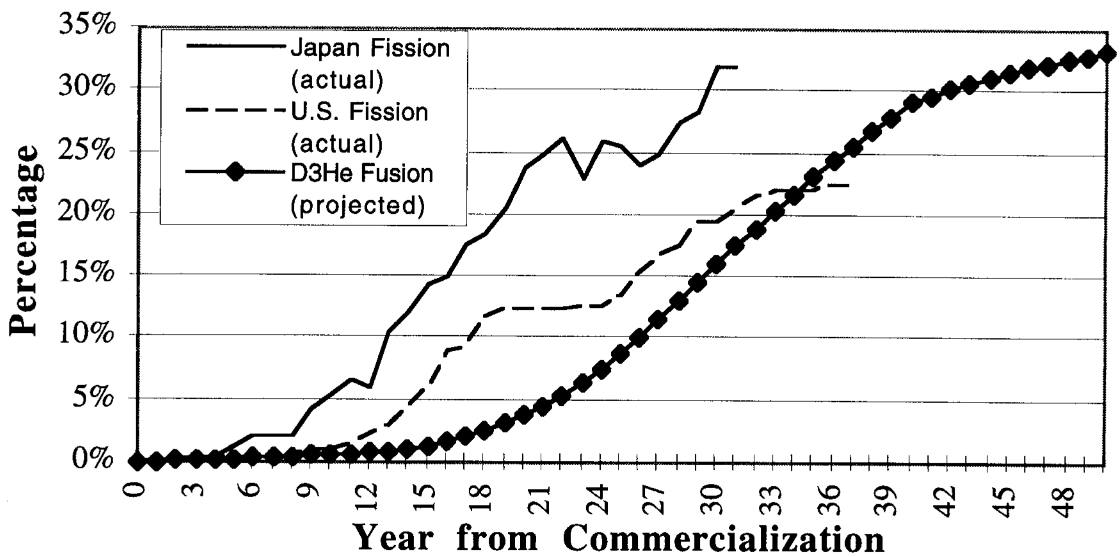

Figure 3.2: D^3He Fusion Projected Penetration Rate in the U.S. Over a 50-Year Period Compared to the Actual Penetration Rates of Fission in the U.S. and Japan.

As seen in Figure 3.3, by combining D^3He fusion's entry rate and the two growth scenarios, it was calculated that by the year 2075, D^3He fusion could be providing between 2,000 and 4,500 TWh of electricity per year. This data was used to calculate the amount of ^3He needed to fuel the power plants.

The D^3He fusion reaction,

$$D + {}^3He \rightarrow p(14.7\ MeV) + {}^4He(3.6\ MeV)\ ,$$

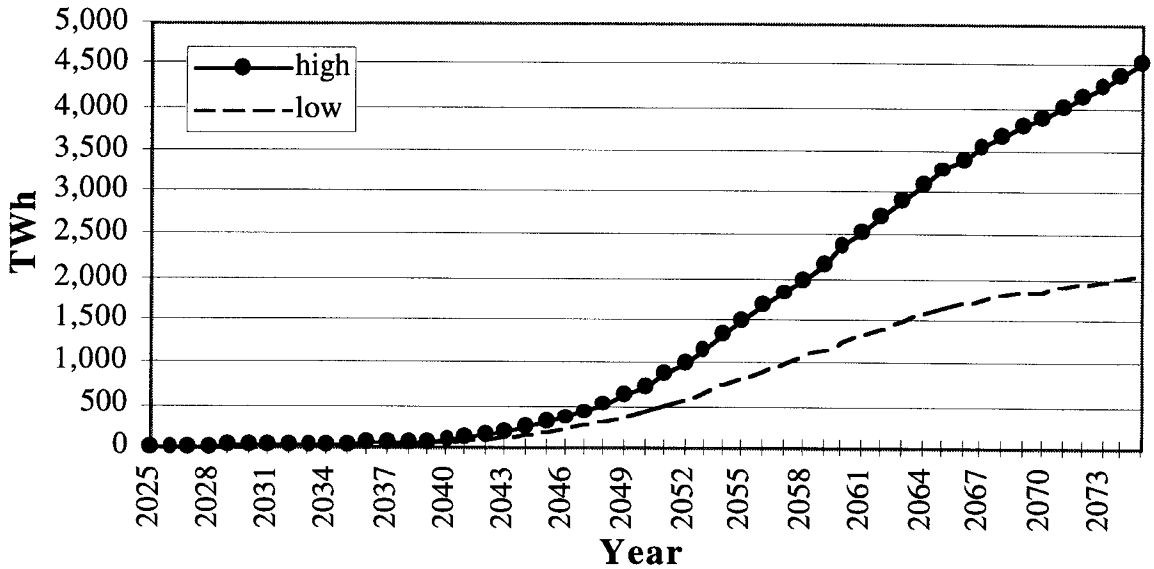

Figure 3.3: Low and High Growth Rate Scenarios for D^3He fusion, 2025-2075.

releases total energy per reaction of 18.3 MeV. The net conversion efficiency is assumed to be 60% with direct conversion of the 14.7 MeV proton into electricity. The equation used to calculate the amount of helium-3 required to supply the D^3He fusion power plants is,

$$M_{F,L} = \sum_{i=1}^{50} \left(\frac{E_{F_i}}{18.35 * \eta * 4.45\left(10^{-29}\right)} \right) * \left(\frac{M_a}{6.0225\left(10^{23}\right)} \right)$$

where $M_{F,L}$ = the mass of helium - 3 required over the 50 year period

E_{F_i} = the amount of electricity from D^3He fusion, (MWh)

M_a = the atomic mass of ^3He

η = the conversion efficiency of the power plant

$6.0225\left(10^{23}\right)$ = Avogadro's Number

$4.45\left(10^{-29}\right)$ = Conversion factor for MeV to MWh

18.35 = energy released from D-^3He reaction, (MeV)

It will take 89 kg of ^3He (and 59 kg of deuterium) to produce 1 GWy (or 8,760 GWh) of electricity and 2.67 tonnes of ^3He to supply a single 1000 MW_e ARIES-III over its lifetime of 30 GW_ey. Table 3.9 shows the mass of deuterium and helium-3 required to produce electricity for one and 30 full-power years in a 1000 MW_e ARIES-III power plant, as well as over the course of both the low and high electricity generation scenarios.

The mass of helium-3 required for the D^3He fusion program influences the number of miners, crew and the infrastructure mass needed on the Moon as well as the required number of launches. These items will be addressed in Sections 3.3.2.1 and 3.3.2.2.

As part of the CO_2 emission analysis, four scenarios were set up to analyze the impact that D^3He fusion's entrance into the electric power market would have on U.S. CO_2 emissions. The four scenarios, as listed in Table 3.10, include 1) a no fusion case (base case), 2) fusion replacing fossil fuel first, 3) fusion replacing nuclear fission first and 4) fusion replacing half fission and half fossil fuel. Based on the two growth projections for U.S. electricity, the share of electricity generated by fossil fuels (70%), fission (20%) and renewable sources (10%) was assumed to reflect the portions of each technology from 1996 to 2025. After this point, the share of electricity for each of these three sources varied depending on which of the four scenarios was employed.

Table 3.9: Mass of Fuel Needed to Supply Various Amounts of Energy in an ARIES-III Class D-^{3}He Fusion Power Plant

	1 GWy (8760 GWh)	**30-GWy (263 TWh)**	**50 Year Requirements - US**	
			low growth	high growth
Deuterium	59 kg	1.78 tonnes	259 tonnes[1]	507 tonnes[2]
Helium-3	89 kg	2.67 tonnes	388 tonnes[1]	760 tonnes[2]

1 38,132 TWeh
2 74,759 TWeh

Table 3.10: U.S. CO_2 Emission Replacement Scenarios from Electric Power, 2025-2075	
Scenario	**Explanation**
Scenario 1: Base Case (No Fusion)	Business as usual, with an assumed 70% of electricity coming from fossil fuels, 20% from nuclear fission and 10% from renewables (i.e. hydro-power).
Scenario 2: Fossil Fuel Replaced First	Assumes that D^3He fusion will replace fossil fuel plants as it enters the market. The emission factor for fossil fuel is assumed to be that of coal.
Scenario 3: Nuclear Fission Replaced First	Assumes that D^3He fusion will replace nuclear fission plants as it enters the market. At some point, there will no longer be fission plants on the market, after which fossil-fuel power plants will be replaced.
Scenario 4: Fossil Fuel and Fission replaced at equal rates	Assumes that D^3He will replace fission and fossil fuel plants equally as it enters the market.

The base case is a "business as usual" scenario, which assumes that there is no fusion and the share from these sources (coal, fission, and renewables) remains the same up through 2075. The fossil case has new D^3He plants replacing fossil fuel's share first. In the fission case, D^3He fusion replaces nuclear fission plants until their share reaches zero, after which fusion will replace fossil fuel plants. In the mixed case, D^3He fusion will replace fossil and fission plants equally as they enter the grid. The emission factor for fossil fuel electricity is assumed to be that of coal. The actual emission factor used for coal, fission and fusion were those generated from the CO_2 analysis. The emission factor of renewable energy was assumed to be that of hydroelectric power (3.1 tonnes CO_2/GWh). The results from these analyses will be given in Section 4.2.

3.3.2.1 Lunar Base

Several assumptions have been made in regard to the lunar helium-3 mining operation. First of all, before the mining operation begins, it is assumed that there will already be a human presence on the Moon. A scientific community will have already been established and with that, the infrastructure relating to the launch pad and lunar orbiting space operation center (LUO-SOC) will already be in place. It is possible that the best area to mine ^{3}He will be remote from the best areas for science, particularly the study of astronomy. For the purpose of this study, however, the two are assumed to be located close enough together to share the same spaceport and launch facilities. It is expected that they will have a separate lunar outpost and living quarters.

The lunar base for helium-3 mining is comprised of the infrastructure for both the mining operation and crew habitat. The mining operation is comprised of the mechanical miners, miner maintenance facilities, volatile separation facilities, and ancillary equipment. The crew habitat is comprised of an initial lunar base, crew habitat modules, and consumables. Table 3.11 lists the parameters pertaining to infrastructure capacity, and number and type of crew.

Figure 3.4 is a schematic of how various parameters are related and calculated. Each miner is capable of mining 1 km^2 of the lunar surface each year down to 3 meters in depth[17]. Eleven square kilometers of the lunar surface will be needed to produce 1 tonne of ^{3}He[17]. This means, that for every 91 kg of ^{3}He required annually on the Earth, another miner will need to be added. This translates roughly to one miner per 1000 MW_e power plant. The number of miners influences both the number of crew required (3 per miner, or 1 person for each shift), the number of miner maintenance facilities (1 facility for every 20 miners) and the amount of ancillary equipment (5 tonnes per miner). The number of volatile separation facilities is influenced by the amount of helium-3 mined (1 facility for every 2 tonnes of ^{3}He mined annually).

As stated above, the number of crew working on the mining operation is estimated to be three persons per miner per year. For every five persons on the mining crew, there will be

Table 3.11: Lunar Base Parameters	
Mining Capability per year per miner (km^2)	1
Area mined per tonne of ^3He (km^2)[a]	11
Number of persons per Miner per year[b]	3
Number of miners per maintenance facility[c]	20
Helium-3 processed per year per volatile separation facility (tonne)[c]	2
No. of habitat support staff per lunar base	9
No. of persons per lunar outpost[c]	60
Amount of Consumables (tonne/person/year)[c]	1
Average tour of duty per Lunar crew (years)[c]	1
No. of persons per habitat module[c]	10
Lunar Food Farm Area[d] - Available - Required	900 m^2 50 m^2/person
Lunar Food Farm Modules per Outpost[d]	3
Embodied energy of lunar base materials (GJ/tonne)[e]	443
Embodied CO_2 of lunar base materials (tonne CO_2/tonne material)[e]	28

approximately one more person working as support at the habitat. Each lunar outpost will have nine support staff; two cooks, two laundry/housekeeping staff, two habitat engineers, one doctor and two persons working on the lunar farm. The number of crew influences the number of lunar outposts (each outpost can serve an average of 60 persons), the number of sleeping/living habitat modules (10 persons each), and the amount of consumables that must be shipped to the Moon (one tonne per person annually). All crew are assumed to have a one year tour of duty after which they will return to Earth. Though it is expected that people will eventually stay on the Moon for longer periods, this was not factored into this study.

In addition to the living quarters (outpost + habitat), there will be the need for a module that produces food. A lunar farm as described by H. Hermann Koelle [20], will require 50 m^2

[a] ref. [17]
[b] one person per shift for each miner
[c] estimated
[d] ref. [19]
[e] based on titanium

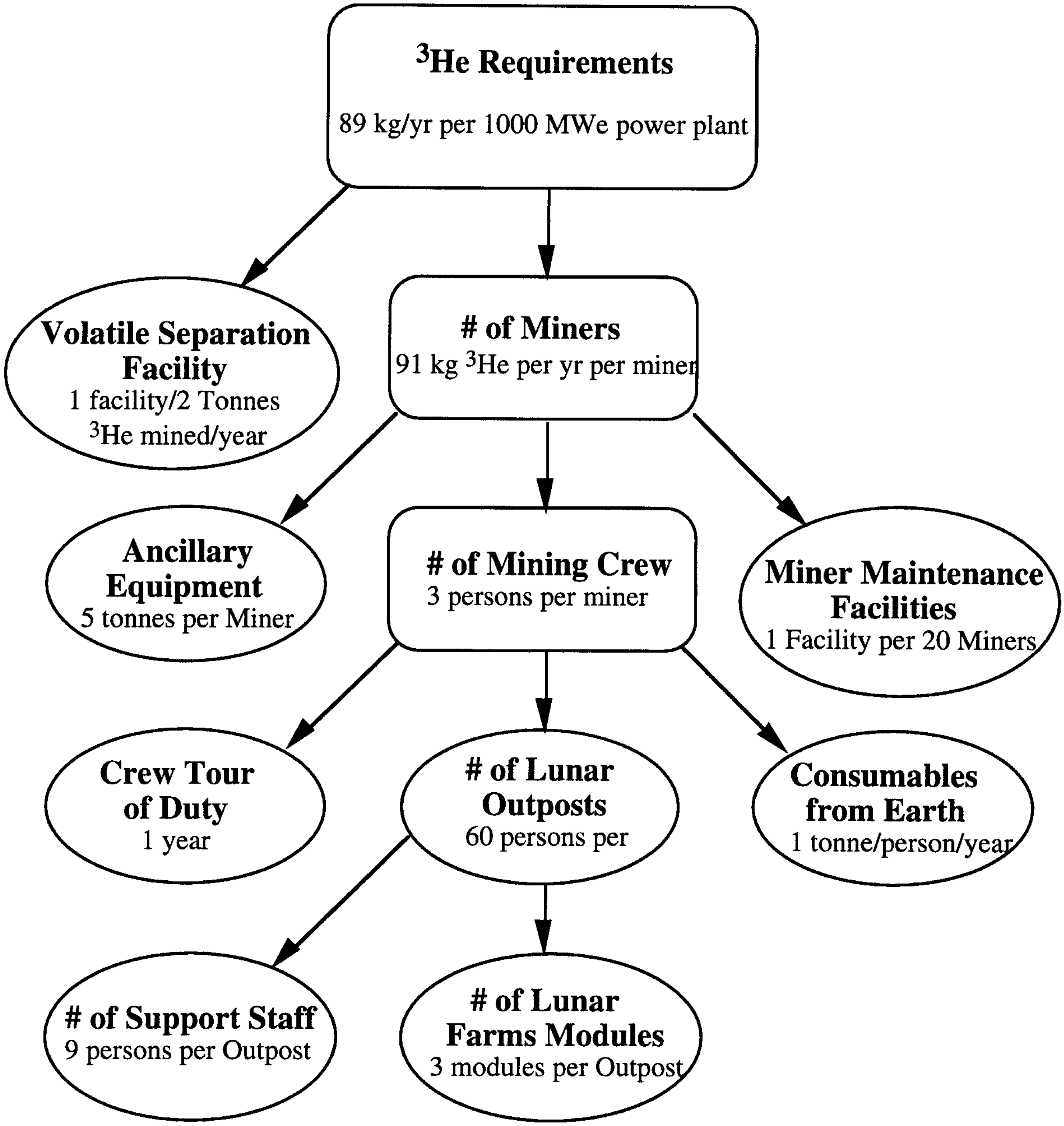

Figure 3.4: Schematic of Lunar Base Parameters Calculations

and 50 kW per person per year to supply enough food. Each module, which is derived from a standard cargo module, has a floor space of 900 m^2 and weighs 100 tonnes. This translates to three lunar farm modules per outpost (at full capacity).

The power source to operate the living quarters, farm, maintenance facilities and separation facilities are likely to come from a variety of sources, such as solar concentrators, fuel cells, solar photovoltaics and nuclear power. The thermal energy needed to separate volatiles and heat the areas will come from solar energy during the lunar day and will not be available during the lunar night. The mass of the volatile separation facility power system is included in the mass of the structure. The power plant for the lunar outpost is included in the total mass of the outpost per Koelle[21] and weighs 50 tonnes. Table 3.12 shows the breakdown of the lunar outpost mass.

It is assumed that all infrastructure materials will last for at least 50 years and will not need to be fully replaced for the length of this study. However, a 20% contingency factor was added to the total mass to account for possible replacements. It is likely that the materials of the habitat infrastructure will be made of composite materials and machinery of strong, light-weight metals. It was assumed that all materials have an embodied energy content and CO_2 emission factor equal to that of titanium. The embodied energy and CO_2 emissions of all

Table 3.12: Typical Mass Model of Lunar Outpost (from Koelle, ref. [21])

Component	Metric Tonnes
Pilot Production Modules	40
Control Center	15
Workshop	15
Central Storage	15
Airlocks	5
Rover Vehicles	15
Multi-purpose trucks	15
Structural Nodes	15
Connecting Tunnels	15
Tools and Minor Equipment	10
Life Support Supplies	20
Road Construction Material	15
Propellant Tanker Vehicle	15
Power Plant	50
Spares and Reserves	45
Total Mass	**315**

materials exported to the Moon were calculated by taking the product of the total infrastructure mass and each of the energy and CO_2 emission factors.

The mass of the habitat modules and lunar outposts were taken directly from work performed by Koelle[22, 23], while the miner and it's parameters are based on Sviatoslavsky's Mark-II miner[24]. Masses for the volatile separation facility, miner maintenance facility, ancillary equipment and consumables were estimated based on Koelle's data for other lunar infrastructure. Between 36,000 - 76,000 tonnes of materials will be exported from the Earth to the Moon over the 50 year period (7-14 HLLV launches/year avg.). Table 3.13 lists the total number and mass of each lunar module for both the low and high energy scenarios.

Table 3.13: Lunar Modules and Infrastructure Mass Requirements

	Mass (Tonnes/unit)	No. needed over 50 yrs		Total Mass over 50 years (1,000 Tonnes)	
		low	high	low	high
LUO-SOC	250[a]	1	1	0.3	0.3
Initial Lunar Base Outpost	315[b]	14	30	4.4	9.5
Habitat Module	15[b]	83	180	1.2	2.7
Miner Maintenance Facility	100[c]	14	30	1.4	3.0
Volatile Separation Facility	50[c]	11	24	0.6	1.2
Lunar Miners	18[d]	232	507	4.2	9.1
Ancillary Equipment	5 (/miner)[c]	-	-	1.2	2.5
Consumables	1 (/person/yr.)[c]	-	-	15.1	29.6
Lunar Farm	100[e]	46	100	4.6	10.0
Subtotal				33.0	67.9
+ 20% Contingency Factor (exl. LUO-SOC)				6.5	13.5
Total				**39.5**	**81.1**

[a] ref. [25]
[b] ref. [21]
[c] estimated
[d] ref. [18]
[e] ref. [20]

3.3.2.2 Fuel Transportation

While the manufacture of the materials require energy which generates CO_2, the mass of materials carry a double penalty in that they require large amounts of energy to be

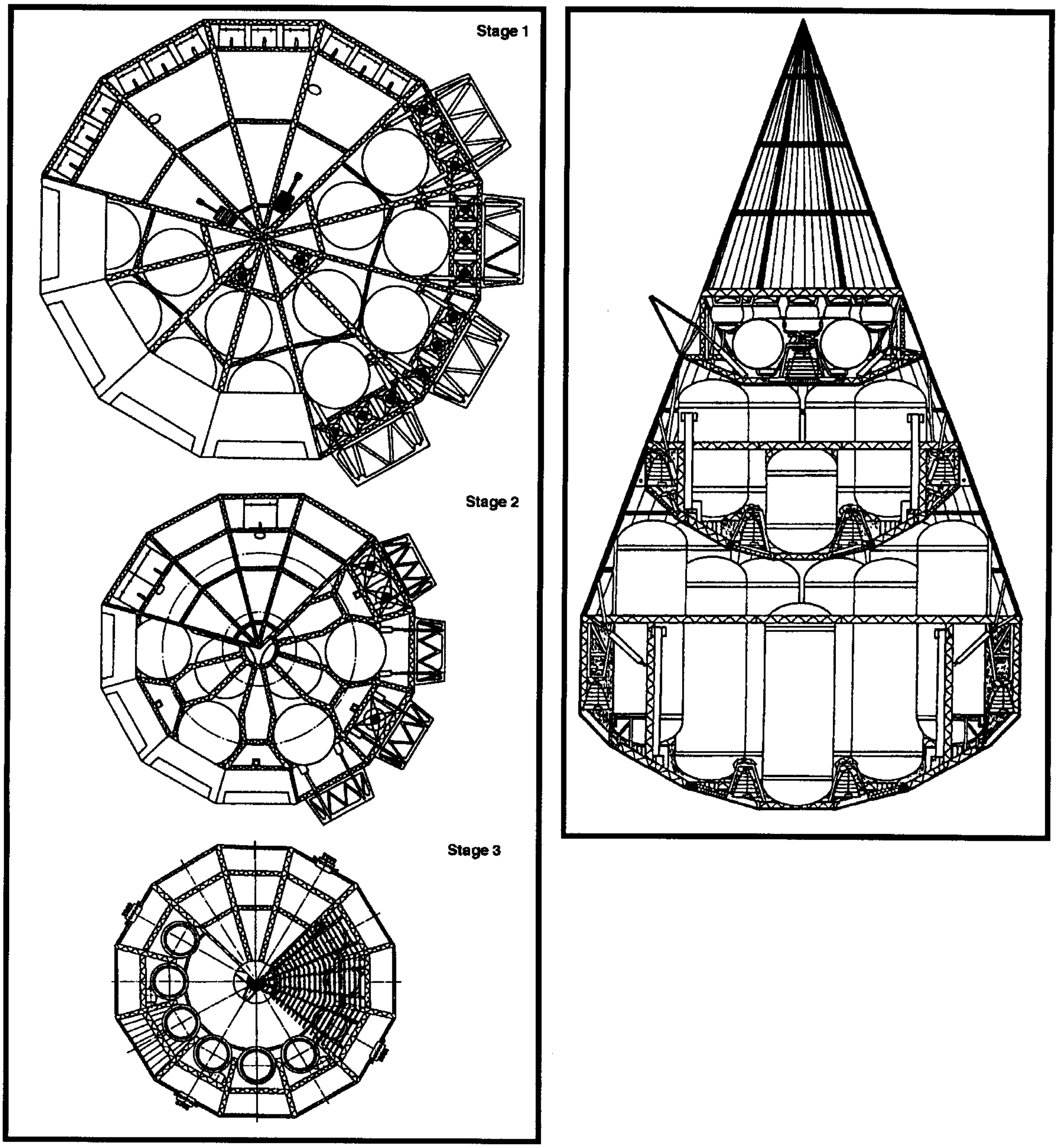

Figure 3.5: Horizontal and Longitudinal cross-sections of the NEPTUNE-2015 Heavy Lift Launch Vehicle. From [22].

transported from the Earth to the Moon. The space transportation system used in this analysis was based upon the 6,000 tonne NEPTUNE heavy lift launch vehicle (HLLV) as detailed by Koelle in ref.[26] and seen in Figure 3.5. The system is comprised of an HLLV with three stages. The first two stages transport the rocket to lower Earth orbit (LEO), while the third

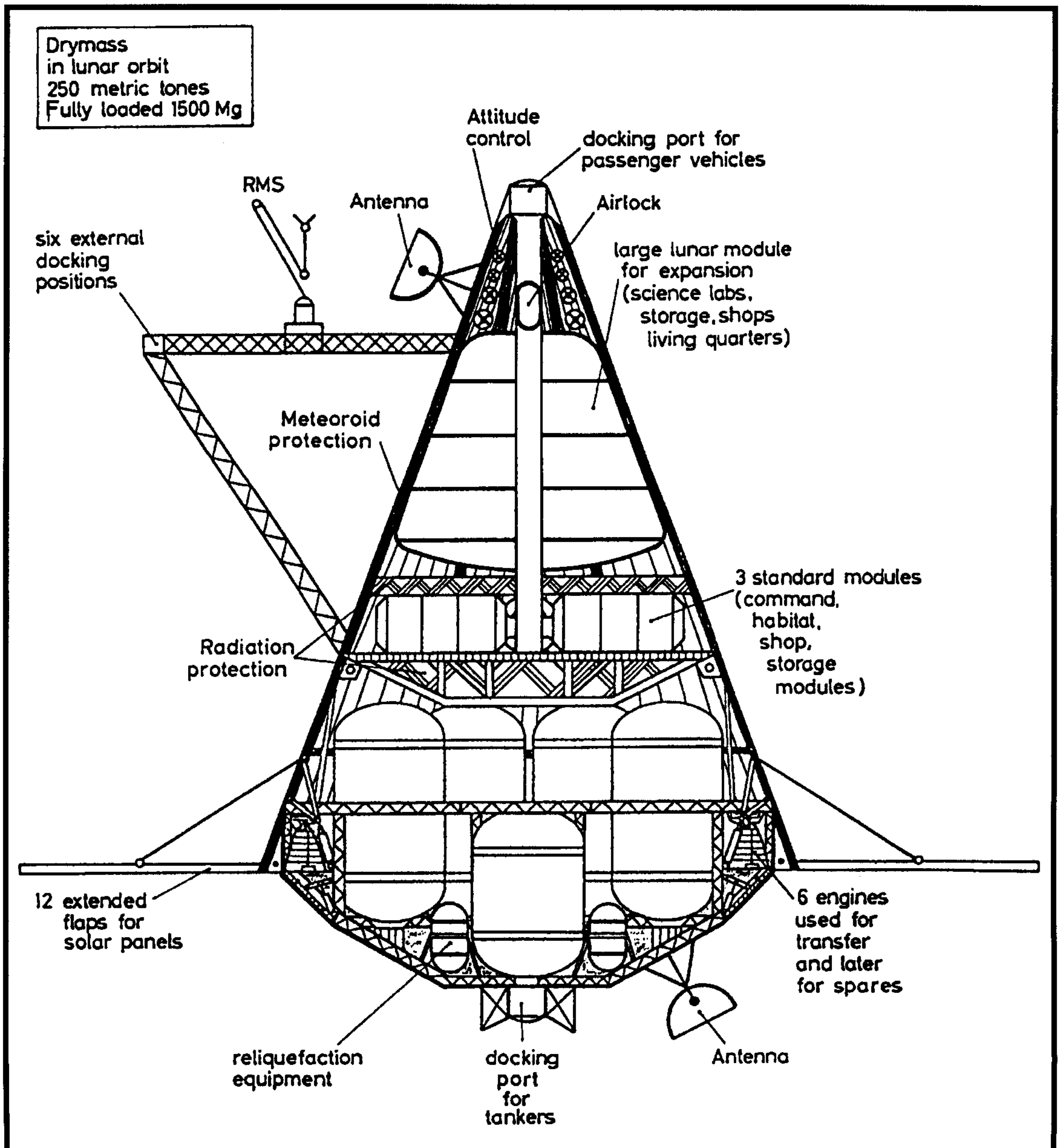

Figure 3.6: Space Operations Center(SOC) derived from the second stage of the NEPTUNE HLLV[22]

stage transports cargo or passengers in one of two stage-3 modules to the LUO-SOC. The LUO-SOC is a modified second stage of the HLLV as seen in Figure 3.6. The stage 3 module will dock at the LUO-SOC in low lunar orbit (100 km) and transfer both cargo and passengers to the lunar bus (LUBUS), a vehicle that travels between LUO-SOC and the Lunar spaceport. The LUBUS is a modified stage 3 module of the NEPTUNE HLLV and is shown in Figure 3.7. By design, the HLLV and LUBUS will be fueled by liquid hydrogen (LH_2) and liquid oxygen (LO_x) for all stages[26]. Oxygen will be produced on the Moon as a byproduct of ^3He volatile separation. It is assumed that after 20 years of ^3He production, in 2045, there will

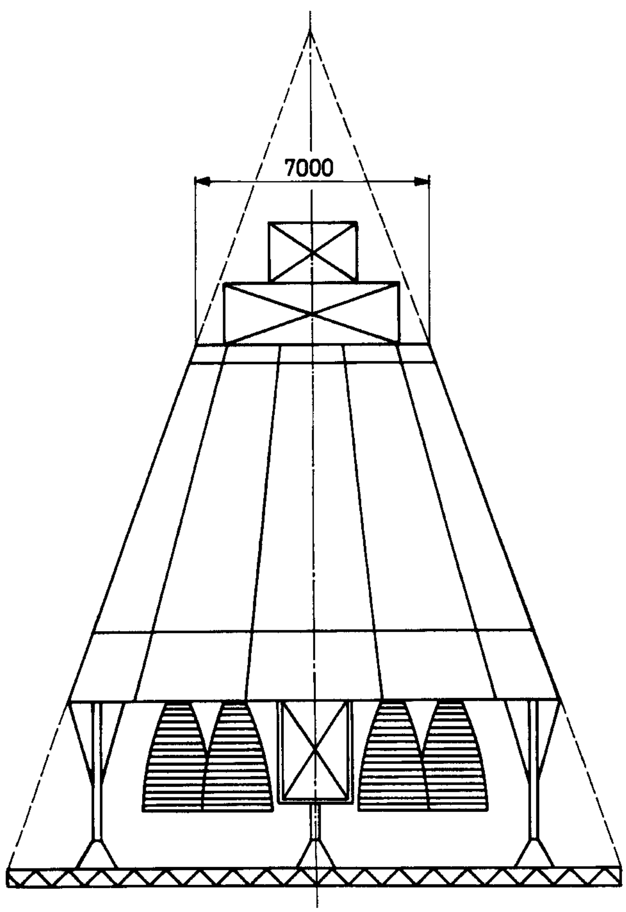

Figure 3.7: The lunar launch and landings vehicle - LUBUS. From [22].

be sufficient lunar oxygen (LULOX) to fuel the return flights of the stage 3 modules. The amount of fuel required for each stage is listed in Table 3.14.

As listed in Table 3.15, the cargo payload capability of the HLLV is 50 tonnes to lunar orbit. The payload will increase by 25 tonnes to 75 tonnes, after LULOX production levels are sufficient to meet the fuel needs for the return flight.

The total number of cargo flights was calculated by dividing the yearly payload mass by 50 (tonnes/launch) for years 1-20 and by 75 for years 21-50. The number of launches was rounded off to the nearest tenth. It is very unlikely that any Moon-bound launches will be less than full. At the same time, it is probable that there will be regular launches to the Moon, even during the first several years after the initial base is in place and before ^3He production levels require more flights. This analysis does not deal with the time-dependent logistics of space transport, but instead has focused on determining the transport needs over the course of this 50 year scenario. The results are listed in Table 3.16.

Table 3.14: Total Mass of Propellants (tonnes/launch)

HLLV	Earth LO_X	Lunar LO_X	LH_2	Total
Stage 1[a]	3,135		627	3,762
Stage 2[a]	893		179	1,072
Stage 3 (cargo) to LUO[b]	12		3	249
Stage 3 (crew) to LUO[b]	25		5	249
Return leg (cargo)[b]		25	5	30
Return Leg (crew)[b]		12	3	15
LUBUS Cargo incl. ascent/descent[b]	0	94	16	110
LUBUS Passenger incl. ascent/ descent[b]	0	93	17	110

[a] ref. [26]
[b] ref. [25]

The passenger module of the HLLV can carry 40 persons and similar to the cargo module, there will be a launch for every 40 passengers each year. The LUBUS, which also has unique passenger and cargo modules, will make the same number of flights as the HLLV.

Table 3.15: Launch Vehicle Parameters

HLLV	**Unit**
Cargo payload capability[c]	50 tonne
Additional cargo payload (post-LULOX production) [c]	25 tonne
Passenger Payload capability (pre LULOX)[c]	40 persons
Operational life of rockets[b]	25 years
Launches per rocket per year[b]	10
LUBUS	
Cargo payload[d]	75 tonne
Passenger payload[b]	40 persons
Operational life[e]	25 years
Launches per rocket per year[e]	10

Table 3.16: Total Payload Mass and Number of Launches for HLLV and LUBUS over 50 Year Period

Space Vehicle	low	high
HLLV Cargo - Payload Mass (tonnes)	36,718	76,020
HLLV Passenger (# of passengers)	15,094	29,608
	Number	
HLLV & LUBUS Cargo Trips	507	1,039
HLLV & LUBUS Passenger Trips	377	740

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[c] ref. [23]
[e] estimate

The energy embodied in the rockets was calculated using the reference mass of the NEPTUNE rocket[26] as shown in Table 3.17. The NEPTUNE HLLV is designed to be fully reusable for 250 launches. As seen in the fourth column of Table 3.17, each subsystem lasts for a different number of launches. This data was used to calculate a lifetime mass of each rocket, based on replacement mass, which is shown in the last column. Table 3.18 shows similar data for the LUBUS.

Table 3.17: Detailed Assumptions for the Operational Model of the 6,000 MT Reference NEPTUNE Vehicle (from Koelle, ref. [26])

HLLV	reference mass (kg)	number of units per vehicle	number of reuses per subsystem	Lifetime mass (tonnes)
STAGE 1:				
cold structure	22,690	12	300	227
hot structure	1,874	12	50	112
fuel tanks	5,111	12	150	102
oxidizer tanks	4,035	6	200	30
equipment	2,225	4	200	11
engines	2,000	40	60	333
recovery eq.	2,758	6	150	28
STAGE 2:			**Subtotal**	**844**
cold structure	4,866	12	300	49
hot structure	1,356	12	20	203
fuel tanks	3,082	6	150	31
oxidizer tanks	2,338	3	200	9
equipment	1,750	2	200	4
engines	2,800	9	40	158
recovery eq.	728	6	100	11
STAGE 3:			**Subtotal**	**464**
cold structure	2,333	6	300	12
hot structure	1,333	12	5	800
fuel tanks	4,000	1	150	7
oxidizer tanks	350	12	200	5
equipment	900	2	100	5
engine	270	12	100	8
recovery eq.	750	6	100	11
shroud optional	3,000	1	200	4
			Subtotal	**851**
			Total Mass	**2,159**

Each rocket is designed for 10 launches per year. For this study, a new launch vehicle is added to the fleet once the annual number of launches exceeds each factor of 10 and after 25 years of service, a rocket will be replaced. The total number of launch vehicles and other lunar infrastructure required over the 50-year period of both the high and low energy growth scenarios is listed in Table 3.19

Due to the unique nature of LO_x and LH_2, it is necessary to analyze two separate scenarios when considering the energy requirements of transporting goods between Earth and the Moon. Since LH_2 and LO_x are not fossil fuels and are renewable in the fact that they are processed from water (H_2O) via electrolysis and return to water vapor upon combustion, their use is different than a fossil fuel propellant such as kerosene. The important measurement in this case is the energy required to produce LH_2 and LO_x. The scenario where only the energy embodied in the fuel is accounted for is the ***rocket fuel scenario***. It takes 460 GJ/tonne of LH_2 and 10 GJ/tonne of LO_x to produce the fuels[7]. The other scenario is called the ***launch***

Table 3.18: Detailed Assumptions for the Operational Model of the LUBUS Launch Vehicle (from Koelle, ref. [25])

LUBUS	reference mass (kg)	no. of units per vehicle	number of reuses per subsystem[1]	lifetime mass (kg)
Structure	3.2	1	250	3
Fuel Tank	4	1	150	7
Oxidizer tanks	1	8	200	10
Equipment	2	1	100	5
Engines	0.35	8	100	7
Total Cargo Module				**32**
LUBUS Crew Module				
Crew Safety Equipment	6.89	1	100	17
Structure	1.9	1	250	2
Life Support Systems	1.83	1	250	2
Power Supplies	7.56	1	250	8
Crew Systems	1.82	1	250	2
Total Crew Module				**30**

[1] estimated, based on HLLV data

Table 3.19: Lunar Base Output from Low and High Scenarios

	Low	High	Mean
Number of Lunar Miners	232	507	370
Number of Habitat Modules	83	180	132
Number of Volatile Separation Facilities	11	24	18
Number of Miner Maintenance Facilities	12	26	19
Number of Lunar Outposts	17	36	27
Number of HLLV Cargo Trips	507	1,039	773
Number of HLLV Passenger Trips	377	740	559
Number of LUBUS Cargo Trips	507	1,039	773
Number of LUBUS Passenger Trips	377	740	559
No. of HLLV Rockets Needed (includes replacements)	11	16	14
No. of LUBUS Rockets Needed (includes replacements)	11	16	14

scenario, where both the embodied energy of the propellants and the energy released during combustion is calculated.

The rocket fuel scenario is the main scenario in the analysis of helium-3 acquisition. The launch scenario is included because of the possibility that if a different fuel is used, such as kerosene, the energy released during oxidation would be relevant to include since oxidation of the propellant would permanently change it.

Table 3.20: Energy Requirement Scenarios for Rocket Launches

Scenario	Explanation
Scenario 1: Rocket Fuel Scenario	Only includes the embodied energy of the rocket propellants, LH_2 and LO_x.
Scenario 2: Launch Scenario	Includes the embodied energy of LH_2 and LO_x as well as the energy released during combustion of the fuels.

In calculating the CO_2 emissions from the launch, the CO_2 emission factor for the standard U.S. electrical mix was used to calculate the embodied emissions. The combustion of the two fuels does not generate CO_2. Though water vapor, the byproduct of LH_2 and LO_x combustion, is a greenhouse gas, it was decided against including it in the analysis due to its short residency time in the atmosphere (8-9 days). It must be noted, however, that some water vapor will be injected in and above the stratosphere, at which the residency time could be much longer. At these levels, the effect on the climate and ozone-layer may not be trivial. Though such an analysis is not included in this thesis, it warrants study in light of the analysis in this thesis.

3.4 Other Power Plant Technologies

As part of the analysis of D^3He-fusion, it is desirable to analyze other technologies because nuclear fusion is not currently established in the electric power market. Two DT-fusion power plants, UWMAK-I[12] and ARIES-RS[27], were included to provide a basis of comparison for D^3He-fusion with fusion technologies that have Earth-based fuel supplies. Since the fusion power plants are still only paper designs, the analysis of D^3He-fusion is particularly relevant in comparison to DT-fusion power plants. Coal and fission power plants represent technologies that are both well-established in the electric power market and frequently subjects of NEA's. These technologies are included to give a basis of comparison of both the fusion power plants as well as to the methodology used. There have not been any other studies of the EPR or CO_2 emissions of D^3He-fusion, of which to compare the results of this thesis. There have been many other studies of coal and fission. The two deuterium-tritium fusion power plants, though also unproven technologies, have been the subject of at least four previous NEA's. Finally, the wind power plant is included because it may be an alternative, lower-emission electric power technology in the 21st century.

The parameters of the six power plants are shown in Table 3.21. For simplicity, the capacity factors of the five baseload power plants (coal, fission and fusion) were chosen to be 75%. Capacity factor is the ratio of electricity produced divided by the possible total possible electricity. While the 75% capacity factor is merely an assumption for the fusion power plants which have not been built, it is close to the current performance of coal and fission plants[28]. The 24% capacity factor for wind is actual, based on 4 years generation data from the Buffalo Ridge Phase-I wind farm[29, 30].

Table 3.21: Summary of Power Plant Parameters ($Tonnes/GW_e$-installed)

Parameter	Coal	Fission	DT-fusion	DT-fusion	D^3He-fusion	Wind
Power Level - MW_e	1,000	1,000	1,494	1,000	1,000	25
Fuel	US avg. - 1990	3% enriched U	Deuterium -Tritium	Deuterium -Tritium	Deuterium -Helium-3	
Capacity Factor	75%	75%	75%	75%	75%	24%
Life - calendar year	40	40	40	40	40	25
Power Plant Design	Conv. Steam	Pressurized Water Reactor	Tokamak UWMAK-I	Tokamak ARIES-RS	Tokamak ARIES-III	Kenetech KVS-33

Power plant material requirements are listed in Table 3.22. The energy and CO_2-emission of power plant materials was performed for all technologies in a manner similar to that of ARIES-III, which was described in section 3.3.1.

The methods used to analyze construction, operations, fuel acquisition and decommissioning data for the other technologies are described briefly in sections 3.4.1 - 3.4.4. Most specific data is included in separate Appendices for each technology.

3.4.1 Coal

The coal plant is assumed to be an average conventional coal plant in the United States. The energy requirements for mining coal is based on a weighted average of Eastern and Western coal. It is assumed that the coal will be transported 700 miles from mine to power plant by rail, which is the most common from of coal transportation. All data on the energy requirements of the construction, fuel acquisition, operation and decommissioning processes came from other sources and can be found in Appendix C.

3.4.2 Fission

The energy requirements for the LWR materials were calculated via the same method used for the D^3He fusion power plant using the materials listed in Table 3.22. The uranium fuel cycle

Table 3.22: Summary of Power Plant Material Requirements (Tonnes/GW_e-installed)

	Coal [31]	Fission [32]	UWMAK-I [12]	ARIES-RS [27]	ARIES-III [1]	Wind [33]
Aluminum	255	18	323	0	0	0
B_4C	0	0	1,374	72	0	0
Chromium	122	0	0	0	0	0
Concrete	74,257	179,681	505,799	444,682	490,050	305,891
Copper	454	729	6,951	818	1,377	211
Fiber Glass	0	0	0	0	0	19,863
Helium	0	0	94	3	3	0
Insulation Materials	0	922	0	0	0	0
Insulators	0	0	0	25	35	0
Lead	0	46	13,898	0	0	0
Lithium	0	0	1,153	507	0	0
Manganese	112	434	0	0	0	0
Mercury	0	0	2	0	0	0
Molybdenum	42	0	0	0	0	0
Nickel	10	125	708	623	2,064	0
NbTi	0	0	144	177	215	0
Silver	0	0.5	0	0	0	0
Sodium Metal	0	0	12,085	998	0	0
Carbon Steel	39,681	33,988	50,835	44,743	52,553	75,516
Stainless Steel	612	2,080	56,883	28,507	12,877	9,049
Tungsten	0	0	0	741	0	0
Vanadium	4	0	0	3,489	0	0
Yttrium	0	0	3	0	0	0
Zirconium	0	0	68	0	0	0
Total	115,550	217,590	650,319	525,385	559,173	410,529

energy requirements and CO_2 emissions were calculated in this study. It was assumed that uranium was enriched via the gas centrifuge method. Data for construction, operations, and decommissioning and waste disposal were from other studies. Details on all energy requirements can be found in Appendix D.

3.4.3 DT Fusion

The energy requirements for the UWMAK-I and ARIES-RS DT-fusion power plant materials were calculated via the same method used for the D^3He fusion power plant using the materials listed in Table 3.22. Data for construction energy came from original reactor designs of each, while data for operations and decommissioning came from other net energy analyses and scaled accordingly. All CO_2 emissions were calculated from the energy requirements data using appropriate emission factors. Details on all energy requirements can be found in Appendix E.

3.4.4 Wind

The wind power plant is a 73-turbine wind farm operating on the Buffalo Ridge in Southwestern Minnesota. The turbines are part of a 25 MW_e wind farm, which provides power for Northern States Power in Minnesota. It is phase I of a three phase is often referred to as Northern Kenetech KVS-33 turbines which are rated at 342.5 kW_e each. These turbines have been operating since March 1994 and are analyzed in detail, along with two other wind farms in ref. [34]. Key tables pertaining to Buffalo Ridge phase I are included in Appendix F.

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4 Result

This Chapter lists the results of both the energy and CO_2 analysis. Due to the amount of data generated, this chapter is limited to the data itself while the *discussion* of the results takes place in Chapter 5, which is set up to parallel the layout of this chapter.

4.1 Energy - General Results

The results of the energy analysis for the six technologies considered in this thesis are listed in Table 4.1 and Table 4.2. Table 4.1 lists the energy investments for each of the six technologies, normalized to TJ_{th} per GW_ey, for each of the nine process categories. Table 4.2 lists the same results normalized to GJ_{th}/GW_e-installed. A breakdown of the energy investments for all nine categories follows in sections 4.1.1 through 4.1.5.

Table 4.1: Comparison of Energy Investments for Electrical Power Plants. (TJ_{th}/GW_ey)

Process	Coal[1]	Fission	DT-Fusion UWMAK-I	DT-Fusion ARIES-RS	D^3He Fusion ARIES-III	Wind[2]
Materials (non-fuel)	55	58	269	563	126	676
Plant Construction	92	137	335	364	440	199
Fuel Mining	1,258	88	48	30	103	NAppl.
Fuel Preparation (cleaning, milling, enrichment, etc.)	incl. in mining	1,203	incl. in mining	incl. in mining	incl. in mining	NAppl.
Fuel Transportation	1,059	8	negl.	negl.	incl. in mining	NAppl.
Operation	440	239	435	318	298	489
Waste Disposal & Transportation	6	172	16	6	4	negl.
Decommissioning	10	19	55	45	48	50
Land Reclamation (fuel only)	4	0.1	negl.	negl.	negl.	none
Total	2,925	1,923	1,158	1,326	1,019	1,414

[1] Based on the US average mix of coal.

[2] Does not include energy storage.

Table 4.2: Comparison of Energy Investments for Electrical Power Plants

(TJ_{th}/GW_e-Installed)

Process	Coal[1]	Fission	DT-Fusion UWMAK-I	DT-Fusion ARIES-RS	D^3He Fusion ARIES-III	Wind[2]
Materials (non-fuel)	1,660	1,746	8,063	16,893	3,778	4,132
Plant Construction	2,749	4,101	10,044	10,911	13,197	1,216
Fuel Mining	37,753	2,644	1,448	898	3,100	NAppl.
Fuel Preparation (cleaning, milling, enrichment, etc.)	incl. in mining	36,096	incl. in mining	incl. in mining	incl. in mining	NAppl.
Fuel Transportation	31,777	227	negl.	negl.	incl. in mining	NAppl.
Operation	13,195	7,158	13,039	9,550	3,009	2,985
Waste Disposal & Transportation	183	5,155	484	185	107	negl.
Decommissioning	296	557	1,664	1,344	1,431	306
Land Reclamation (fuel only)	126	4	negl.	negl.	negl.	none
Total	87,738	57,691	34,743	39,781	30,560	8,639

1 Based on the US average mix of coal.

2 Does not include energy storage.

4.1.1 Materials

The energy requirements for the power plant materials used by the six technologies included in this study are listed in Table 4.3.

Table 4.3: Breakdown of the Energy Requirements for Materials (TJ_{th}/Power Plant) & (TJ_{th}/GW_e-Installed)

	Coal[1]	Fission[1]	UWMAK-I[1]	ARIES-RS[1]	ARIES-III[1]	Wind[2]
Aluminum	51	4	96	0	0	0
B_4C	0	0	427	15	0	0
Chromium	10	0	0	0	0	0
Concrete	102	248	1,028	613	675	14
Copper	59	91	1,338	107	180	696
CuZn28Sn	0	2	0	0	0	0
Fiber Glass	0	0	0	0	0	6
Helium	0	0	74	1	2	0
Insulation Materials	0	87	0	0	0	0
Insulator	0	0	0	1	2	0
Lead	0	2	727	0	0	0
Lithium[3]	0	0	1,450	433	0	0
Manganese	6	0	0	0	0	0
Mercury	0	0	0.3	0	0	0
Molybdenum	16	0	0	0	0	0
Nickel	2	23	193	115	381	0
NbTi	0	0	45	37	45	0
Silver	0	9	0	0	0	0
Sodium Metal	0	0	2,208	124	0	0
Carbon Steel	1,366	1,170	2,582	1,541	1,810	59
Stainless Steel	33	110	4,456	1,514	684	9
Tungsten	0	0	0	309	0	0
Vanadium	14	0	0	12,948	0	0
Yttrium	0	0	7	0	0	0
Zirconium	0	0	161	0	0	0
Total - TJ_{th}/plant	1,660	1,746	13,343	17,325	3,778	89
Total – TJ_{th}/GW_e-installed	1,660	1,746	9,046	17,325	3,778	3,558

[1] GJ/GWe

[2] GJ/25 MWe

[3] For comparative analysis, lithium is included in the "fuel mining" section for each DT-fusion reactor.

4.1.2 Construction

The summary of construction energy requirements for ARIES-III is listed in Table 4.4. This table parallels Table 3.4 and does not include data for the sectors dedicated solely to construction materials (i.e. structures, turbine plant equipment, etc.). The energy requirements to construct power plants are listed in Table 4.5.

Table 4.4: Summary of Energy Required for the Construction of ARIES-III Power Plant - Does Not Include Materials

Account number	Account Description	TJ_{th}/GW_e	TJ_e/GW_e	TJ_{th}/GW_e (tot)
21	Structures & Improvements	Included in Materials	Included in Materials	Included in Materials
22	Reactor Plant Equipment			
22.1.04	supplemental-heat./CD system[a]	3,632	459	5,168
22.1.0.5	primary structure & support	Included in Materials	Included in Materials	Included in Materials
22.1.0.7	power supply, switching, energy storage	564	73	807
22.1.0.8	impurity control	91	13	134
22.1.0.10	ecrh breakdown equip.	49	6	70
22.1	Reactor Equipment			
22.2	2 main heat transfer. & transport.	Included in Materials	Included in Materials	Included in Materials
23	Turbine Plant Equipment	Included in Materials	Included in Materials	Included in Materials
24	Electric Plant Equipment	1,275	171	1,847
25	Misc. Plant Equipment	710	138	1,673
26	Special Materials	23	2	29
90	Direct Cost (not incl. contingency)			
91	Construction Services	2,501	200	2,669
92	Home Office Engineering	588	55	773
93	Field Office Engineering	588	55	773
	Total	10,018	1,172	13,944

Table 4.5: Energy Requirements for Construction of Power Plants

	TJ_{th}	TJ_e	TJ_{th}/GW_e
Coal	2,111	235	2,749
Fission	3,167	344	4,101
UWMAK-I	7,557	917	10,044
ARIES-RS	8,172	1,010	10,911
ARIES-III	10,018	1,172	13,197
Wind			1,216

4.1.3 Fuel Acquisition

The energy requirements for the acquisition of fuel for each technology are listed in Tables 4.6 and 4.7, normalized per $GW_e y$ and GW_e-installed respectively.

Table 4.6: Energy Requirements Associated with Fuel Acquisition for Power Plants (TJ_{th}/GW_ey)

Process	Coal (US avg.)	Fission	DT-Fusion (UWMAK-I)	DT-Fusion (ARIES-RS)	D^3He Fusion		Wind
					Rocket Fuel Scenario	Launch Scenario	
Fuel Mining	1,258	88	48	30	103	120	NAppl.
Fuel Preparation (cleaning, milling, enrichment, etc.)	incl. in mining	1,203	incl. in mining	incl. in mining	incl. in mining	incl. in mining	NAppl.
Fuel Transportation	1,059	8	negl.	incl. in mining	incl. in mining	incl. in mining	NAppl.
Total	2,318	1,299	48	30	103	120	0

Table 4.7: Energy Requirements Associated with Fuel Acquisition for Power Plants (TJ_{th}/GW_e-Installed)

Process	Coal (US avg.)	Fission	DT-Fusion (UWMAK-I)	DT-Fusion (ARIES-RS)	D^3He Fusion		Wind
					Rocket Fuel Scenario	Launch Scenario	
Fuel Mining	37,753	2,644	1,448	898	3,100	3,608	NAppl.
Fuel Preparation (cleaning, milling, enrichment, etc.)	incl. in mining	36,095	incl. in mining	incl. in mining	incl. in mining	incl. in mining	NAppl.
Fuel Transportation	31,777	227	negl.	negl.	incl. in mining	incl. in mining	NAppl.
Total	69,530	38,969	1,448	898	3,100	3,608	0

As detailed in section 3.3.2.2, results for ^3He acquisition were generated for two scenarios; the *launch scenario*, which includes the energy released from the propellants during the launch, and the *rocket fuel scenario*, which only includes the embodied energy of producing the rocket fuel. Table 4.8 lists the breakdown of energy requirements for ^3He acquisition.

The total energy requirements of each case are listed in Table 4.9 for the low and high U.S. electrical energy growth scenarios as well as their mean, which is used in all subsequent analyses. The energy requirements to procure the ARIES-III fuels, deuterium and helium-3, are listed in Table 4.10.

Table 4.8: Lifetime Energy Requirements for Helium-3 Acquisition, Does Not Include Energy Released from Rocket Fuel Combustion.

Transportation	Cargo Flights (TJ_{th}/GW_e -Installed)	Passenger Flights (TJ_{th}/GW_e -Installed)	Total Energy (TJ_{th}/GW_e -Installed)	Total Energy (TJ_{th}/Tonne ^3He) - mean elect. energy growth scenario
Embodied Energy of Lunar Base and Mining Equipment	101	-	101	30
HLLV Embodied energy	88	-	88	26
LUBUS Embodied energy	3	-	3	0.75
HLLV Propellant - embodied	2,011	1,369	3,380	991
LUBUS Propellant - embodied	35,992	26	62	18
HLLV Propellant combustion	6,781	4,617	11,398	3,344
LUBUS Propellant combustion	154	104	258	76

Table 4.9: Total Energy Requirements from Low and High Electric Energy Growth Consumption Scenarios, Launch and Rocket Fuel Scenarios.

	Mean	Low	High
TJ_{th}/GW_e-Installed			
Launch Scenario	4,281	4,220	4,310
Rocket Fuel Scenario	3,633	3,584	3,657
TJ_{th}/Tonne ^3He			
Launch Scenario	1,256	1,238	1,264
Rocket Fuel Scenario	1,066	1,051	1,073

Table 4.10: Energy Requirements for Deuterium and Helium-3 Procurement from Both Launch and Rocket Fuel Scenarios.

	Tonne/ 30 $GW_e y$	TJ_{th}/Tonne		Total TJ/ 30 $GW_e y$	
		Rocket Fuel	Launch	Rocket Fuel	Launch
Deuterium	1.78	140	140	250	250
Helium-3	2.67	1,066	1,256	2,849	3,357
Total		**1,206**	**1,396**	**3,100**	**3,607**

4.1.4 Operation and Maintenance

Table 4.11 lists the breakdown of operational energy for the three fusion plants. The energy requirements for power plant operation and maintenance (O&M) are listed in Tables 4.12.

Table 4.11: Breakdown of Operational Energy Consumption for Various Fusion Power Plants. ($TJ_{th}/GW_e y$)

	UWMAK-I DT	ARIES-RS DT	ARIES-III D^3He
Cryogenics Plant	26	14	9
Liquid Metal Heating - Lithium	54	35	NAppl.
After heat cooling	2	2	2
HVAC (incl. misc, vac. pumps, fans)	203	157	177
Chemical Activities	negl.	negl.	negl.
Tritium Separation	negl.	negl.	negl.
Personnel	40,438	31,241	35,273
TJ_{th}/GW_e-cy	**326**	**239**	**224**
TJ_{th}/30 $GW_e y$	**13,039**	**9,550**	**8,947**
TJ_e/30 $GW_e y$	**4,807**	**3,521**	**3,298**

Table 4.12: Energy Requirements for Operations and Maintenance of Power Plants

	TJ_{th}	TJ_e	TJ_{th}/GW_e
Coal - Uchiyama	NA	NA	13,195
Fission	5,866	476	7,158
UWMAK-I	negl.	4,807	13,039
ARIES-RS	negl.	3,521	9,550
ARIES-III	negl.	3,298	8,947
Wind	2,985	negl.	2,985

4.1.5 Decommissioning, Waste Disposal and Land Reclamation

The energy requirements for decommissioning, waste disposal and land reclamation are listed in Table 4.13.

Table 4.13: Energy Requirements Associated with Decommissioning and Waste Disposal for Power Plants ($TJ_{th}/GW_{e}y$)

Process	Coal (US avg.)	Fission	DT-Fusion UWMAK-I	DT-Fusion ARIES-RS	D^3He Fusion	Wind
Waste Disposal & Transportation	6	172	16	6	4	negl.
Decommissioning	10	19	55	45	48	50
Land Reclamation (fuel only)	4	0.1	negl.	negl.	negl.	none
Total	20	191	71	51	52	50

4.2 CO_2 Emissions - General Results

The results of the CO_2 analysis are listed in Table 4.14 and Table 4.15. Table 4.14 lists the energy investments for each of the six technologies, normalized to Tonne CO_2/GW_eh, for all nine categories. Table 4.15 lists the same results normalized to Tonne CO_2/GW_e-installed. Discussion of all results takes place in Section 5.2.

Table 4.14: Comparison of CO_2 Emissions from Energy Systems, by Process (Tonne CO_2/GW_eh)

Process	Coal[1]	Fission	DT-Fusion UWMAK-I	DT-Fusion ARIES-RS	D^3He Fusion ARIES-III	Wind [2]
Materials (non-fuel)	0.6	0.7	2.8	4.7	1.8	8.6
Plant Construction	0.7	1.2	2.7	2.9	3.5	1.6
Fuel Mining	8.4	0.4	0.4	0.2	1.9	NAppl.
Fuel Preparation (cleaning, milling, enrichment, etc.)	incl. in mining	8.9	incl. in mining	incl. in mining	incl. in mining	NAppl.
Fuel Transportation	9	0.2	negl.	negl.	incl. in mining	NAppl.
Operation	956	2.2	3.1	2.3	2.1	4.0
Waste Disposal & Transportation	0.05	1.4	0.04	0.01	0.01	negl.
Decommissioning	0.1	0.01	0.4	0.4	0.4	0.4
Land Reclamation (fuel only)	0.03	0.001	negl.	negl.	Negl.	none
Total[3]	974	15	9	11	10	15

[1] Based on the US average mix of coal.

[2] Does not include energy storage.

[3] Columns may not equal totals due to independent rounding.

Table 4.15: Comparison of CO_2 Emissions from Energy Systems, by Process

(10^3 Tonne CO_2/GW_e-Installed)

Process	Coal (US avg.)	Fission	DT-Fusion (UWMAK-I)	DT-Fusion (ARIES-RS)	D^3He Fusion	Wind[1]
Materials (non-fuel)	148	197	735	1,248	460	460
Plant Construction	193	327	702	762	923	88
Fuel Mining	2,203	105	95	61	487	NAppl.
Fuel Preparation (cleaning, milling, enrichment, etc.)	include. in mining	2,339	incl. in mining	incl. in mining	incl. in mining	NAppl.
Fuel Transportation	2,330	56	negl.	negl.	incl. in mining	NAppl.
Operation	251,326	575	819	599	562	216
Waste Disposal & Transportation	13	371	10	4	2	negl.
Decommissioning	21	3	117	94	105	22
Land Reclamation (fuel only)	7	0.3	negl.	negl.	Negl.	none
Total[2]	256,242	3,972	2,477	2,768	2,540	786

1 Does not include energy storage.

2 Columns may not equal totals due to independent rounding.

4.2.1 Materials

The CO_2 emissions for the power plant materials that are typical for the six technologies analyzed here are listed in Table 4.16.

Table 4.16: Breakdown of the CO_2 Emissions for Materials (Tonnes CO_2/power plant)

	Coal[1]	Fission[1]	UWMAK-I[1]	ARIES-RS[1]	ARIES-III[1]	Wind[2]
Aluminum	3,390	239	6,325	0	0	0
B_4C	0	0	26,729	952	0	0
Chromium	660	0	0	0	0	0
Concrete	38,604	93,411	387,852	231,178	254,763	5,166
Copper	3,377	5,168	76,340	6,091	10,250	40
CuZn28Sn	0	146	0	0	0	0
Fiber Glass	0	0	0	0	0	399
Helium	0	0	4,644	87	94	0
Insulation Materials	0	5,237	0	0	0	0
Insulators	0	0	0	161	223	0
Lead	0	115	51,212	0	0	0
Lithium[3]	0	0	90,135	26,899	0	0
Manganese	393	0	0	0	0	0
Mercury	0	0	15	0	0	0
Molybdenum	858	0	0	0	0	0
Nickel	100	1,228	10,270	6,121	20,284	0
NbTi	0	0	44,677	2,330	2,835	0
Silver	0	560	0	0	0	0
Sodium Metal	0	0	137,746	7,714	0	0
Carbon Steel	98,059	83,990	185,294	110,569	129,868	4,256
Stainless Steel	2,005	6,811	274,743	93,348	42,168	578
Tungsten	0	0	0	19,103	0	0
Vanadium	880	0	0	796,806	0	0
Yttrium	0	0	420	0	0	0
Zirconium	0	0	9,715	0	0	0
Tonnes CO_2/plant	148,327	196,905	1,174,102	1,274,461	460,486	10,439
Tonnes CO_2/GW_e-Installed	148,327	196,905	796,001	1,274,461	460,486	417,574

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1 GJ/GWe

2 GJ/25 MWe

3 For comparative analysis, lithium is included in the "fuel mining" section for each DT-fusion reactor.

4.2.2 Construction

The CO_2 emissions from power plant construction are listed in Table 4.17.

Table 4.17: CO_2 Emissions Associated with Power Plant Construction	
Technology	**10^3 Tonne CO_2/GW_e**
Coal	193
Fission	327
UWMAK-I	702
ARIES-RS	762
ARIES-III	923
Wind	88

4.2.3 Fuel Acquisition

The CO_2 emissions from fuel acquisition are listed in Table 4.18 and Table 4.19. Table 4.18 is normalized per GW_eh, while Table 4.19 shows the CO_2 emissions per installed GW_e.

Table 4.18: CO_2 Emissions Associated with Fuel Acquisition for Power Plants (Tonne CO_2/GW_eh)

Process	Coal (US avg.)	Fission	DT-Fusion (UWMAK-I)	DT-Fusion (ARIES-RS)	D^3He Fusion	Wind
Fuel Mining	8.4	0.4	0.4	0.2	1.9	Nappl.
Fuel Preparation (cleaning, milling, enrichment, etc.)	include. In mining	8.9	include. In mining	include. In mining	include. In mining	Nappl.
Fuel Transportation	9	0.2	negl.	Include. In mining	negl.	Nappl.
Total	17	10	0.4	0.2	1.9	0

Table 4.19: CO_2 Emissions Associated with Fuel Acquisition for Power Plants

(10^3 Tonne CO_2/GW_e-Installed)

Process	Coal (US avg.)	Fission	DT-Fusion (UWMAK-I)	DT-Fusion (ARIES-RS)	D^3He Fusion	Wind
Fuel Mining	2,203	105	95	61	487	Nappl.
Fuel Preparation (cleaning, milling, enrichment, etc.)	include. In mining	2,339	include. In mining	include. In mining	include. In mining	Nappl.
Fuel Transportation	2,330	56	negl.	Negl.	Include. In mining	Nappl.
Total[1]	**4,533**	**2,499**	**95**	**61**	**487**	**0**

[1] Columns may not equal totals due to independent rounding.

Table 4.20 shows the breakdown of CO_2 emissions from ^3He acquisition. Unlike the energy requirements for D^3He fusion, there is no difference between the emissions for the launch scenario and fuel scenario. The energy requirements to procure the ARIES-III fuels, deuterium and helium-3, are listed in Table 4.21.

Table 4.22 shows the total CO_2 emissions from the D^3He-fusion penetration scenarios. The results of both the low and high electric energy growth scenarios are listed as well as their mean. Table 4.23 shows the total amount of CO_2 emissions that were replaced by the penetration of D^3He-fusion into the electric power market for each of the four replacement scenarios. Further analysis is in Section 5.2.6.

Table 4.20: Lifetime Emissions of CO_2 for Helium-3 Acquisition.

Transportation	Cargo Flights (Tonne CO_2/GW_e-Installed)	Passenger Flights (Tonne CO_2/GW_e-Installed)	Total Emissions (Tonne CO_2/GW_e-Installed)	Total Emissions (Tonne CO_2/Tonne ^3He)-mean
Embodied Energy of Lunar Base and Mining Equipment	6,243	-	6,243	1,831
HLLV Embodied energy	5,484	-	5,484	1,609
LUBUS Embodied energy	158	-	158	46
HLLV Propellant – embodied	342,465	233,044	575,509	168,819
LUBUS Propellant – embodied	6,129	4,420	10,549	3,095
Total			**597,942**	**175,400**

Table 4.21: CO_2 Emissions from Deuterium and Helium-3 Procurement.

	Tonne Fuel/ 30 GW_ey	Tonne CO_2/ Tonne Fuel	Tonne CO_2/ 30 GW_ey
Deuterium	1.78	10,311	18,353
Helium-3	2.67	25,359	468,974
Total			**487,327**

Table 4.22: U.S. CO_2 Emissions from Four D^3He-Fusion Replacement Scenarios into the U.S. Electric Power Market, 2025-2075

Scenario	**Low Energy Growth** (10^6 Tonne CO_2)	**High Energy Growth** (10^6 Tonne CO_2)	**Mean Energy** (10^6 Tonne CO_2)
Scenario 1: Base Case	176,111	308,915	242,513
Scenario 2: Fossil Fuel Replaced First	139,490	237,011	188,251
Scenario 3: Nuclear Fission Replaced First	167,046	290,312	228,679
Scenario 4: Fossil Fuel and Fission Replaced at Equal Rates	157,679	272,724	215,201

Table 4.23: The Amount of CO_2 Emissions Avoided by D^3He Fusion's Penetration into the Electric Power Market, 2025-2075

Scenario	**Low Energy Growth** (10^6 Tonne CO_2)	**High Energy Growth** (10^6 Tonne CO_2)	**Mean Energy** (10^6 Tonne CO_2)
Scenario 1: Base Case	0	0	0
Scenario 2: Fossil Fuel Replaced First	36,621	71,904	54,262
Scenario 3: Nuclear Fission Replaced First	9,065	18,603	13,834
Scenario 4: Fossil Fuel and Fission replaced at equal rates	18,432	36,191	27,312

4.2.4 Operation and Maintenance

Results of the CO_2 emissions from O&M are listed in Table 4.24. Discussion of the results can be found in Section 5.2.4.

Table 4.24: CO_2 Emissions Associated with Power Plant O&M

Technology	10^3 Tonne CO_2/GW_e
Coal	251,326
Fission	575
UWMAK-I	819
ARIES-RS	599
ARIES-III	562
Wind	216

4.2.5 Decommissioning and Waste Disposal

Table 4.25 lists the CO_2-emissions per installed GW_e from waste disposal, decommissioning and land reclamation for the six technologies.

Table 4.25: CO_2 Emissions Associated with the Decommissioning of Power Plants (Tonnes CO_2/GW_e-Installed)

Process	Coal (US avg.)	Fission	DT-Fusion (UWMAK-I)	DT-Fusion (ARIES-RS)	D^3He Fusion	Wind
Waste Disposal & Transportation	13,384	371,210	10,201	3,891	2,260	negl.
Decommissioning	21,359	2,745	116,622	94,217	104,933	22,110
Land Reclamation (fuel only)	7,119	299	negl.	negl.	negl.	none
Total	41,863	374,254	126,823	98,108	107,192	22,110

5 Discussion of the Results

5.1 Energy

The nine power plant categories that are listed in Tables 4.1 and 4.2 have been reduced to five in this chapter for the purpose of discussion. The processes discussed in section's 5.1.1 - 5.1.5 include power plant materials, construction, operation and maintenance (O&M), decommissioning and waste disposal (which also includes land reclamation for fuel mining), and fuel acquisition (combining fuel mining, processing, and transportation). In section 5.1.6, the material and construction categories are combined, and the overall results of four categories are discussed.

5.1.1 Materials

It is shown in Table 4.3 that the energy required to procure and manufacture the materials is greatest for wind and DT-fusion power plants when normalized per unit of electricity produced. Figure 5.1 shows that wind power plants require slightly more energy per GW_ey than the ARIES-RS DT-fusion power plant, five times more than the ARIES-III D^3He-fusion power plant and ten times more than either coal or fission.

There are two explanations for wind having greater energy requirements compared to other technologies. One is that a significant amount of steel and concrete is required to build a wind turbine. Nearly 2,000 tonnes of steel and 10,000 tonnes of concrete are needed to build a 73-turbine wind power plant (25 MW_e). Individual turbines require 87 tonnes of steel and 376 tonnes of concrete for the 120-foot structure. The second explanation is that the intermittent nature of wind leads to smaller capacity factors. The actual capacity factor of the 25 MW_e Buffalo Ridge Phase I wind farm is 24%, which is one third the 75% capacity factor's for the other technologies. Even though wind power plants require less energy per installed GW_e than

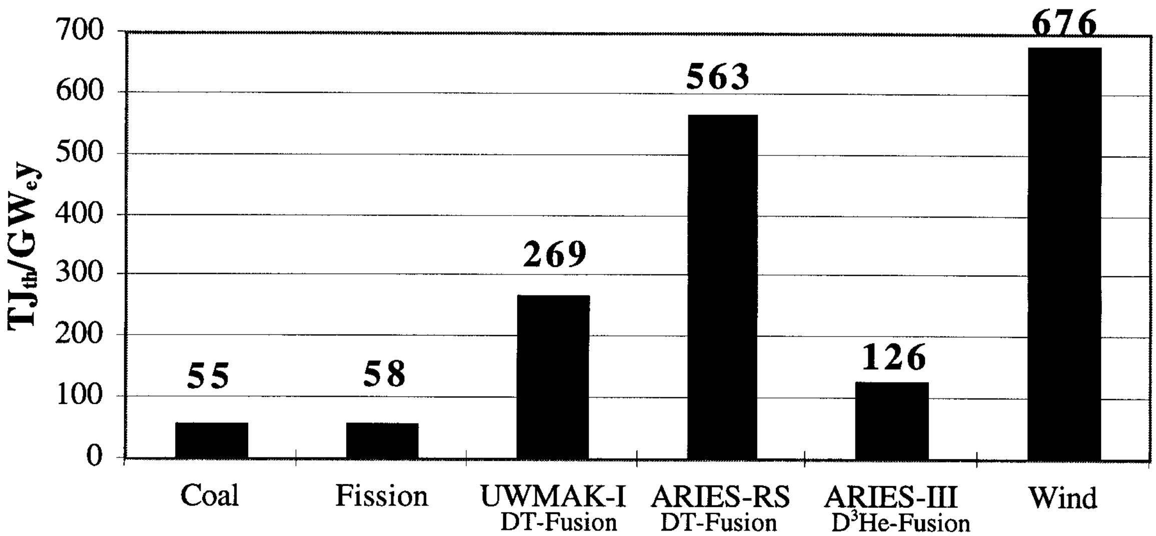

Figure 5.1: Materials procurement for Wind and the ARIES-RS power plants require ten times the energy used for coal and fission power plants.

any of the fusion power plants, the smaller capacity factor equates to less energy produced and therefore greater energy requirements per unit of electricity produced.

Even with a 24% capacity factor, the wind power plant does not require much more energy per $GW_e y$ than the ARIES-RS fusion plant. ARIES-RS requires nearly twice the energy per installed GW_e in comparison to UWMAK-I, the next highest. This is due largely to the use of vanadium in the blanket of the ARIES-RS nuclear island. Vanadium is very energy intensive compared to steel, the blanket structural material for both UWMAK-I and ARIES-III. Vanadium requires 3,711 GJ/tonne compared to 53 GJ/tonne for steel. Nearly 75% of the energy input for materials in ARIES-RS is attributed to vanadium, despite the fact that vanadium contributes less than 1% of it's total mass.

The mass and energy requirements for the D^{3}He-fueled ARIES-III fusion plant is significantly smaller compared to either DT-fusion power plant due to the difference in neutron production rates. The need to shield people and equipment from 14 MeV neutrons in DT-fusion reactors results in rather thick (1-2 meter thick) concrete shielding. This shielding adds to the materials inventory (see Table 3.20) and consequently to the energy needed to make the building itself. The smaller mass of the D^3He-fusion reactor is due to a smaller amount of neutrons produced during operation, which thereby requires less shielding for worker safety and equipment. At the same time, due to the fewer neutrons, the first wall of the D^3He reactor will not have to be replaced during the operating lifetime of the power plant. The first wall of the DT-fusion reactors will need to be replaced every two years or 19 times over the lifetime of the plant.

5.1.2 Construction

The three fusion plants require the greatest amount of energy to construct, followed by wind, fission, and coal in that order. The fusion plants require more energy to construct due to both their greater mass and technological complexity. The nuclear island of the fusion plant is much more complex than the inner core of the fission or coal power plants.

The energy requirements for wind construction are higher than coal and fission due again to the low capacity factor, as well as the material intensive nature of the wind plants. As seen in Table 3.20, wind plants require twice as much mass per installed-GW_e than the PWR and nearly four times as much as the coal plant. The greater complexity of both baseload plants reduces these ratios for construction. The actual energy requirements per installed GW_e are the least for wind power plants of the six technologies, as shown in Table 4.2. Coal, then fission requires more energy than wind, but less than fusion plants. Figure 5.2 compares all the technologies with respect to construction energy requirements.

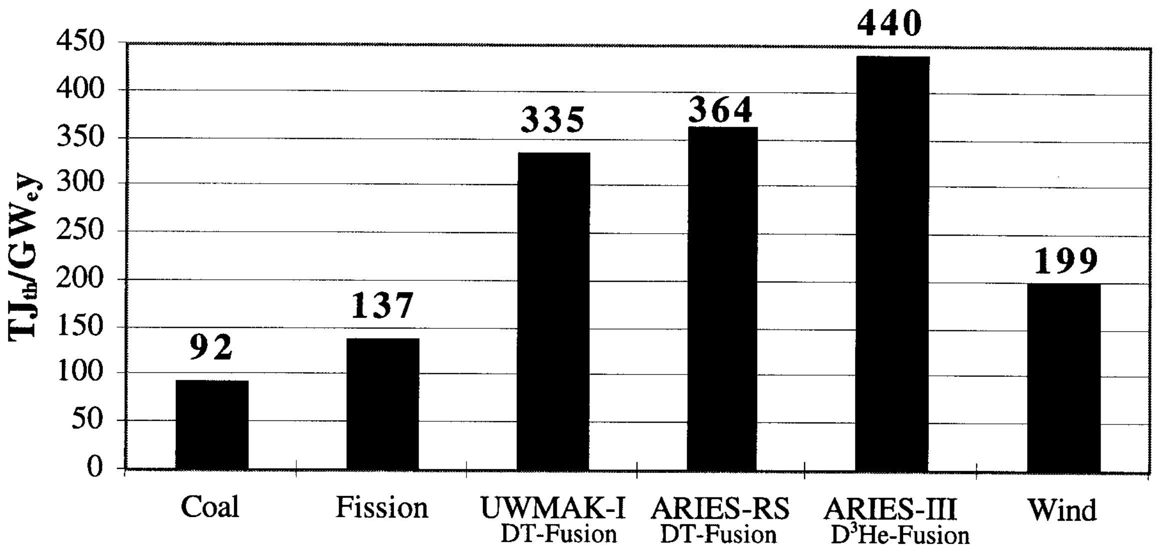

Figure 5.2: Comparison of Power Plant Construction Energy Requirements

5.1.3 Fuel Acquisition

The energy requirements for the acquisition of fuel for each technology are listed in Tables 4.5 and 4.6. As can be seen in Figure 5.3, the technologies with the greatest mass of fuel, coal then fission, also have the greatest energy requirements for its acquisition. Wind obviously requires no energy for fuel.

Nearly 55% of the energy needed to acquire coal is due to mining and cleaning. The other 45% of the energy are due to transporting the coal by rail. The distance of coal transportation greatly effects the total amount of energy required. Coal plants located closer to the mine than the 700 miles assumed for this study will have smaller energy requirements and those located farther will have increased requirements.

The nuclear fission PWR requires just under half the energy for the fuel cycle of coal, but is also significantly greater than any of the fusion power plants. The results are for a PWR with uranium enriched via the gas centrifuge process, which uses 1/60th as much energy as gaseous diffusion enrichment, the method currently used in the United States. This means that using current enrichment methods, the energy requirements to process uranium would be even

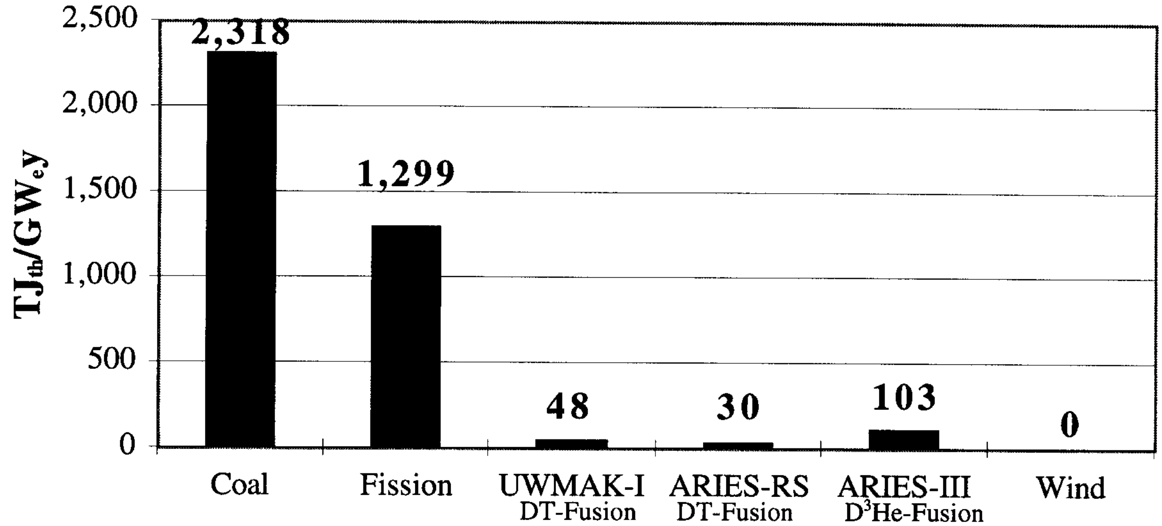

Figure 5.3: Coal and fission require the most energy for fuel acquisition of the six technologies.

higher. However, 40% of the world enrichment capacity is now in gas centrifuges and that fraction is increasing. This makes a gas centrifuge assumption reasonable for the future (~2050 AD).

Though the two DT-fusion plants will require the same amount of fuel over their lifetimes (assuming equal efficiencies and output) the results show that the UWMAK-I requires 60% more energy for fuel than ARIES-RS. This is due solely to the fact that UWMAK-I uses twice as much lithium than ARIES-RS. Remember that lithium is used as both a tritium breeder and a coolant for both UWMAK-I and ARIES-RS.

The fact that ARIES-III requires more energy to procure fuel than either DT-fusion power plant is not surprising, when considering that it is necessary to go to the Moon to retrieve the helium-3. What may be surprising is that, despite having terrestrial resources, fission requires twelve times more energy and coal ≈ twenty-three times more energy to procure fuel than the D^3He-fusion power plant.

As detailed in Section 3.3.2.2, results for ^3He acquisition were generated for two scenarios; the *launch scenario*, which includes the energy released from the propellants during the launch, and the *rocket fuel scenario*, which only includes the embodied energy of producing the fuel. Table 4.7 lists the breakdown of energy requirements for ^{3}He acquisition. Figure 5.4 compares the total energy requirements per tonne of helium-3 procured for each scenario. There is a difference of less than 20% between the two scenarios. The amount of energy released in the combustion of the rocket fuel comprises a small percentage of the total energy required in the Launch scenario.

Figure 5.5 shows that in the rocket fuel scenario the embodied energy of LO_x and LH_2 makes up 94% of the total energy requirements for ^{3}He acquisition, while both the embodied energy of the rockets and lunar base infrastructure comprise 3% each. For the launch scenario, as shown in Figure 5.6, the combustion energy comprises only 15% of the total, while the embodied energy of the propellant makes up 81% and the infrastructure and rockets each comprise 1% of the total.

The total energy requirements of each case are listed in Table 4.8 for the low- and high-energy growth scenarios as well as their mean, which is used in all subsequent analyses. As was shown in the above figures, the energy requirements of the launch scenario are only 20% higher than that of the rocket fuel scenario.

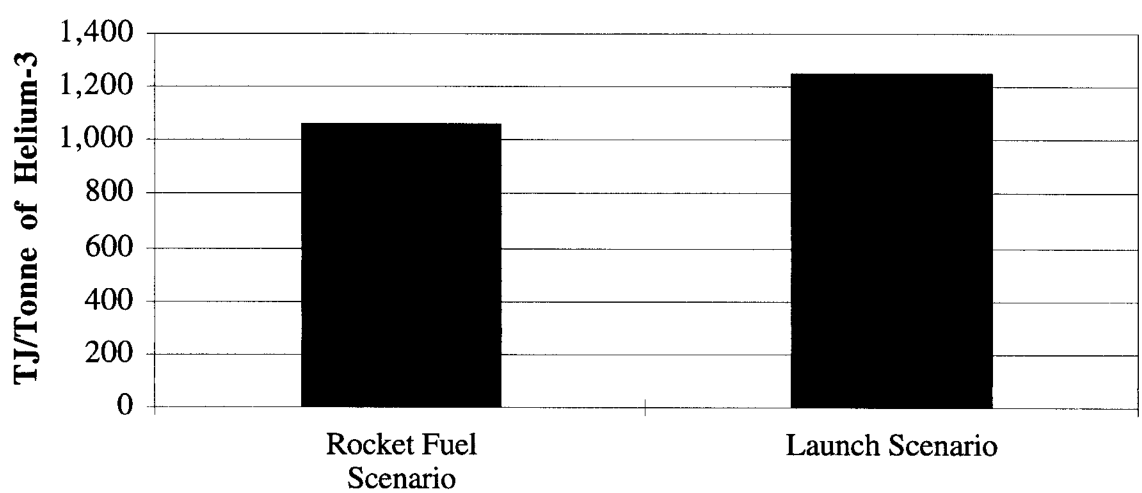

Figure 5.4: Comparison of Total Energy Requirements for Both the Fuel and Launch Scenarios of Helium-3 Transportation.

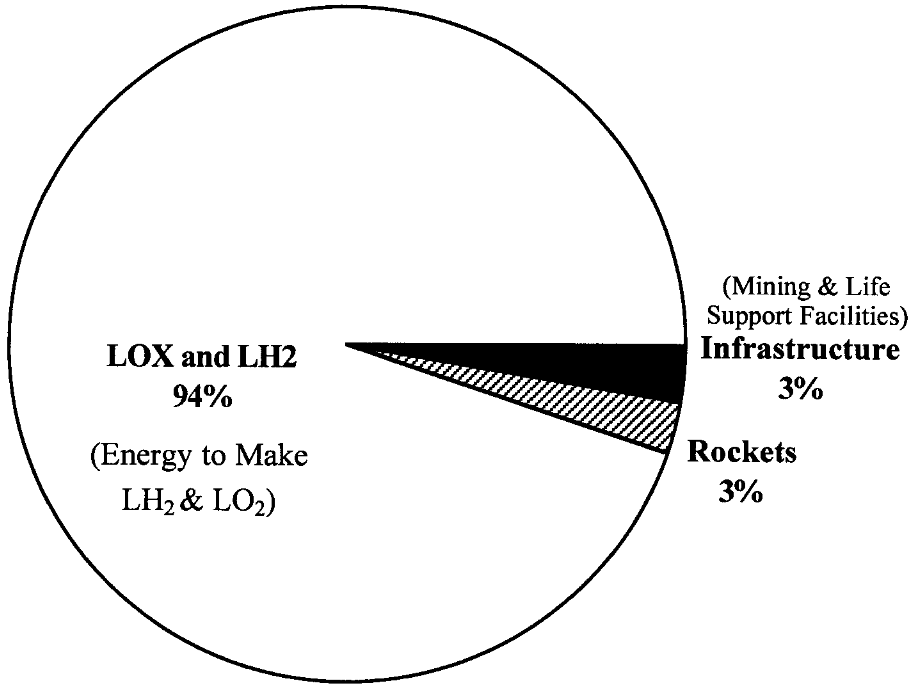

Figure 5.5: In the Rocket Fuel Scenario of Helium-3 Transportation, 94% of the Energy Required to Procure Helium-3 is Related to Production of Rocket Fuel.

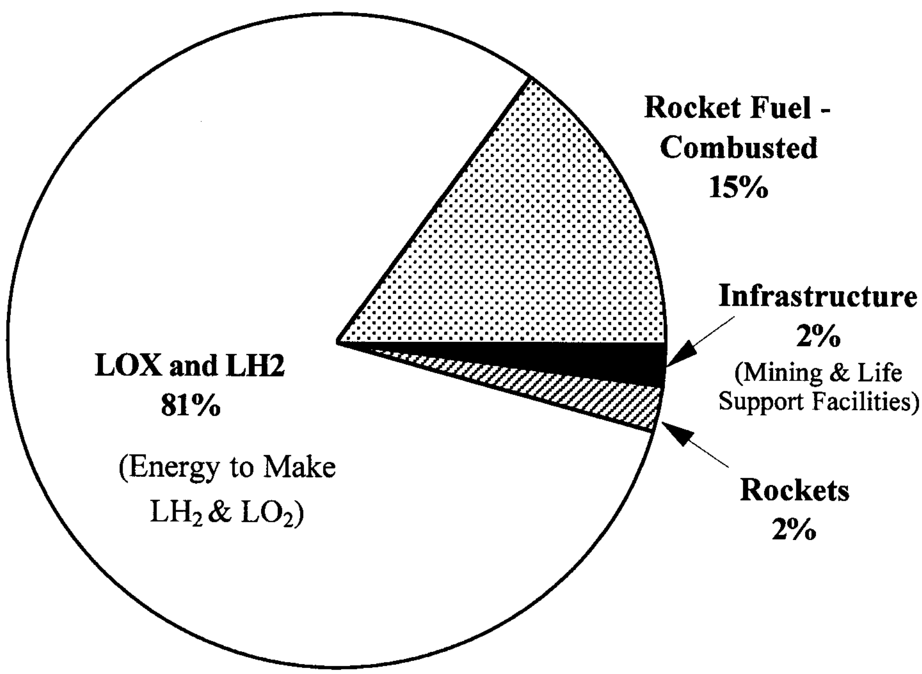

Figure 5.6: In the Launch Scenario of Helium-3 Transportation, 81% of the Energy Required to Procure Helium-3 is Related to Procurement of Rocket Fuel and Only 15% is from Fuel Combustion.

The energy requirements to procure the ARIES-III fuels, deuterium and helium-3, are listed in Table 4.9. It takes between 10 - 50 times more energy to procure ^3He than deuterium over the life of the power plant.

5.1.4 Operation and Maintenance

The energy requirements for power plant operation and maintenance (O&M) are listed in Table 4.10 and compared in Figure 5.7. The wind power plant requires the greatest amount of energy per unit of electricity produced of the six technologies, followed by the DT-fusion power plant, UWMAK-I, and the coal power plant. Again, the primary reason wind is highest is due to the low capacity factor. Other significant factors include the modularity of the wind farm. There are 73 separate nacelles (turbines) all with numerous moving parts. Maintaining a wind farm is not unlike that of maintaining a fleet of cars. Each nacelle will need to be monitored and serviced regularly, which will require significant amounts of lubricating oil and fuel for service vehicles, which may require long drives for service personnel because of the typical remoteness of wind turbines. In terms of energy required per installed GW_e, wind is the lowest of the six technologies (see Table 4.2).

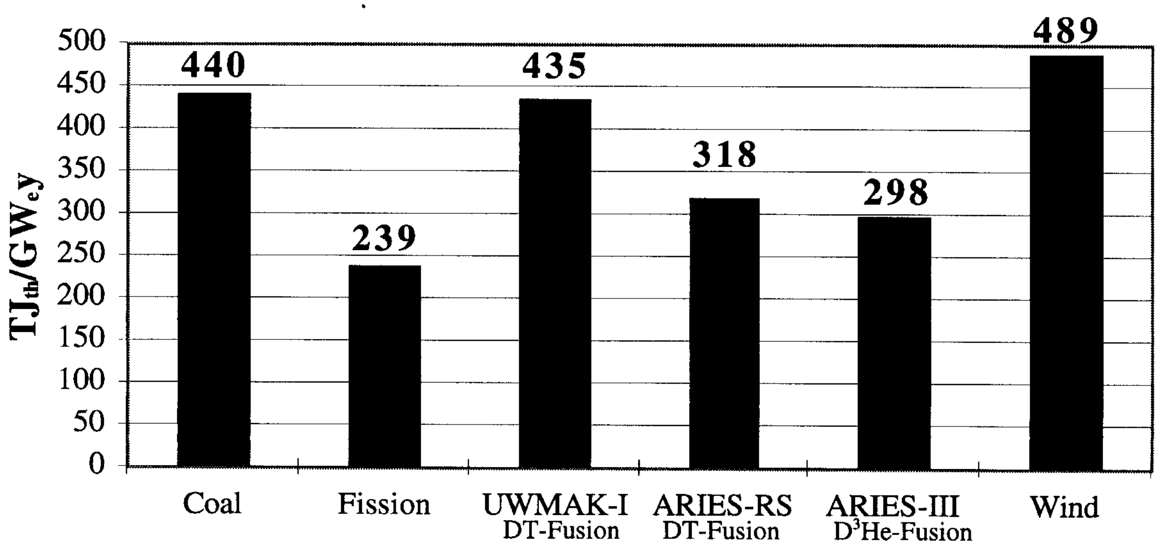

Figure 5.7: Comparison of Power Plant Operational Energy Use

The large amount of energy required for coal plant operations is not surprising when considering the large mass of fuel (and ash) that needs to be transported within the power plant. Over 111 million tonnes of coal is required to fuel a 1 GW_e coal plant over its operating lifetime, which is an exceedingly greater mass than the 885 tonnes of uranium needed to fuel a PWR. While some of the coal will be transported with electrical motors, a large amount requires large diesel-fueled machinery to move coal from trains or ships to storage piles to the conveyer belt.

The O&M energy requirements for the fusion plants were all based on UWMAK-I data and include only the energy needed to keep the plant operational when it's down 25% of the year for maintenance. The UWMAK-I has the greatest energy requirements due to having larger components than the ARIES power plants. The larger magnets (cryogenics) of UWMAK-I means that more energy is necessary to keep them cool during downtime. A larger balance of plant for UWMAK-I will require more energy for the HVAC system and the liquid metal heating needs are greater for the UWMAK-I due to a larger mass of lithium in comparison to ARIES-RS. ARIES-III has an organic coolant, which will not require heating during downtime.

Operational energy requirements of the 1000 MW_e PWR plant are the least of the six technologies. This data is based on results from Tsoulfanidis[1]. Since there are no cryogenics systems or liquid metals to keep warm, it is not surprising that fission plants require the least operational energy when they are down.

5.1.5 Decommissioning and Waste Disposal

The energy requirements for decommissioning and waste disposal are listed in Table 4.11. As can be seen in Figure 5.8, fission requires two and a half times more energy per GW_ey for decommissioning than either wind or UWMAK-I. The fact that fission has the greatest energy requirements for waste disposal and decommissioning is not a surprise when considering that

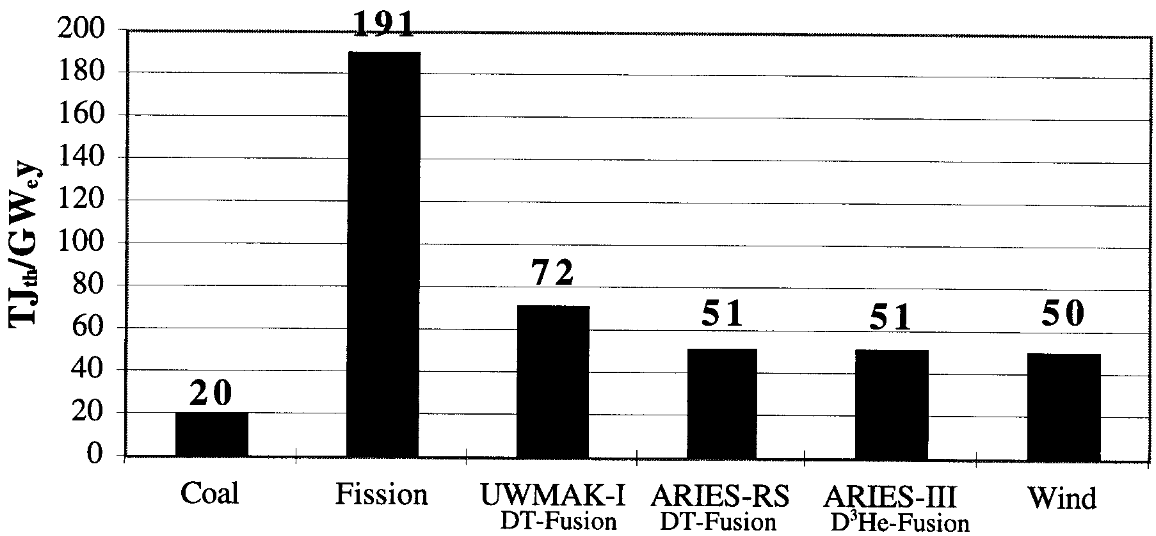

Figure 5.8: Fission plants require 2.5 times more energy to decommission than UWMAK-I and ~4 Times More Than Wind or the ARIES Reactors.

all spent fuel is high-level radioactive waste, which will eventually require long-time storage in a deep geological waste repository such as the one being built at Yucca Mountain in Nevada. Because the data used here is 20 years old and The Yucca Mountain Deep Geological Waste Repository is not finished, it is possible that the energy required for this type of disposal could actually be higher or lower than that shown in this study.

For the fusion power plants, the UWMAK-I requires the most energy for decommissioning while ARIES-RS and ARIES-III the least. The energy requirements for this process were scaled based on the mass of the plants. Both ARIES reactors have nearly equal energy requirements for decommissioning and waste disposal combined.

Decommissioning the wind plant will require more energy than the coal plant and nearly the same as both ARIES fusion plants when normalized per $GW_{e}y$. Though logic may suggest wind should require even less energy to decommission, there are at least three reasons that its energy requirements are as high as they are. One is that wind plants are more material intensive than coal plants. A second reason is, again, the low capacity factor. And third, the method used to determine the energy costs of decommissioning a wind power plant was a rough estimate based on the energy required to construct the plant. Because no data on the decommissioning of wind turbines was found, it was estimated for this thesis that dismantling the wind plant would require as much energy as constructing it. However, it is estimated that the towers will last the lifetime of two nacelles, which means the energy requirements for dismantling the entire wind farm can be amortized over the life of two turbines.

For comparison, a study by the Danish Wind Turbine Manufacturers Association[2] concludes that the energy required to scrap the turbines is more than twice the amount calculated in this thesis. The same study also concluded that the energy gain from recycling the scrapped materials was greater than that necessary to dismantle it, therefore making decommissioning a net energy gain for wind. When compared in terms of GJ_{th}/GW_e-installed, wind power plants require less energy to decommission than all technologies except coal.

5.1.6 Energy Payback and Overall Results

To better analyze the data, the nine categories listed above were regrouped into four categories:

- Fuel related (Mining, Preparation, and Transportation)
- Plant Materials and the Construction of the Plant
- Operation of the Plant
- Decommissioning, Waste Disposal and Land Reclamation.

The regrouped results are listed in Table 5.1. As shown in Figure 5.9, the total energy input for coal and fission power plants is dominated by processes related to the fuel cycle, while the largest energy investment for the fusion and wind power plants is related to construction and plant materials. The fuel related energy requirements for the coal power plant are greater than the total energy requirements for the other five power plants, doubling those of UWMAK-I DT-fusion plant and the D^3He-fusion ARIES-III.

Table 5.1: Energy Investments for Energy Systems, Regrouped into Four Categories ($TJ_{th}/GW_{e}y$)

Process	Coal[1]	Fission	DT-Fusion UWMAK-I	DT-Fusion ARIES-RS	D3He-Fusion ARIES-III Rocket Fuel	D3He-Fusion ARIES-III Launch	Wind[2]
Fuel Related	2,318	1,299	48	30	103	120	0
Plant Materials & Construction	147	195	604	927	566	566	875
Operation	440	239	435	318	298	298	489
Decommissioning & Waste Disposal	20	191	72	51	51	51	50
Total[3]	2,925	1,923	1,158	1,326	1,019	1,036	1,414
Energy Payback Ratio	11	16	27	24	31	30	23

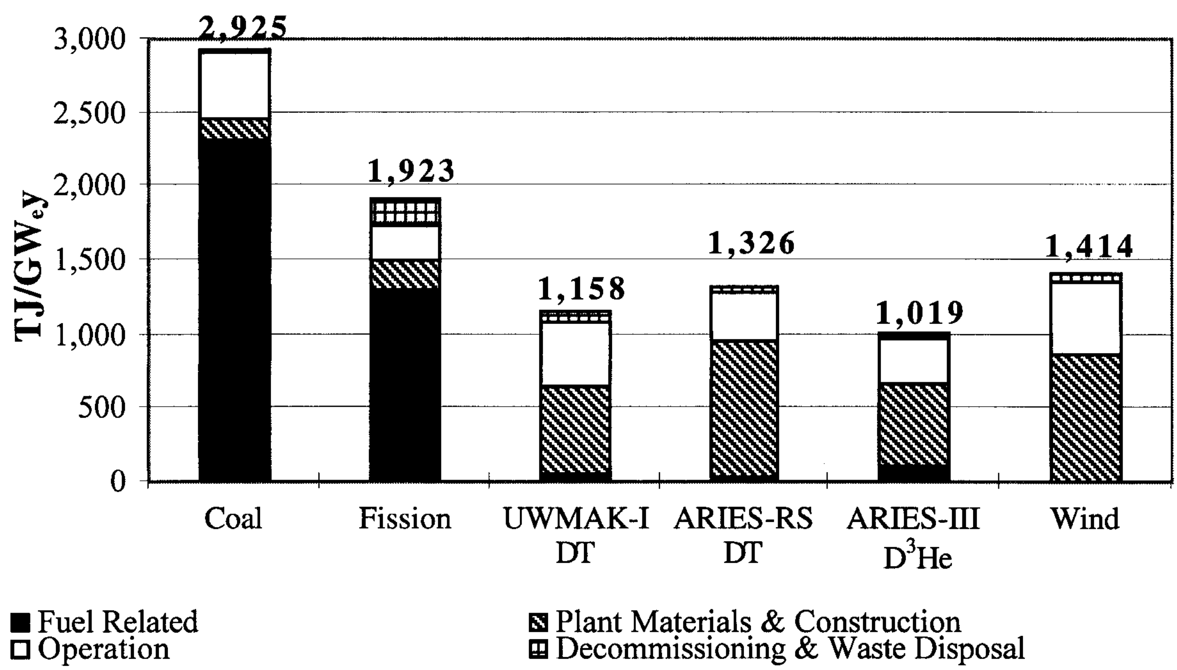

Figure 5.9: Fuel-related energy inputs for coal and fission are large in comparison to the other technologies.

1 Based on the US average mix of coal.

2 Does not include energy storage.

3 Columns may not equal totals due to independent rounding.

Table 4.13 and Figure 5.10 reflect the share of the energy inputs related to each of the four subgroupings. While the energy investments of coal and fission are dominated by their fuel cycles, the majority of the fusion and wind power plant energy investments are from power plant materials and construction activities. The percentage of the total energy input associated with the materials and construction for these plants ranges from 52% to 70%. For the coal and fission plant, these processes account for only 5% and 10% respectively. In terms of total energy requirement per net electrical output, the materials and construction account for ≈920 $TJ_{th}/GW_{e}y$ for the ARIES-RS DT-fusion plant which is more than 50% higher than that for the other two fusion plants and more than 4 times greater than either coal or fission. Only the wind power plant, at ≈860 $TJ_{th}/GW_{e}y$ was close to this. Wind's high energy requirements for materials and construction are due to the fact that it is an intermittent energy source with a capacity factor of 24% (compared to capacity factors of 75% for the other five technologies).

Table 5.2: Energy Investments for Energy Systems, Regrouped into Four Categories. (Percentage)

Process	Coal[4]	Fission	DT-Fusion UWMAK-I	DT-Fusion ARIES-RS	D^3He-Fusion ARIES-III		Wind[5]
					Rocket Fuel	Launch	
Fuel Related	79%	67%	4%	2%	10%	10%	0%
Plant Materials & Construction	5%	10%	52%	70%	56%	55%	62%
Operation	15%	12%	38%	24%	29%	29%	35%
Decommissioning & Waste Disposal	1%	10%	6%	4%	5%	5%	4%

[4] Based on the US average mix of coal.

[5] Does not include energy storage.

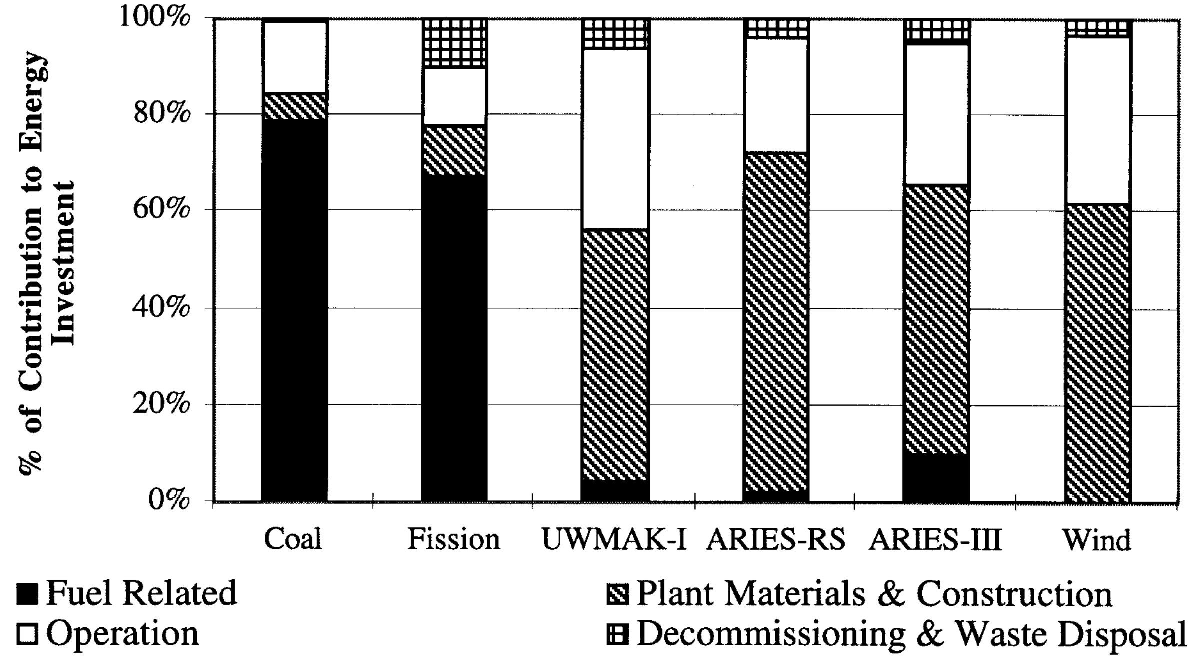

Figure 5.10: The energy inputs for coal and fission are dominated by the fuel cycle, while inputs for fusion and wind facilities are dominated by plant materials and construction.

The contribution of the fuel cycle to the ARIES-III energy requirements range from 10-24%. The fuel cycle for DT-fusion comprises approximately 4% of the total. The energy requirements to procure helium-3 is from 3 to 27 times greater than the energy needed to procure lithium for the UWMAK-I and ARIES-RS DT-fusion reactors. One reason the difference in the energy investment for these two fuels is not greater is due to the large difference in mass required of each (3 and 1,700 tonnes for ^{3}He and Lithium respectively). It should also be noted that lithium functions as a heat transfer medium as well and the D^{3}He-fusion plants must include H_20 or an organic coolant.

The large percentage of energy invested in the materials and the construction of the fusion power plants should not be surprising due to the fact that both DT- and D^{3}He-fusion have very low power densities compared to fission. This results in bigger "nuclear cores". In addition, the surrounding buildings need to be bigger for fusion.

The largest part of the ^3He-fuel cycle energy investment is from the transportation of mining equipment, habitat, and personnel to the Moon. Even though ^3He must be transported via rocket from the Moon, the fact that all lunar base and mining materials are amortized over a 50-year period, significantly reduces the energy/tonne of ^3He.

The operational energy of both fusion reactors was mainly calculated based upon the energy consumption of the plant when it is not producing electricity. During the 25% of the year required for maintenance, the plants need to purchase electricity for such things as keeping superconducting magnets cold, liquid metals hot, HVAC, etc. That 24-38% of DT- and 19-29% of D^3He-fusion's total energy requirement comes during the downtime for maintenance is not very surprising. The primary difference between the operational energy for both is the fact that the DT-fusion UWMAK-I uses liquid lithium and sodium in its primary and secondary loop's respectively, both of which need to be kept hot during the downtime.

A summary of the overall energy payback ratios (EPR) is given in Figure 5.10. The results of this study found the coal units to produce 11 times more energy in electricity than is required to make it over the lifetime of the plant. The EPR is somewhat higher in LWR fission (16) and wind plants (21) and predicted to be between 24 and 27 for the DT-fusion power plants and 31 for the D^3He-fusion facilities.

It is important to remember that the values for fusion are projected on the basis of fusion reactor designs, not operating facilities. This makes it difficult to conclude that the higher energy payback ratios of DT- and D^3He-fusion reflect a distinguishable advantage over the other technologies in this one area. It does mean, that given what is known now from the perspective of their energy requirements and EPR, fusion technologies should continue to be considered as possible replacements for coal and/or fission technologies in the future.

Likewise, it must be noted that a fair comparison of wind power plant technologies to baseload technologies would include energy storage for wind. Wind and other intermittent technologies will never be able to fully compete with baseload technologies without a means to store energy for the times when they are not directly producing electricity. However, at this time, the amount of electricity produced by wind power, is small enough that all of the electricity is undoubtedly used. In the case where wind comprises a sizeable share of the electricity market, some form of energy storage will have to be used, and the inclusion of this component will degrade the energy payback ratio (by increasing energy requirements) as well as increase the emissions of CO_2.

Other studies have concluded that coal has an EPR ranging between 5 [1, 3] and 16.5 [4]. Perry et al [3], performed net energy analyses of four different coal-burning technologies all of which had EPRs between 5 and 7.

As mentioned in section 2.1.5.3, there have been numerous NEA's performed for fission power plants. For those using the gaseous diffusion enrichment process, the EPR of these studies have ranged between 3.5 [1] and 10. For LWR's using gas centrifuge enriched uranium, the low EPR was 10 by Tsoulfanidis[1] and the high was 18 in a paper by Uchiyama [5]. It was assumed in this paper that uranium for the fission-fueled PWR was enriched via the gas centrifuge process.

Other papers have reported EPR's for wind turbines ranging from 4 [5] to 80 [2]. The lower EPR was for a small 100 kW_e wind turbine while the higher one was for a 600 kW_e turbine performed by the Danish Wind Turbine Manufacturers.

In three previous papers, the EPR of DT-fusion has been determined to be 5 by Tsoulfanidis[1], 28 by Tokimatsu[6], and 63 by Bünde[7]. There have not been any previous studies on D^3He-fusion.

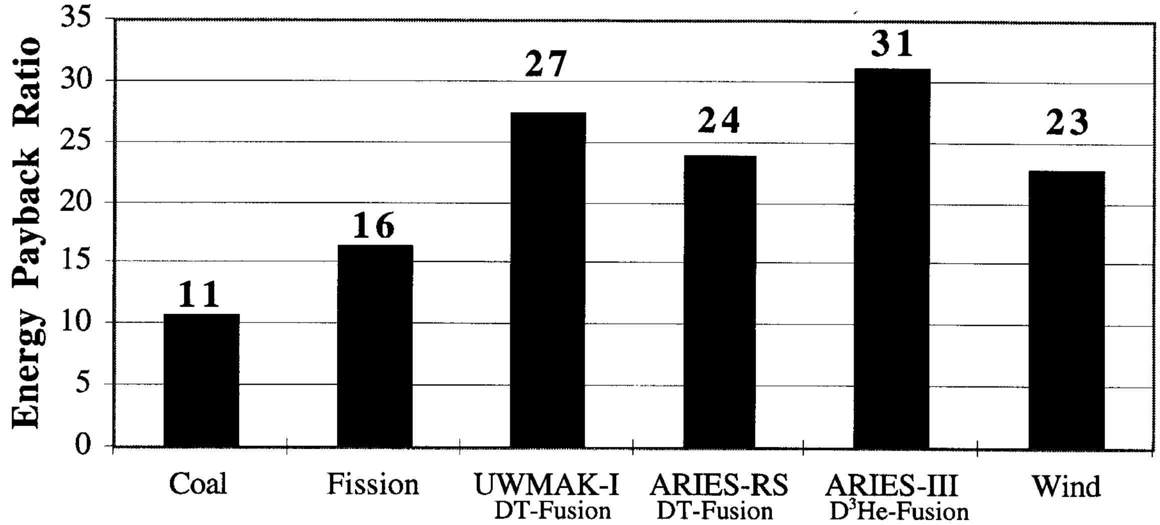

Figure 5.11: The energy payback ratio varies by more than a factor of two between coal and wind and fusion power plants.

5.1.7 Estimated Uncertainty

An uncertainty analysis was performed on the energy payback ratio data of each power plant using a Monte Carlo simulation[8]. The results as shown in Figure 5.12 are based on 10,000 trial runs of the analysis. As expected, the energy payback results of the three fusion power plants have greater uncertainties than the three technologies that currently employed and proven, coal, fission and wind. Of the three fusion power plants, the D^3He-fusion power plant, ARIES-III, had the greatest estimated uncertainty. This also was expected, due to the higher uncertainties surrounding the procurement of helium-3 as compared to proven methods of obtaining deuterium and tritium for the DT-fusion power plants. The two best understood and proven technologies, coal and nuclear fission, had the lowest uncertainty. The uncertainty of the wind plant is slightly higher than the coal and fission power plants, which was expected since the current generation of wind turbines are not as well-proven as current coal and fission power plants.

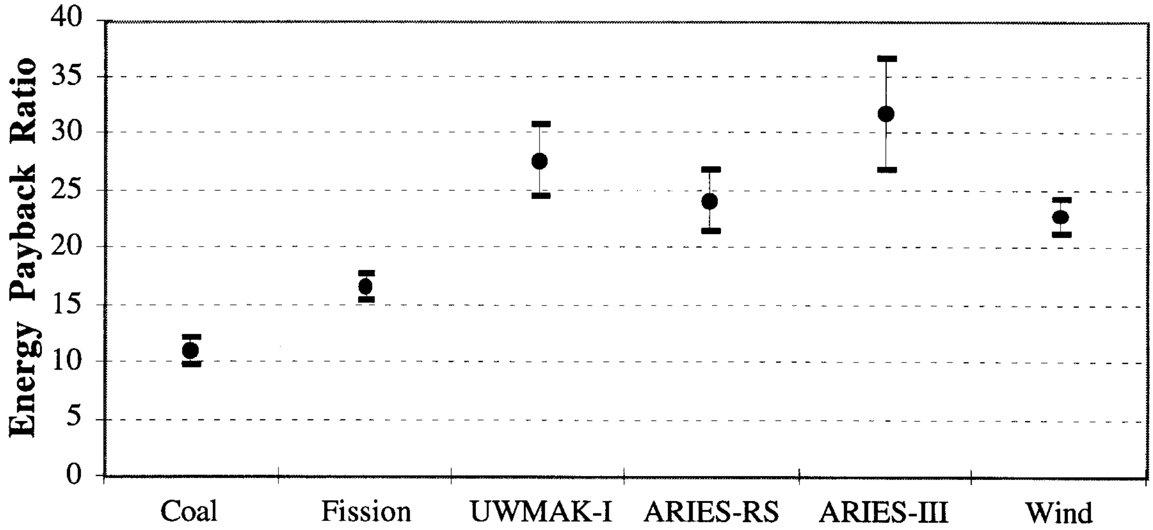

Figure 5.12: The Estimated 1-Sigma Uncertainty of Power Plant Energy Payback Ratios Based on 10,000 Runs.

CO_2 Emissions

The results of the CO_2 analysis are listed in Table 4.12 and Table 4.13. It is expected that the comparison of CO_2 emissions for the six technologies will parallel those of the energy requirements, since similar processes will likely require similar mixes of fuel, which in turn have similar carbon contents. Sections 5.2.1 - 5.2.5 allow for discussion of the same five processes analyzed in section 5.1. However, since the expectation is that the comparative results will parallel those of the energy requirements, in the cases where that is true, the analysis will be left for the end in section 5.2.6. Detailed discussion of individual processes will only ensue when the results vary from the expected.

5.2.1 Materials

The CO_2 emissions for the power plant materials that are typical for the six technologies analyzed here are listed in Table 4.16. As can be seen in Figure 5.13, the trend for CO_2 emissions parallels the energy requirements.

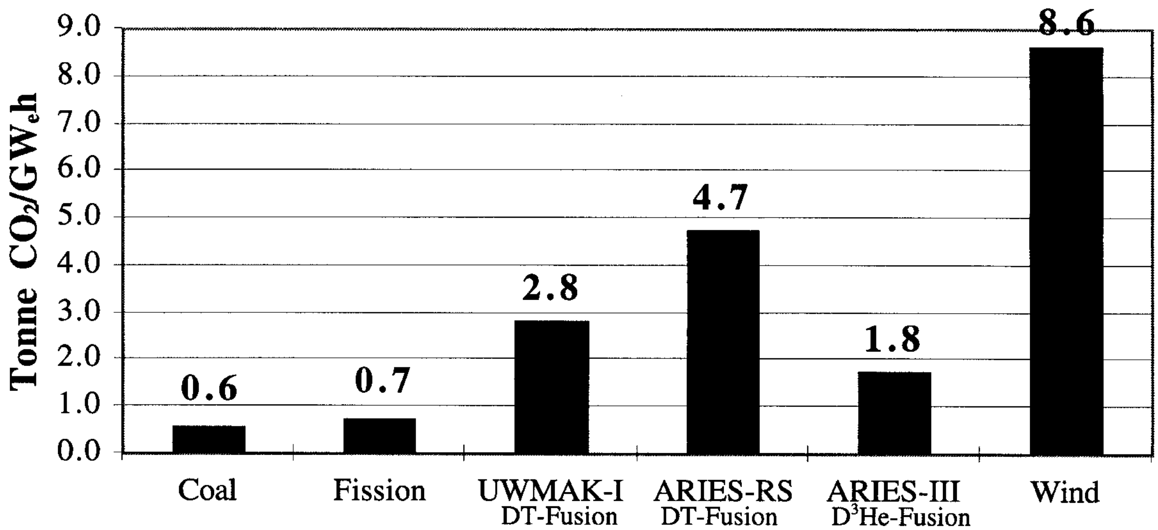

Figure 5.13: Materials procurement for wind power plants produce twice as much CO_2 as ARIES-RS and more than 12 times as much as coal or fission power plants.

5.2.2 Construction

The CO_2 emissions from power plant construction are listed in Table 4.17. As can be seen in Figure 5.14, the trend for CO_2 emissions parallels the energy requirements.

5.2.3 Fuel Acquisition

Again, the CO_2 emissions of fuel acquisition largely parallel the results of the energy requirements, as seen in Figure 5.15. Of particular note is for the rocket fuel and launch scenarios of D^3He-fusion which emit the same amount of CO_2. This is due to the fact that the propellant for the HLLV is carbonless. During combustion, liquid oxygen and liquid hydrogen combine to form water. Though water vapor is a greenhouse gas, it was not measured in this case.

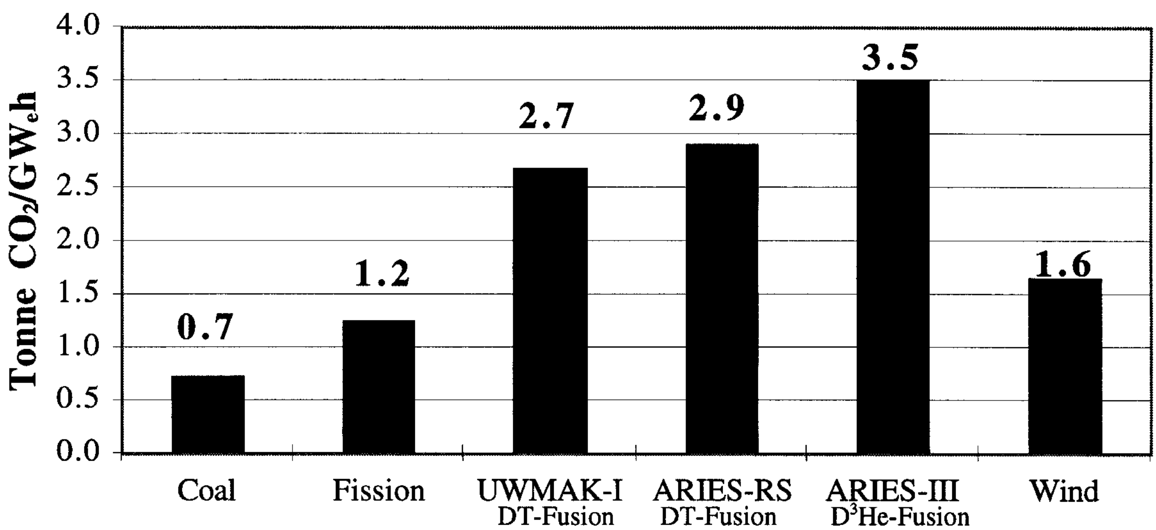

Figure 5.14: The three fusion power plants have the greatest CO_2 emissions from construction.

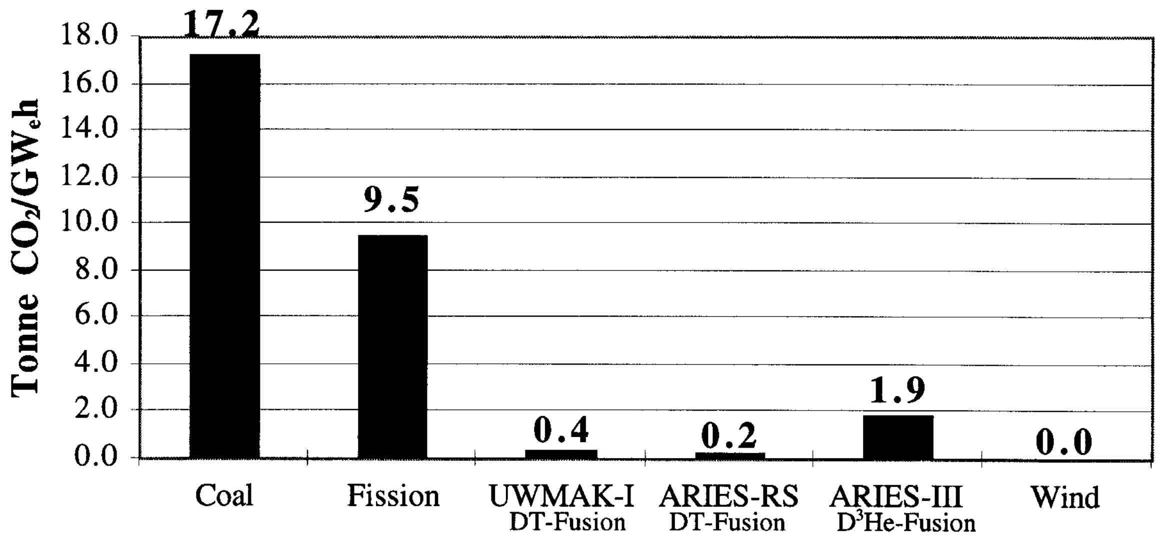

Figure 5.15: The CO_2 emissions related to fuel acquisition parallel those of the energy requirements, except for D^3He-fusion.

5.2.4 Operation and Maintenance

Results of the CO_2 emissions from O&M are listed in Table 4.12 and shown in Figure 5.16. The dominance of coal is the most noticeable difference between the CO_2 emissions and energy requirements. The vast majority of coal plants CO_2 emissions are released during operations. Though the other five technologies follow pretty close in rank to that of the energy requirements, the ratio of energy to CO_2 varies for the PWR and wind power plant in relation to that of the three fusion power plants. The fission plant, though requiring slightly less energy to operate than the D^3He-fusion power plant, ARIES-III, is responsible for slightly more CO_2 emissions.

This difference is due to the difference in fuels used for operations. The energy requirements for the fusion power plants are entirely based on electrical use during the time the plants are down for maintenance. The operational energy of the PWR is based on 82% thermal

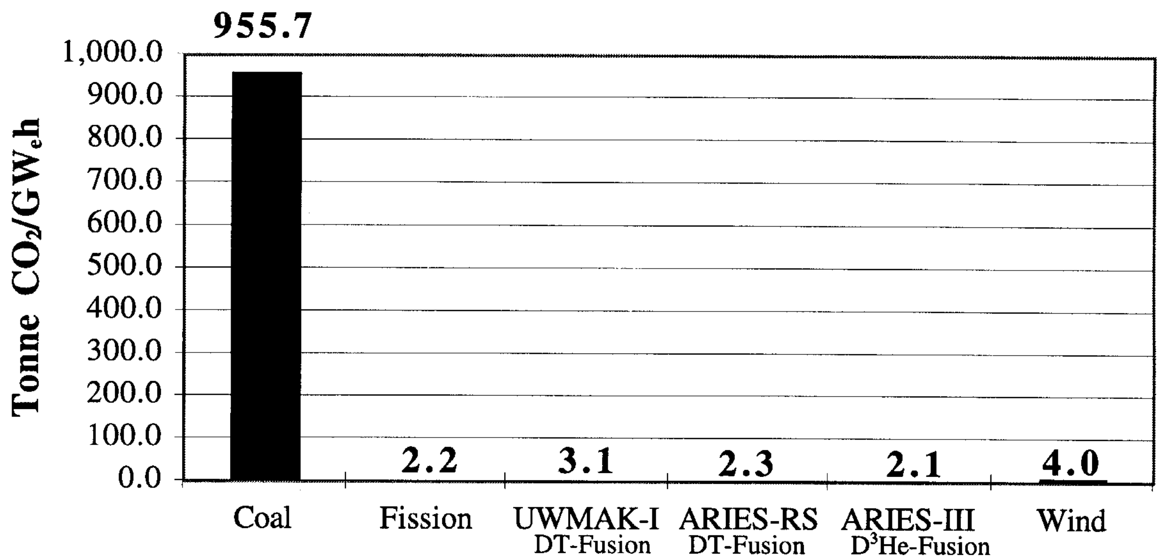

Figure 5.16: Relative to the large emission of CO_2 from coal power plants, the other five technologies produce similar amounts of CO_2 during operations.

energy (see Table 4.12) and the wind plant operational energy is based on 100% thermal energy. In both cases, the thermal energy was assumed to be diesel fuel and multiplied by the subsequent emission factor. The CO_2 emission factor for fossil fuel use is higher than it is for electrical use. Diesel fuel releases 72 kg of CO_2/GJ_{th}, while electricity is responsible for 63 kg CO_2/GJ_{th}-equivalent.

5.2.5 Decommissioning, Waste Disposal, and Land Reclamation

Table 4.13 lists the CO_2-emissions/installed GW_e from waste disposal, decommissioning and land reclamation for the six technologies. The results largely parallel those of the energy requirements as seen in Figure 5.17.

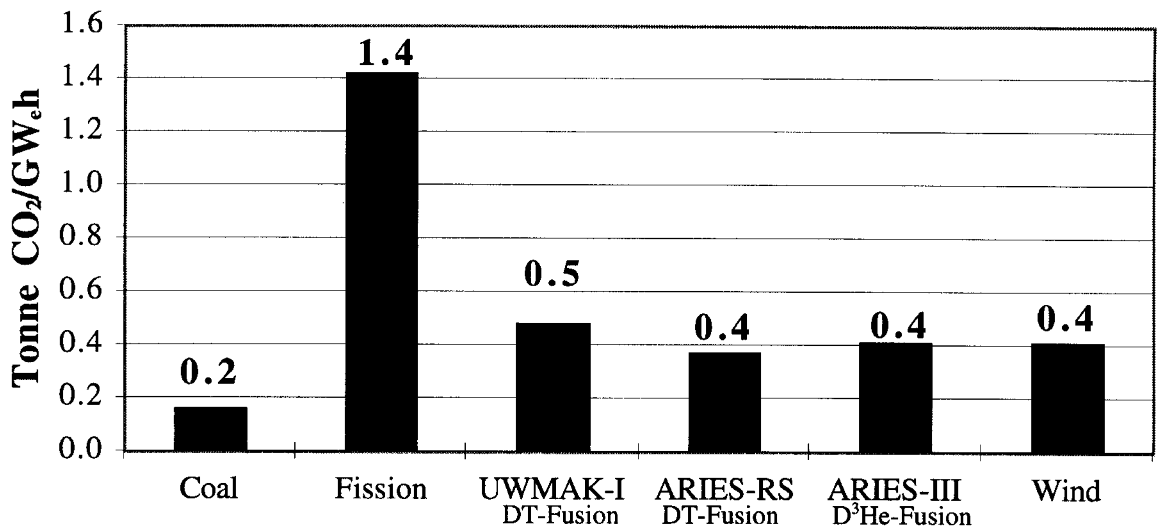

Figure 5.17: CO_2 emissions from decommissioning, waste disposal, and land reclamation parallel the energy use for the six technologies.

5.2.6 Overall Results of CO_2 Emissions

To better analyze the data, the five categories listed above were again regrouped into four categories, combining materials and construction processes:

- Fuel related (Mining, Preparation, and Transportation)
- Plant Materials and the Construction of the Plant
- Operation of the Plant
- Decommissioning, Waste Disposal and Land Reclamation.

The regrouped results are listed in Table 5.3. Figure 5.18 graphically shows the results and emphasizes the dominance of emissions from coal operations. Of the 974 tonnes per GW_eh overall, 956 tonnes are from coal combustion during operations. The emissions from the other technologies are small in comparison.

Table 5.3: CO_2 Emission from Energy Systems, Regrouped into Four Categories (Tonne CO_2/GW_eh)

Process	Coal[6]	Fission	DT-Fusion UWMAK-I	DT-Fusion ARIES-RS	D^3He-Fusion ARIES-III[7]	Wind[8]
Fuel Related	17	10	0.4	0.2	2	0.0
Plant Materials & Construction	1	2	5	8	5	10
Operation	956	2	3	2	2	4
Decommissioning & Waste Disposal	0.2	1	0.5	0.4	0.4	0.4
Total[9]	974	15	9	11	10	15

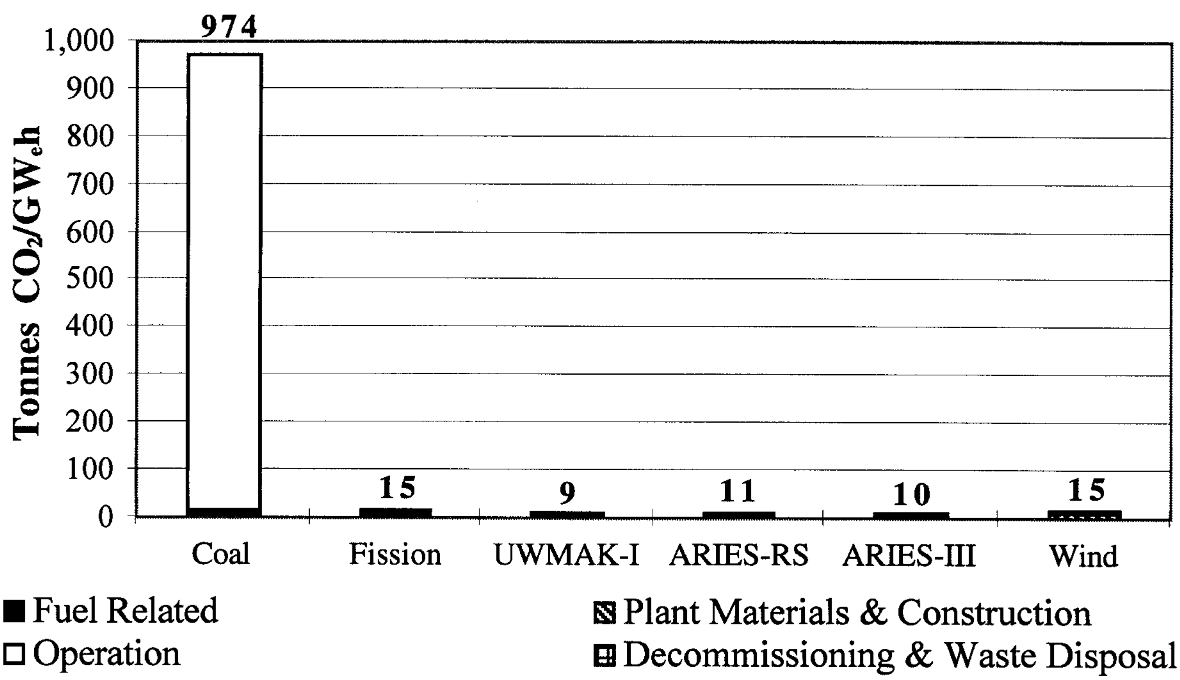

Figure 5.18: Coal operations CO_2 emissions dominate emissions from all other sources.

[6] Based on the US average mix of coal.

[7] Rocket Fuel Scenario

[8] Does not include energy storage.

[9] Columns may not equal totals due to independent rounding.

Table 5.4 lists the percentage of emissions from each of the four categories, which are also shown in Figure 5.19. The share of CO_2 emissions for each category vary by only a couple percentage points from the share of energy requirements for fission and both DT-fusion power plants. The variance is slightly more for the wind and D^3He-fusion power plants. For the wind power plant, 70% of its emissions are related to construction and manufacture of materials. The share of energy from these same processes is around 62%. Operations is responsible for a greater share of the energy requirements (35%), than CO_2 emissions. For the ARIES-III D^3He-fusion power plant, the largest variance is in the operations, which require 29% of the energy but emit only 21% of the CO_2.

The coal plant obviously releases most of its emissions (98%) during operations, while only consuming 15% of its total energy requirements during this process. The sum of energy that is related to operations and fuel procurement, however, is around 94% for coal.

Table 5.4: CO_2 Emission from Energy Systems, Regrouped into Four Categories (Percentage)

Process	Coal[10]	Fission	DT-Fusion UWMAK-I	DT-Fusion ARIES-RS	D^3He-Fusion ARIES-III	Wind[11]
Fuel Related	2%	63%	4%	2%	19%	0%
Plant Materials & Construction	0.1%	13%	58%	73%	54%	70%
Operation	98%	14%	33%	22%	22%	27%
Decommissioning & Waste Disposal	0.02%	9%	5%	4%	4%	3%

[10] Based on the US average mix of coal.

[11] Does not include energy storage.

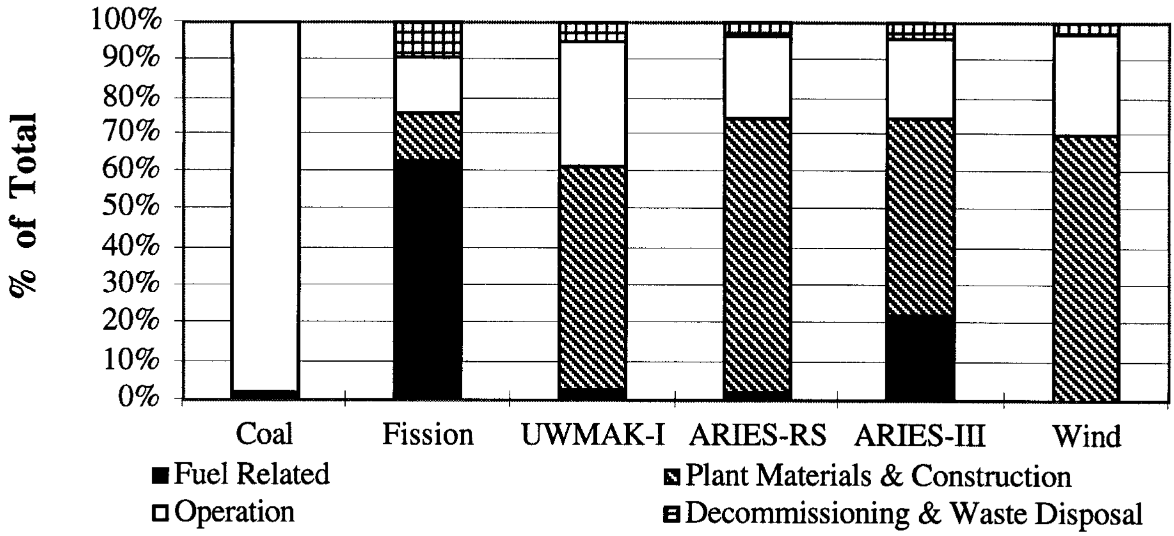

Figure 5.19: The contribution to the CO_2 emission rates varies widely between the six technologies.

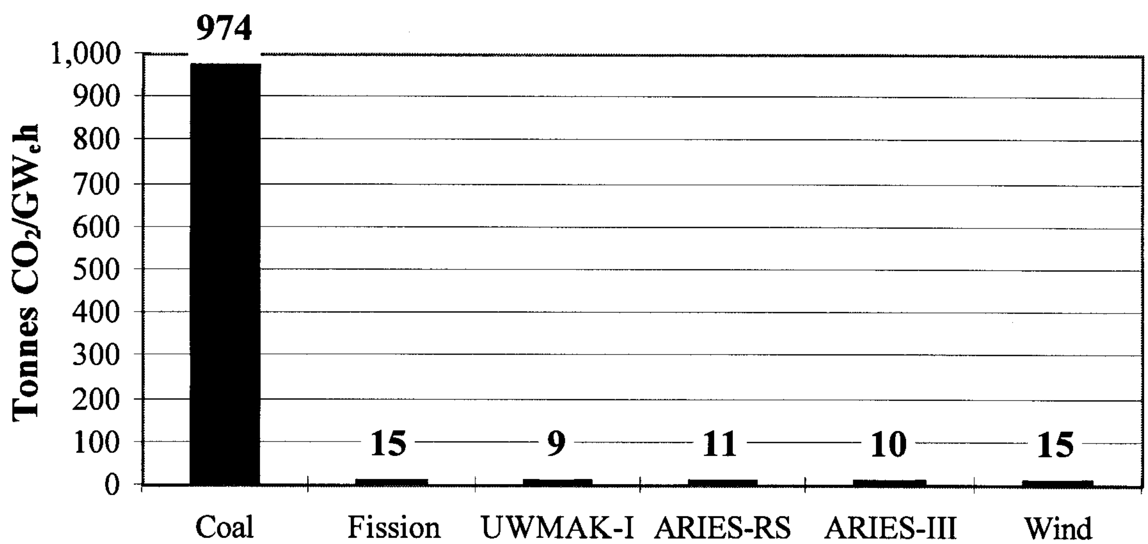

Figure 5.20: The CO_2 emission rates of electrical power plants are dominated by coal.

The CO_2 emission rate of coal compares favorably with results from other studies of conventional coal plants. Fritsche[9] determined that coal emits 929 tonnes/GW_eh, San

Martin[10] 964 tonnes/GW_eh, and a DOE study performed by the Meridian Corporation calculated that coal emits 1,058 tonnes/GW_eh[11].

The CO_2 emissions from the PWR analyzed in this study average out to 16 tonnes/GW_eh. Other studies have shown that LWR's with gas centrifuge enrichment have had similar results. Uchiyama concluded that a similar plant emitted 15 tonnes of CO_2/GW_eh, while the Meridian Corporation report had a total of 8 tonnes of CO_2 per GW_eh.

The wind power plant in this study emits 15 tonnes of CO_2 per GW_eh. Results from other studies (in similar units) are, 7.4 from San Martin[10], 18 from Friedrich and Marheineke[12], and 73 from Uchiyama and Yamamoto[5]. There have not been any other CO_2 analyses performed for DT- or D^3He-fusion.

In general, the CO_2 emission analysis results are about what would be expected. The lone fossil-fuel burning technology, coal, produces significantly greater emissions than those non-fossil fuels. The rank of emissions from the nuclear technologies and wind are all fairly similar to each other and have an inverse relationship to the energy payback ratio. Those with the highest EPR have the lowest CO_2 emission rate, though not by a significant amount. This relationship is far from pure, however, since the mix of fuels used effects the amount of CO_2 emitted.

Fusion's greatest impact on U.S. or world CO_2 emissions will occur when a fusion power plant, upon entering the electric power market, replaces a coal (or other fossil fuel) plant. When D^3He-fusion replaces fission, there's almost no distinction in total emission levels, as seen in Figure 5.21. In fact, the drop in emissions from the base case for Scenario Three (fusion replaces fission first), only occurs after all fission plants have been replaced and all subsequent fusion plants replace fossil-fuel plants.

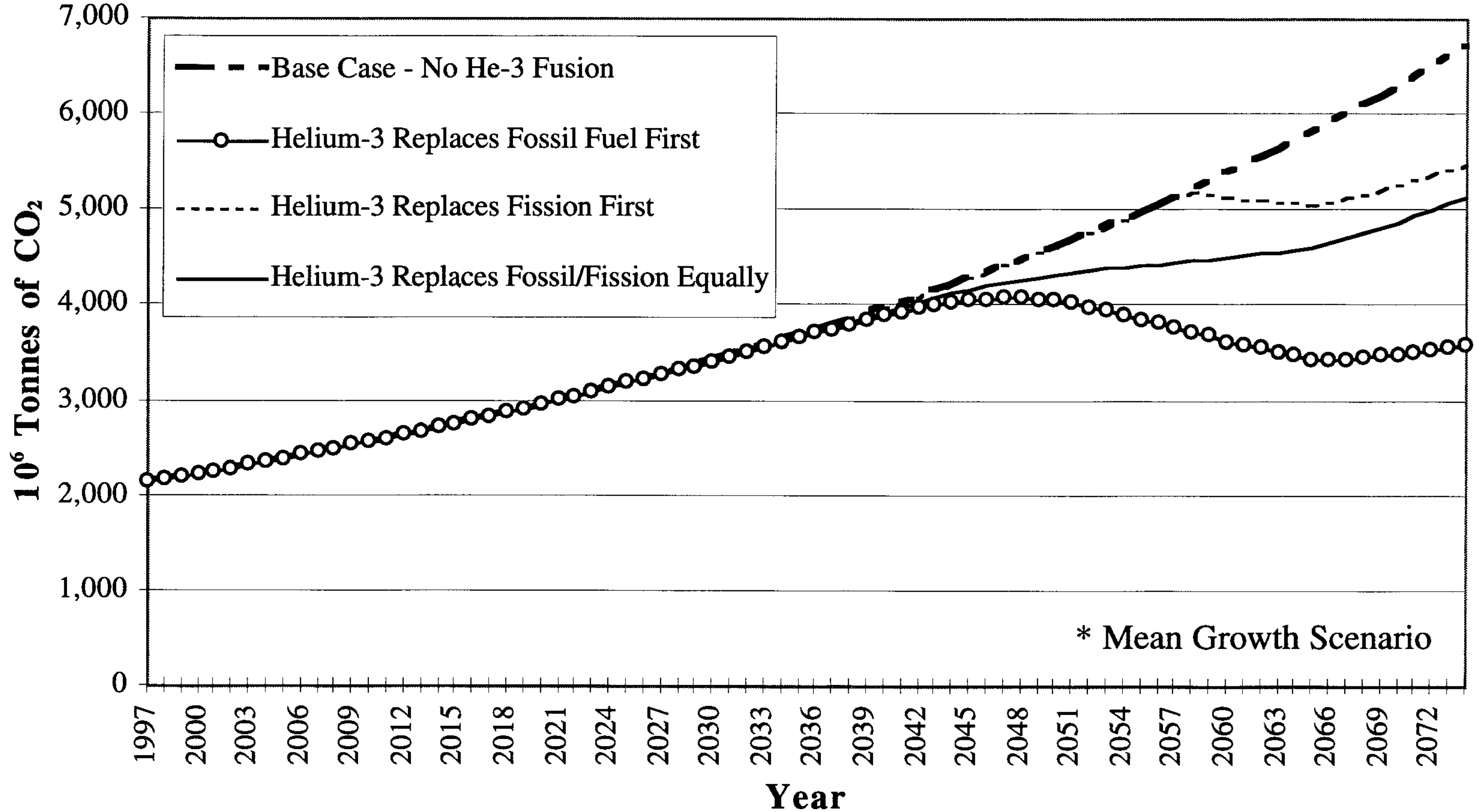

Figure 5.21: Comparison of Projected CO_2 Emissions from Different Helium-3 Fusion Replacement Scenarios for U.S. Electric Utilities, 1997-2075.

As shown in Table 4.23 and Figure 5.22, the amount of CO_2 offset over the 50-year analysis period has a difference of a factor of three between the low- and high-energy growth scenarios. The difference in emissions between Scenario 2 (fossil fuel replaced first) and Scenario Three (fission replaced first) is a factor two.

One could conclude that in a case where CO_2 mitigation is of primary concern, any low-carbon technology (i.e. fission, fusion, and wind in the case of this thesis) would have a similar result. On a broader scale that is outside the scope of this thesis, it would be relevant to analyze the impact of these results on the overall CO_2 emissions of the U.S. or world in light of international agreements on greenhouse gas reductions (such as the Kyoto protocol).

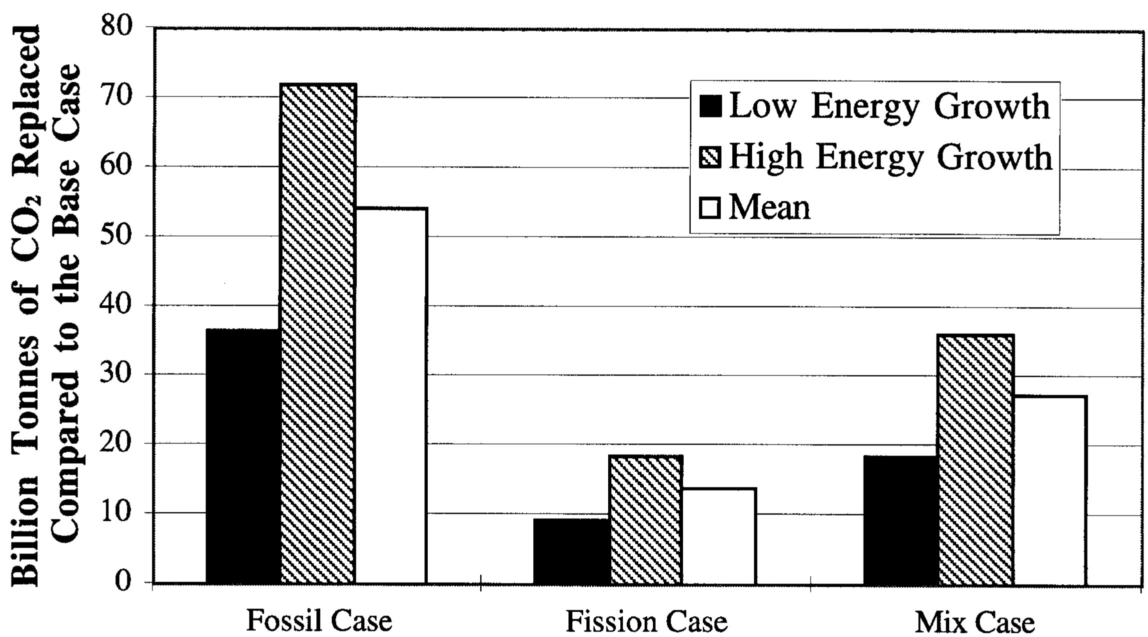

Figure 5.22: Comparison of the CO_2 replacement scenarios with low- and high-energy growth scenarios.

5.2.7 Estimated Uncertainty

The estimated uncertainty of power plant CO_2 emissions are shown in Figure 5.23. Performed in the same manner as the energy data, the estimated uncertainty of coal emissions is the largest of the power plants in absolute value. In terms of percentage, the coal plant has the smallest standard deviation, less than 5% of the mean, while fission has the largest estimated standard deviation of 13% of the mean. The coal power plants small percentage deviation is relative to the other power plants, and is due to the relatively high certainty of the coal carbon content. The fission power plants high percentage uncertainty is due to variations in the mix of electricity producing technologies used to enrich the uranium. Mixes of fuels and variances of data effect the certainty of other power plants.

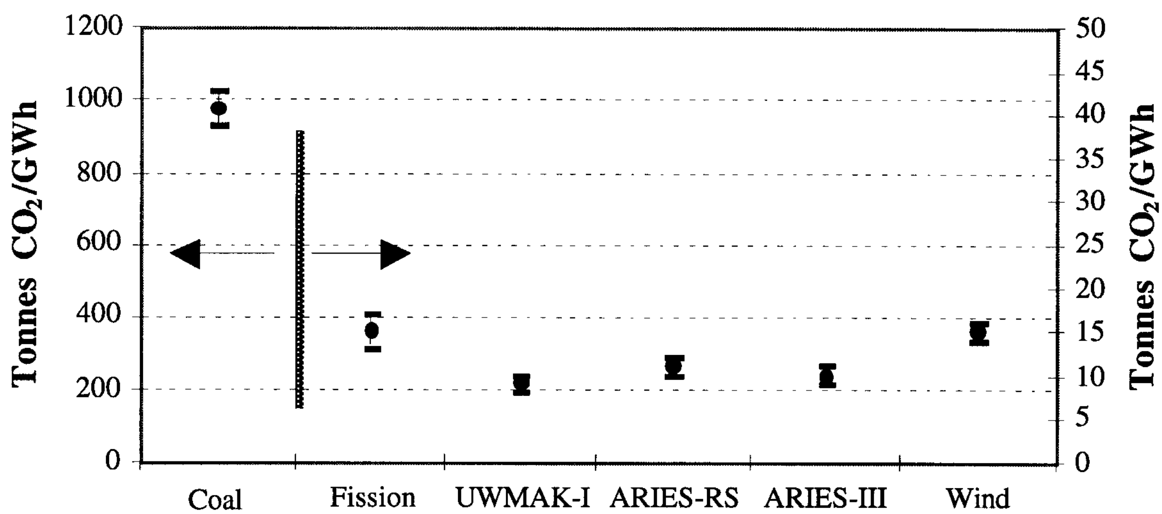

Figure 5.23: The Estimated 1-Sigma Uncertainty of Power Plant CO_2 Emissions

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6 Conclusions

There are 7 main conclusions of this thesis:

- There is more than a factor of two difference between the energy payback ratios of coal (11), fission(16), wind(23), DT-fusion(24-27), and D-^{3}He-fusion(31) power plants.
- The procurement of fuel tends to dominate the energy requirements of coal and fission power plants, while the procurement of plant materials and power plant construction dominate fusion and wind units.
- Carbon dioxide emissions from coal plants (974 tonnes CO_2/GW_eh) are between 50 – 100 times higher than those from fission(15), wind(15), DT-fusion(9-11), and D^{3}He-fusion(10).
- The low-capacity factor is the main reason that wind power plants are not significantly better than baseload technologies with respect to EPR and CO_2 emission factors.
- The use of vanadium in DT-fusion power plants should be reexamined in light of the high energy investment and large CO_2 emissions associated with that metal system.
- The use of lunar helium-3 for fuel in D^{3}He-fusion power plants does not significantly effect the EPR and CO_2 emission factor of those facilities (compared to DT-fusion systems).

The total energy requirements and the EPR of electrical power plants are inversely related. The high energy requirements of coal mining and transportation cause the EPR of coal to be as low as it is. The normalized energy requirements for coal *mining* alone are greater than the total energy requirements of UWMAK-I and ARIES-III. The normalized energy requirements for coal *transportation* are also higher than the total energy requirements of ARIES-III. The energy-intensive uranium fuel cycle (especially enrichment) also requires more normalized energy than the total energy requirements of UWMAK-I and ARIES-III and is responsible for the PWR having the second lowest EPR. The four power plants with the highest EPR (wind and the three fusion power plants) have the lowest energy requirements for fuel acquisition.

Despite popular rhetoric in both the nuclear and renewables communities, these technologies *are* responsible for some CO_2-emissions. Though on the surface and in comparison to the high emissions of coal power plants, the distinction between "no CO_2 emissions" and "low CO_2 emissions" may seem trivial. However, it is an important distinction to make, since exaggerated claims such as "wind power plants are carbon-free" are used as rhetoric by proponents of the technology in the Global Warming debate to draw attention to only one positive feature of that technology. Similar statements are made by proponents of nuclear power. Though it should be enough that wind and nuclear technologies are responsible for 1% to 2% as much CO_2 as conventional coal power plants, the exaggerated claims only tend to polarize their opponents. Misinformation raises the question, "if this claim is exaggerated how much of their other claims are also?"

Obviously the coal plant emits the greatest amount of CO_2 of the five technologies analyzed. Emissions from the fusion plants are low in comparison to coal and are similar to one another, while fission and wind are responsible for similar amounts of CO_2 per unit of electrical energy produced.

The main reason wind power plants are not significantly better than baseload power plants in terms of both energy payback and CO_2 emissions is due to its low capacity factor. Despite a capacity factor of 24% for wind that is 1/3 that of coal and nuclear technologies (75%), the EPR of wind power plants is better than coal and fission. Its CO_2 emission factor is also the same as fission. A higher capacity factor would mean more generated electricity, but would not require significantly more energy input.

It must be noted that for wind and baseload technologies to compete, an analysis such as this would need to include the energy requirements and CO_2 emissions from energy storage units for the wind power plant. Since wind-generated electric power can never fully compete with baseload technologies until it can supply electricity at all times, a comparison of baseload technologies to wind without energy storage favors wind. It is likely that the inclusion of energy storage units would decrease the EPR of wind due to both increased energy requirements and decreased overall efficiency. At the same time, the CO_2 emissions per unit of electricity produced for wind would increase.

The largest difference in the energy requirements between the two DT-fusion power plants is due to the first wall and blanket materials and the disparity of embodied energy for each. Vanadium, which is used in ARIES-RS, uses nearly 70 times more energy per tonne to produce than stainless steel, the first wall material of UWMAK-I. The difference in energy requirements for the power plant materials for the UWMAK-I (269 $TJ_{th}/GW_{e}y$) and ARIES-RS (563 $TJ_{th}/GW_{e}y$) is the most significant difference in the total energy requirements between the two fusion power plants.

The use of lunar helium-3 for fueling D^3He-fusion power plants does not significantly effect the EPR or CO_2 emission factor of the ARIES-III power plant. By simply not including the energy or CO_2 emissions from helium-3 procurement in these analyses, the EPR for D^3He-fusion would only rise 34 and the CO_2 emission factor would only drop to 8 tonnes CO_2 per GW_eh. By amortizing the energy requirements and CO_2 emissions of the entire infrastructure and transportation system over a 50-year period of growth, the energy and CO_2 emission factor per tonne of ^3He (as well as per GW_ey) is still considerably less than those of coal and fission. Even if the infrastructure mass was doubled, the total normalized energy requirements for D^3He-fusion would still be less than all technologies except UWMAK-I.

Recommendations for Further Study

There are other areas related to this project that warrant further study. These include:

- Include energy storage in a NEA of Wind Electrical power plants.
- Perform a NEA of a natural gas-fired electrical power plant. This is especially important as the share of natural gas in the U.S. electrical market increases. An analysis of this kind has yet to be published.
- Perform an indepth study of the energy requirements to produce pure vanadium. The references used in this study are over 20 years old and are only for producing ferrovanadium.
- Perform a thorough study of decommissioning nuclear power plants, and waste disposal using actual decommissioned power plants and waste disposal sites (Yucca Mountain) as the subject. A thorough analysis of the energy requirements of uranium disposal will require a special study.
- Inclusion of all greenhouse gases (i.e. water vapor, NO_x, etc.) in the CO_2 analysis and not limited only to CO_2.
- Though the combustion of the rocket fuels, LH_2 and LO_x do not produce CO_2, there are other greenhouse gases such as water vapor, N_xO and NO_x that will be produced during the launch that will have an impact on the Earth's stratosphere and above. While these gases were omitted from this analysis, they should be included in a more detailed study of helium-3 procurement.

- Analyze the impact of the CO_2-replacement scenarios with regard to the impact they could have on the overall CO_2 emissions of the U.S. or world in light of international agreements on greenhouse gas reductions (such as the Kyoto protocol).
- Analysis of other air pollutants and their environmental impacts as associated with fossil fuel combustion from the processes included in this study. Particularly, those pollutants associated with the rocket launches.

Glossary and Terms

ARIES-RS	A specific design for a DT nuclear fusion tokamak reactor, RS stands for Reversed Shear
ARIES-III	A nuclear fusion tokamak design that uses D^3He for fuel.
CAC	Center for Advanced Computation, University of Illinois
CO_2	Carbon Dioxide
CY	Calendar Year
D^3He	Deuterium - Helium-3, fuels for advanced nuclear fusion reactors
DT	Deuterium - Tritium, fuels for nuclear fusion reactors
FPY	Full Power Years
GJ	Giga-joule, or 10^9 joules
GW_e	Giga-watt electric, or 10^9 watts
GW_{th}	Giga-watt thermal
GWh	Giga-watt hour, can be in thermal or electrical
GWy	Giga-watt year
^3He	Helium-3, an isotope of helium
HLLV	Heavy Lift Launch Vehicle, a space launch vehicle that transports cargo and crew from the Earth's surface to space. There are three stages, the first two that take goods to LEO and the third stage which transports goods to the LUO-SOC.
HVAC	Heating, Ventilation and Air Conditioning
kW	Kilowatt, or 10^3 watts
LEO	Lower Earth Orbit

LH_2	Liquid Hydrogen
LO_x	Liquid Oxygen
LUBUS	LUnar BUS, a space launch vehicle concept of Koelle's that transports cargo and crew to and from the lunar surface to the LUO-SOC.
LUO-SOC	LUnar Orbitting, Space Operation Center, a space station for the moon, which serves as a transfer point for cargo and crew.
LWR	Light Water Reactor - a general classification of nuclear fission reactors including boiling water reactor (BWR) and pressurized water reactor (PWR)
Mg	Megagram or 10^6 grams or 1 metric tonne
MW	Mega-watt, 10^6 watts
Nacelle	The housing and gears of a wind turbine.
NA	Not Available
NAppl.	Not Applicable
negl.	negligible
O&M	Operations and Maintenance
PWR	Pressurized Water Reactor, a specific type of nuclear fission power plant
TJ	Terra-joule, or 10^{12} joules
Tonne	Metric tonne, or 1000 kilograms
TW	Terrawatt, or 10^{12} watts
UWMAK-I	A specific design for a DT nuclear fusion tokamak reactor

Appendix A – Energy and Emission Factors

Table A.1 lists the standard U.S. electrical distribution as used in this thesis. The thermal conversion efficiencies in the fourth column are for individual technologies. The net conversion efficiency in the final column, takes into account the energy used in other areas of the power plant (construction, operations, fuel acquisition, etc.). To determine the net conversion efficiency, the equation

$$\eta_n = \eta_{th}\left(1 - \frac{1}{EPR}\right)$$

where η_n = net conversion efficiency,

η_{th} = thermal conversion efficiency,

and EPR = initial Energy Payback Ratio.

The initial energy payback ratios are listed in Table A.2 and are based on previous work for coal and fission, and on other reports. Table A.3 shows the electrical efficiencies used in this thesis.

Table A.1: Standard U.S. and Aluminum Smelter Electrical Distribution and Thermal and Net Conversion Efficiencies of Power Plants

Power Plant Technology	Standard U.S. Distribution[1]	Aluminum Smelter Mix[2]	Thermal Conversion Efficiency[3]	Net Conversion Efficiency[4]
Coal	56.5%	41.9%	35%	32%
Hydro	10.7%	39.9%	83%	78%
Nuclear -PWR	21.9%	10.3%	33%	31%
Petroleum	2.2%	1.6%	35%	32%
Natural Gas	8.7%	6.5%	37%	36%

[1] From Monthly Energy Review, March 1997[1] based on 1996 U.S. electrical energy mix.

[2] From ref. [2].

[3] From the DOE's Energy Technology Characterization Handbook[3]

[4] For Standard U.S. Distribution, uses the equation η*(1-1/EPB), where EPB = initial Energy Payback Ratio (see Table A.2).

Table A.4 lists the energy requirements of transportation via rail, ship and truck. These factors were used in determining the energy requirements to transport coal as well as wind-plant components.

Table A.5 lists the CO_2 emission factors for all fuels used in this thesis, thermal and electrical. Much of this data was only used in determining the CO_2 emissions from materials

Table A.2: Initial Energy Payback Ratios

Power Plant Technology	Initial Energy Payback Ratio
Coal[5]	11
Hydro[6]	16.9
Nuclear –PWR[5]	16
Petroleum[6]	13.6
Natural Gas[7]	25

Table A.3: Electricity Efficiency Average in U.S.

Electrical Mix	Efficiency
Standard	36.9%
Aluminum	53.4%

Table A.4: Energy Requirements for Transportation

Transportation Method	GJ/net-tonne mile
Rail[8]	0.000408
Ship[9]	0.000291
Truck[9]	0.002790

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5 From White, 1998, ref. [4].

6 From Uchiyama, ref. [5].

7 Estimated. No other references could be found.

8 From Ref. [3].

9 Values used in refs. [6, 7].

production. Table A.6 lists the weighted CO_2 emissions from both the standard U.S. electrical mix and the aluminum electrical mix. The aluminum electrical mix is the mix of electricity that is used in aluminum production. Table A.7 lists the heating values of various fossil fuels and electricity.

Table A.5: CO_2 Emissions from Fuels and Electricity

Fuel	Fuels[10] kg CO_2/GJ_{th}	Electricity[11] kg CO_2/MW_eh
Coal	92.77	975
Hydro	NAppl.[12]	3.1
Nuclear (PWR)	NAppl.	17
Petroleum	69.30	726
Natural Gas	50.53	484
Oil	73.33	NAppl.
Petroleum Coke	96.81	NAppl.
Metallurgical Coke	89.06	NAppl.
Diesel	72.23	NAppl.
Residual Fuel oil	78.00	NAppl.
Propane	59.77	NAppl.
Butane	61.60	NAppl.
Kerosene	71.20	NAppl.
LPG	59.65	NAppl.

Table A.6: Air Emissions from the Standard U.S. and Aluminum Smelter Electrical Mix

Technology	Standard U.S. Electrical Mix Weighted Tonnes CO_2/MW_eh	Aluminum Smelter Mix Weighted Tonnes CO_2/MW_eh
Conventional Coal plant	0.5509	0.4082
Petroleum	0.016	0.0118
Natural Gas	0.0421	0.0312
Hydroelectric	0.0003	0.0012
Nuclear Fission (BWR)	0.0037	0.0017
	0.613	0.4541

[10] All emission factor are from Mintzer, ref. [8], except natural gas[9], metallurgical coke [1], and LPG[10].

[11] CO2 emission factors for electricity from hydroelectric, petroleum and natural gas are from San Martin[11]; emission factors for coal and fission are from White[4].

[12] Not Applicable.

Table A.7: Heating Values of Various Fuels

Fuel	Units	BTU/Unit	MJ/Unit
Electricity (Standard)[13]	MW_eh	10,500,000	11,078
Petroleum Coke[13]	Tonne	30,000,000	31,650
Metallurgical Coke[14]	Tonne	24,800,000	26,164
Coal[14]	Tonne	22,195,000	23,416
Diesel Gas[13]	Gal.	139,000	147
Distillate Fuel Oil[13]	Gal.	139,000	147
Residual Fuel Oil and Other HC Fuels[13]	Gal.	150,000	158
Petroleum/gasoline[13]	Gal.	125,000	132
Natural Gas[13]	Ft^3	1,000	1
Propane[13]	Gal.	95,000	100
Kerosene[13]	Gal.	135,000	142
LPG[13]	Gal.	94,000	99
Propane[15]	Ft^3	830	0.9
Ethane[15]	Ft^3	670	0.7

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[13] From ref. [12].

[14] From ref. [13].

[15] Propane is based on 83% of natural gas heating value and ethane is based on 67% of natural gas heating value, as calculated in Table A1 in ref. [14].

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[14] Energy Information Administration, "Annual Energy Review 1994", EIA, DOE/EIA-0384(94) (July 1995).

Appendix B – Energy Requirements and CO_2 Emissions from the Production of Power Plant Materials

Table B.1 lists the materials used in the analysis of all six electricity-generating technologies, their energy requirements and source. Some of the energy requirements vary from those listed by the original author due to the use of varying heating values of fuels. Materials references such as Penner[1] and the Bureau of Mines[2-5] reports, list the energy requirements by fuel type and quantity for each process of the materials processing. To calculate the CO_2 emissions of each material, the quantity of each type of fuel used to process a material was tallied and entered into the database. From these totals, the heating value of each type of fuel (see Table A.7) was multiplied by the quantity, the sum of which totaled the "calculated" energy requirements of that material. In cases where the "calculated" sum was close to that of the original author, that value was used.

Using the same fuel requirement data, the CO_2 emission factor of each fuel type was multiplied by the quantity of fuel, the sum of which equals the CO_2 emission factor of the material as seen in Table B.2. The source listed for the materials in Table B.2 were calculated from original data of the sources listed. The CO_2 emission factors of all fuels are listed in Table A.5.

Table B.1: Energy Requirements for Power Plant Materials

Element or Alloy	Source	GJ/Tonne of Material
Aluminum	[2]	208.12
Antimony	[1]	533.62
Bismuth	[1]	5,567.10
B_4C	[6]	210.74
Cadmium	[1]	522.25
Calcium[1]	[4]	9.23
Chromium[2]	[1]	82.93
Concrete[3]	[7]	1.38
Copper[4]	[1]	130.55
CuZn28Sn	[6]	68.28
Fiber Glass	[8]	12.81
Fluorospar[5]	[1]	14.03
Gallium Metal	[7]	1,837.16
Helium[6]	[9]	536.00
Insulation Materials	[6]	94.66
Insulators[7]	[10]	54.00
Carbon and Low Alloy Steels[8]	[6]	34.44
Stainless and High Alloy Steels	[6]	53.11
Lead[9]	[1]	35.48
Lithium[10]	[6]	852.66
Magnesium	[3]	379.66
Manganese	[3]	51.51
Mercury	[1]	87.42
Molybedenum[11]	[1]	378.01
Nickel[12]	[1]	184.48
NbTi and Nb_3Sn	[6]	210.74
Silicon Carbide	[1]	140.42
Silver	[1]	16,809.45
Sodium Metal	[3]	123.87
Tin pig[13]	[1]	1,230.20
Titanium	[3]	444.40
Tungsten[14]	[4]	417.57
Vanadium[15]	[1]	3,711.17
Yttrium	[4]	1,470.70
Zinc	[11]	73.05
Zirconium	[4]	1,611.57

[1] Based on data for quicklime.

[2] Based on data for high-carbon ferrochromium.
[3] Based on data for Portland Cement.
[4] Based on refined copper.
[5] Fluorospar pellets
[6] Helium gas.
[7] Based on the energy requirements of plastics.
[8] Assembled low alloy steel.
[9] Differs from author's value due to variance in heat and energy content of fuels.
[10] Assembled Lithium metal.
[11] Based on ferromolybdenum.
[12] Based on electrolytic nickel.
[13] Based on electrolytic, grade AA tin.
[14] Differs from author's value due to variance in heat and energy content of fuels.
[15] Based on Ferrovanadium

Table B.2: CO_2 Emissions from Materials Production

Element or Alloy	Source Based upon:	kg CO_2 per Tonne of Material
Aluminum	[1]	13,288
Antimony	[1]	35,120
Bismuth	[1]	323,126
B_4C	[6]	13,193
Cadmium	[1]	30,149
Calcium (Quicklime)	[2]	619
Carbon (Graphite Flakes & Fines)	[4]	12,797
Chromium (High C Fe Cr)	[1]	5,393
Concrete	[2]	520
Copper (Refined)	[2]	7,446
CuZn28Sn	[6]	4,168
Fiber Glass	[8]	804
Fluorospar	[1]	634
Gallium Metal	[4]	93,559
Helium - gas	[9]	33,649
Insulation Materials	[6]	5,680
Carbon and Low Alloy Steels[16]	[2]	2,471
Stainless and High Alloy Steels	[6]	3,275
Lead	[1]	2,498
Lithium (assembled)	[6]	53,021
Magnesium	[3]	21,917
Manganese	[3]	3,502
Mercury	[1]	4,941
Molybedenum[17]	[1]	20,279
Nickel	[1]	9,828
NbTi	[6]	13,193
Plastic	[10]	6,387.58
Silicon Carbide	[1]	8,203
Silver	[1]	1,055,919
Sodium Metal	[3]	7,727
Tin pig (electr'lytic-grade AA)	[4]	31,258
Titanium	[3]	27,582
Tungsten	[4]	25,797
Vanadium[18]	[1]	228,379
Yttrium	[4]	84,065
Zinc	[2]	4,929
Zirconium	[4]	97,150

[16] Carbon Steel Castings
[17] Based on ferromolybdenum.
[18] Based on Ferrovanadium

References - Appendix B

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Appendix C - Coal

The parameters of the coal plant are listed in Table C.1. The coal plant analyzed in this thesis is assumed to be an average plant using average coal with average heat content. It was assumed that the coal used in this power plant is an average of all U.S. coal. As seen in Table C.2, 43% of the coal is surface-mined west of the Mississippi River, 34% is underground mined east of the Mississippi, etc. It takes different amounts of energy to mine coal in these regions. Table C.3 lists the energy requirements for coal mining in these regions. The last

Table C.1: Coal Power Plant Parameters	
Heat Content of Coal (10^6 BTU/short ton)[1]	20.9
Heat Content of Coal (GJ/tonne)	24.30
Power Plant Output (design in MW_e)	1,000
Net Coal Plant Efficiency[2]	32%
Coal Plant Thermal Conversion Efficiency[3]	35%
Power Plant Life Expectancy (Full Power Years)	30
Lifetime Electrical Output (MW_eh)	262,980,000
Coal Use 1 FPY (tonnes)	3,708,158
Coal Use 30 FPY (tonnes)	111,244,738
Transportation Distance (miles)[3]	700
Sulfur Content of Coal (% by weight)[4]	1.1%
Tonnes of Lime/30 GW_ey	920,828

1 From ref. [1].

2 Calculated for this study. See Appendix A for explanation on net conversion efficiency.

3 From ref. [2].

4 Based on utility coal consumption in 1996, ref. [3].

column lists the energy requirements of supplying all of the coal (111 million tonnes) for an average coal-fired power plant by the given type of coal. The U.S. average, which was used in this analysis, is listed in the last row. Also, the weighted energy requirements of each type of coal is listed in the fourth column of Table C.2.

The CO_2 emissions from coal mining are listed in Table C.4, which corresponds with Table C.3. The third column shows the lifetime CO_2 emissions from 111 million tonnes being mined by each type. In the bottom row is the U.S. average, which was used for this thesis.

Table C.2: 1996 U.S. Coal Production and the Weighted Mining Energy Requirements[5]

Region	Short Tons	% of Total	GJ/30 FPY
West of Mississippi			
Surface	454,141,000	43%	7,736,010
Underground	46,005,000	4%	2,070,657
East of Mississippi			
Surface	199,006,000	19%	11,588,856
Underground	363,416,000	34%	16,357,136
Total	1,062,568,000		37,752,659

Table C.3: Energy Requirements to Mine U.S. Coal

Mining	Electricity (kWh)	Diesel Fuel (gal)	Ammonium Nitrate[6] (tons)	GJ/Tonne Coal	GJ/30 FPY
Eastern Underground[7]	1.96E+06	1,900	0	0.430	47,825,548
Eastern Surface[7]	3.42E+05	163,000	0	0.556	61,877,265
Western Surface[7]	6.00E+03	25,000	8.2	0.163	18,100,186
Average U.S.Total[7]					37,752,659

5 From Coal Industry Annual, ref. [3], Table 11.

6 Assumed "Ammonium Nitrate fuel mixture" has an energy value of 0.3 x 106 BTU/lb, based on explosives energy factor in Ref. [4], p A-3.

7 Includes Coal Preparation. From ref. [2].

Table C.4: CO_2 Emissions from Coal Mining, Based on U.S. Average		
Region	**Tonne CO_2/ tonne Coal**	**Tonne CO_2 30 FPY**
Eastern Underground[8]	0.027	3,008,666
Eastern Surface[8]	0.040	4,397,842
Western Surface[8]	0.005	514,550
Average U.S. Mining Energy[8]	0.020	2,202,858

The energy required to transport coal were based on both the distance and mode of which coal would be transported. The average distance of coal transportation as used in the Department of Energy's "Energy Technology Characterizations Handbook"[2] was 700 miles. Another DOE/EIA document, "Coal Data"[1] states that 60% of all coal is transported via rail, 20% by ship and 10% by truck. For simplicity, it was assumed that all coal was transported via rail. The energy factor for transportation is listed in Appendix A.

It was also calculated how much lime would be needed to scrub sulfur out of the coal. Though determining the quantity of SO_x was outside the scope of this thesis, it was necessary to determine the amount of sulfur that would need to be scrubbed from smokestack gases to meet Federal standards in order to know the amount of energy required for this activity.

To make this calculation it was necessary to know the sulfur content of the coal, the maximum allowable emissions of SO_x and the amount of lime needed to remove the pollutant. The average sulfur content of U.S. coal is 1.1% by weight[3]. The Federal air pollution limits from the Clean Air Amendments of 1990 (ref. [5]) for coal are 1.2 lbs $SO_x/10^6$ BTU (0.52 kg SO_x/GJ). The equations used for lime scrubbing flue gas are from Cooper and Alley[6]:

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8 Includes Coal Preparation.

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (D.1)$$
$$SO_2 + H_2O \Leftrightarrow H_2SO_3 \quad (D.1)$$
$$H_2SO_3 + Ca(OH)_2 \rightarrow CaSO_3 \bullet 2H_2O \quad (D.3)$$
$$CaSO_3 \bullet 2H_2O + \frac{1}{2}O_2 \rightarrow CaSO_4 \bullet 2H_2O \quad (D.4)$$

It was calculated that to meet Federal standards, only 43% of the SO_x produced by coal combustion will need to be removed. This equates to a lifetime mass of 921,000 tonnes of lime that will be required and will amount to 2,236,000 tonnes of $CaSO_4$ waste. The $CaSO_4$ will need to be transported away for disposal. It was estimated that it would be transported via rail for a distance of 200 miles, as shown in Table C.6. The energy requirements and CO_2 emission factor for lime (quicklime) is listed in Table C.7 as are the lifetime quantities of each per installed GW_e.

Table C.5: Lifetime Tonnes of Coal and Lime Needed for a 1 GW_e Coal Plant

Material	Source	Tonnes	GJ
Coal	Calculated	111,244,738	37,752,659
Lime	Calculated	920,828	8,497,831

Table C.6: Energy Requirements to Dispose of Coal Waste.

	Mass $CaSO_4$	Distance, mile (estimate)	Total GJ
Coal Waste Disposal	2,236,297	200	182,516

Table C.7: Energy Requirements and CO_2 Emission Factor Associated with the Production of Quicklime

	Unit	Total
Energy Requirements[9] (GJ/Tonne)	9.2	8,497,831 GJ/GW_e
CO_2 Emission Factor (kg CO_2/Tonne)	619	570,026 Tonne CO_2/GW_e

[9] Energy requirements are from ref. [10]. CO2 emission factor was calculated from energy requirements.

The energy requirements for construction and land reclamation were both from Tsoulfanidis[7] and are listed in Table C.8. Table C.9 lists the energy requirements of all nine categories. Data for coal plant operation is listed in this table and was taken verbatim from the sources cited. Decommissioning data is based on the energy requirements to decommission a PWR, normalized by mass of the power plant materials.

Table C.10 lists the CO_2 emissions associated with each process. CO_2 emissions for materials are listed in Table 4.14. Emissions associated with coal mining are explained in Table C.4. Emissions associated with construction and land reclamation are based on the energy requirements data in Table C.8. Thermal energy data is multiplied the CO_2 emission factor for fuel oil, while the electrical energy is multiplied by the emission factor for electricity.

The CO_2 emissions from operations were calculated by multiplying the total mass of coal combusted over the lifetime of the plant (see Table C.1) and the CO_2 emission factor of coal (see Appendix A). Emissions associated with waste disposal were calculated by multiplying the emission factor for oil by the energy requirements. The emissions for decommissioning are the product of the diesel fuel and the energy requirements.

Table C.8: Energy Requirements for Construction and Land Reclamation of Coal Power Plants

	TJ_{th}	TJ_e	TJ_{th}/GW_e
Construction[10]	2,111	235	2,748
Land use Reclamation	82	7	126

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10 From Ref. [7]. Construction data includes the following sectors from the author's I/O assessment: Instrumentation control for both the boiler plant equip. and turbine plant equip., electrical plant switchgear, transportation and lift equip., HVAC mechanical equipment, construction services, home office engineering service and field office engineering service. All other sectors were assumed to have been already accounted for in the materials. Data for land reclamation are based on the author's low value.

Table C.9: Lifetime and Annual Energy Investments for a Coal Power Plant

Process	Source	Total Energy per Installed GW_e GJ/GW_e	Annual Energy per GW_ey GJ/GW_ey
Embodied Energy of Materials and Equipment	See Table 4.3	1,659,997	55,333
Coal Mining	See Tables C.2-C.3	37,752,659	1,258,422
Lime Production		8,497,831	283,261
Coal Transportation - 700 miles	Battelle	31,777,424	1,059,247
Fuel Cycle Subtotal		78,027,914	2,600,930
Construction	[7]	2,748,973	91,632
Operation - Station Use	[8]	4,696,692	156,556
Waste Disposal	See Table C.6	182,516	6,084
Decommissioning	[9]	295,689	9,856
Land Reclamation	[7]	126,235	4,208
Total Required Energy		87,738,016	2,924,601

Table C.10: Lifetime and Annual Emissions of CO_2 for a Coal Power Plant

Process	Source	Total Emissions per Installed GW_e Tonne CO_2/GW_e	Annual Emissions per GW_e-y Tonne CO_2/ GW_ey	Annual Emissions per GW_eh Tonne CO_2/ GW_eh
Embodied Emissions for Materials and Equipment	See Table C.14	148,327	4,944	0.56
Coal Mining	See Table C.4	2,202,858	73,429	8.4
Lime Production		570,026	19,001	2
Coal Transportation - 700 miles		2,330,344	77,678	9
Fuel Cycle Subtotal		5,103,228	170,108	19
Construction		192,531	6,418	0.73
Operation		250,756,251	8,358,542	954
Waste Disposal	From Table C.6	13,384	446	0.05
Decommissioning		21,359	712	0.08
Land Reclamation		7,119	339	0.03
Total CO_2 Emitted		256,242,200	8,541,062	974

References – Appendix C

[1] Energy Information Administration, "Coal Data: A Reference", Energy Information Administration, Office of Coal, Nuclear, Electric and Alternative Fuels, DOE/EIA-0064(90) (November 1991).

[2] "Energy Technology Characterizations Handbook", U.S. DOE, DOE/EP-0093 (March 1983).

[3] Energy Information Administration, "Coal Industry Annual 1996", DOE/EIA, DOE/EIA-0584(96) (November 1997).

[4] "Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing (Phase 5 - Energy Data and Flowsheets, Intermediate Commodities)", Bureau of Mines, PB-246 357 (16 September 1975).

[5] U.S. Environmental Protection Agency, "The Plain English Guide to the Clean Air Act", U.S. Environmental Protection Agency, EPA 400-K-93-001 (April 1993).

[6] Cooper, C.D. and F.C. Alley, *Air Pollution Control: A Design Approach.* Prospect Heights, IL: Waveland Press, Inc. (1994).

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[8] Uchiyama, Y., "Life Cycle Analysis of Electricity Generation and Supply Systems", presented at Symposium on Electricity, Health and the Environment: Comparative Assessment in Support of Decision Making, Vienna, Austria, 16-19 October 1995, pp. 279-291.

[9] El-Bassioni, A.A., "A Methodology and a Preliminary Data Base for Examining the Health Risks of Electricity Generation from Uranium and Coal Fuels", Oak Ridge National Laboratory, NUREG/CR-1539 (August 1980).

[10] "Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing (Phase 4 - Energy Data and Flowsheets, High-Priority Commodities)", Bureau of Mines, PB-245 759 (27 June 1975).

Appendix D - Nuclear Fission PWR

Parameters for the pressurized water reactor are listed in Table D.1. Data for calculating the energy requirements of the uranium fuel cycle are found in Table D.2. This table includes results for both gas centrifuge and gaseous diffusion enrichment. These results stem from previous work, in which the details of this assessment can be found[1].

It was assumed that the uranium would be enriched via the gas centrifuge, instead of via gaseous diffusion. U.S. uranium is currently enriched via gaseous diffusion, a process that requires 60 times more energy per Separative Work Unit (SWU) than gas centrifuge enrichment. Details of the CO_2 emissions from the uranium fuel cycle are also found in ref. [1].

Table D.2 lists the energy requirement results for both gaseous diffusion and gas centrifuge. For the analysis in the body of this thesis, the data for gas centrifuge enrichment was used. The total results for fission using gaseous diffusion enrichment is listed at the end of this section. The details of how the CO_2 emissions associated with the fuel cycle were calculated are in ref. [1].

Table D.1: PWR Parameters

Designed Output (MW_e)	1000
Reactor Lifetime (years)	40
Operating Capacity	75%
Operational Lifetime (Full-Power Years)	30
Lifetime Electrical Output MW_eh	262,980,000
Lifetime U Requirements - 3% U-235 Enriched (kg/30 FPY)	884,848
Enrichment Process	Gas Centrifuge

Table D.2: Uranium Fuel Cycle

Assuming all electricity from a mix of coal and fission				
Fuel Cycle Parameters	**Units**	**Gaseous Diffusion**	**Gas Centrifuge**	
Feed U-235	% U-235	0.711	0.711	
Final U-235 Enrichment	% U-235	3.0	3.0	
Tails Concentration	% U-235	0.2	0.2	
Production Rate	kg U	1	1	
Tails Concentration	%	0.20% tails		
SWU's Required	SWU	4.30647	4.30647	
Feed Rate	kg U(nat)/(enr)	5.47945	5.47945	
Electrical Input	MW_e-hr/kg U (enriched)	12.10119	2.58388	
Lifetime Energy Input - U Fuel				**Source**
Mining	GJ_{th}	2,644,275	2,644,275	[2]
Milling	GJ_{th}	3,658,040	3,658,040	[2]
Conversion	GJ_{th}	7,866,027	7,866,027	[2]
Enrichment to 3%	GJ_{th}	104,140,654	22,236,439	[1]
Fuel Fabrication	GJ_{th}	2,231,902	2,231,902	[2]
Transportation of Uranium	GJ_{th}	226,777	226,777	[2]
subtotal	GJ_{th}	120,767,675	38,863,459	

It was assumed that all electricity consumed in the fuel cycle came from the standard U.S. electrical energy mix. The energy requirements and CO_2 emissions from materials are listed in Tables 4.3 and 4.14 respectively. All other data (construction, decommissioning, operation and maintenance, spent fuel transportation and land reclamation come from Tsoulfanidis[3], normalized to 1 GW_e. Tsoulfanidis' results are shown in Table D.3.

The construction energy requirements in Tsoulfanidis paper were calculated using the Input-Output method based on the monetary costs of various power plant components and processes. Since the energy requirements and CO_2 emissions of power plant materials were calculated separately in this thesis, the components in Tsoulfanidis' I/O table that were strictly related to materials, were removed. These sectors include, land and land rights, structure and improvement, boiler plant equipment (rest of 22), turbine plant equipment (rest of 23), electrical wiring structure, rest of 24, rest of 25 and heat rejection system structures.

The CO_2 emissions of all of these sectors were calculated from the energy data. Thermal energy was multiplied by the emission factor for diesel fuel, while the electrical energy was multiplied by the emission factor for the standard U.S. electrical mix.

Table D.3: Lifetime Energy Requirements for a 1138 MW_e PWR, from Tsoulfanidis[3]

Process	Thermal (GJ)	Electric (GJ)	Total Energy[1] (GJ)
Construction[2]	15,018,000	1,863,000	20,071,530
Construction[3]	3,604,000	392,000	**4,667,330**
Operation & Maintenance	6,676,000	542,000	8,146,216
Uranium Mining - 0.208%	2,902,000	362,000	3,883,953
Uranium Milling	2,881,000	413,000	4,001,294
U transportation[4]	79,000	2,000	84,425
U. Conversion	7,410,000	273,000	8,150,533
U. enrichment[5]	3,440,000	41,537,000	116,112,282
Fuel Fabrication	2,569,000	1,028,000	5,357,528
Fresh Fuel Transportation	44,000	4,000	54,850
Spent Fuel Transport.	127,000	4,000	137,850
Spent Fuel Disposal	5,601,000	47,000	5,728,491
Land Reclamation	4,000	300	4,814
Public Welfare	35,000	3,500	44,494
Decommissioning	517,000	43,000	633,641
	47,303,000	46,121,800	172,411,902
GJ/ GW_e	41,566,784	40,528,822	151,504,307

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[1] Total energy may not equal that of Tsoulfanidis due to the use of a different electrical energy efficiency.

[2] Verbatim from author.

[3] Author's data less all construction sectors that include materials. Materials were analyzed separately for this thesis. This data was used in this thesis.

[4] From Mill to enrichment facility.

The results of the energy analysis are listed in Table D.4. These results assume gas centrifuge enrichment. The corresponding CO_2 emissions are listed in Table D.5.

Table D.4: Lifetime and Annual Energy Investments for a PWR with No Recycle and Gas Centrifuge Enrichment

Process	Source	Total Energy per Installed GW_e GJ/GW_e	Annual Energy per GW_ey GJ/GW_ey
Embodied Energy of Materials and Equipment	see Table 4.3	1,745,984	58,199
Construction	[3]	4,101,344	136,711
Mining - 0.208% U3O8	[2]	2,644,275	88,143
Milling	[2]	3,658,040	121,935
Conversion	[2]	7,866,027	262,201
Gas Centrifuge Enrichment to 3%	[1]	22,236,439	741,215
Fuel Fabrication	[2]	2,231,902	74,397
Transportation of Uranium	[2]	226,777	7,559
Fuel Cycle Subtotal		38,863,459	1,295,449
Operation and Maintenance	[3]	7,158,362	238,612
Spent Fuel Transportation	[3]	121,134	4,038
Spent Fuel Disposal	[3]	5,033,823	167,794
Land Reclamation	[3]	4,230	141
Decommissioning	[3]	556,802	18,560
Decommissioning etc. Subtotal		5,715,989	190,533
Total Required Energy		57,585,139	1,919,505

[5] Uranium enriched to 3% via Gaseous Diffusion enrichment.

Table D.5: Lifetime and Annual Emissions of CO_2 for a Fission Power Plant with Gas Centrifuge Enrichment

Process	Total Emissions per Installed GW_e **Tonne CO_2/GW_e**	Annual Emissions per GW_e-y **Tonne CO_2/ GW_ey**	Annual Emissions per GW_eh **Tonne CO_2/ GW_eh**
Embodied Energy of Materials and Equipment	196,905	6,564	0.75
Construction	327,083	10,903	1.24
Mining	106,444	3,548	0.40
Milling	140,420	4,681	0.53
Conversion	346,544	11,551	1.32
Gas Centrifuge Enrichment to 3%	1,832,913	61,097	6.97
Fuel Fabrication	375,184	12,506	1.43
Tranportation of U	56,078	1,869	0.21
Fuel Cycle Subtotal	2,857,583	95,253	10.87
Operation and Maintenance	574,528	19,151	2.18
Spent Fuel Transportation	8,660	289	0.03
Spent Fuel Disposal	362,551	12,085	1.38
Land Reclamation	299	10	0.00
Decommissioning	2,745	92	0.01
Decommissioning etc. Totals	374,254	12,475	1.42
Total CO_2 Emitted	4,330,354	144,345	16.47

Tables D.6 and D.7 show the results for energy requirements and CO_2 emissions respectively for nuclear fission with gaseous diffusion enrichment.

Table D.6: Lifetime and Annual Energy Investments for a PWR with No Recycle and Gaseous Diffusion Enrichment

Process	Source	Total Energy per Installed GW_e GJ/GW_e	Annual Energy per GW_ey GJ/GW_ey
Embodied Energy of Materials and Equipment	see Table 4.3	1,745,984	58,199
Construction	[3]	4,101,344	136,711
Mining - 0.208% U3O8	[2]	2,644,275	88,143
Milling	[2]	3,658,040	121,935
Conversion	[2]	7,866,027	262,201
Gaseous Diffusion Enrichment to 3%	[1]	104,140,654	3,471,355
Fuel Fabrication	[2]	2,231,902	74,397
Transportation of U	[2]	226,777	7,559
Fuel Cycle Subtotal		120,767,675	4,025,589
Operation and Maintenance	[3]	7,158,362	238,612
Spent Fuel Transportation	[3]	121,134	4,038
Spent Fuel Disposal	[3]	5,033,823	167,794
Land Reclamation	[3]	4,230	141
Decommissioning	[3]	556,802	18,560
Decommissioning etc. Totals		5,715,989	190,533
Total Required Energy		139,489,355	4,649,645
Energy Payback Ratio	6.79		

Table D.7: Lifetime and Annual Emissions of CO_2 for a Fission Power Plant with Gaseous Diffusion Enrichment

Process	Total Emissions per Installed GW_e **Tonne CO_2/GW_e**	Annual Emissions per GW_e-y **Tonne CO_2/ GW_ey**	Annual Emissions per GW_eh **Tonne CO_2/ GW_eh**
Embodied Energy of Materials and Equipment	196,905	6,564	0.75
Construction	327,083	10,903	1.24
Mining	106,444	3,548	0.40
Milling	140,420	4,681	0.53
Conversion	346,544	11,551	1.32
Enrichment to 3%	8,223,896	274,130	31.27
Fuel Fabrication	375,184	12,506	1.43
Transportation of U	56,078	1,869	0.21
Fuel Cycle Subtotal	9,248,565	308,286	35.17
Operation and Maintenance	574,528	19,151	2.18
Spent Fuel Transportation	8,660	289	0.03
Spent Fuel Disposal	362,551	12,085	1.38
Land Reclamation	299	10	0.00
Decommissioning	2,745	92	0.01
Decommissioning etc. Totals	374,254	12,475	1.42
Total CO_2 Emitted	10,721,336	357,378	40.77

References – Appendix D

[1] White, S.W., "Environmental and Energy Analysis of the Refeed Option of Depleted Uranium Hexafluoride", Fusion Technology Institute, UW-Madison, UWFDM-1044 (Feb. 1997).

[2] Rotty, R.M., A.M. Perry, and D.B. Reister, "Net Energy from Nuclear Power", Federal Energy Administration, FEA/B-76/702 (May 1976).

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Appendix E - DT-Fusion

The parameters for both the UWMAK-I and ARIES-RS are shown in Table E.1. The UWMAK-I has a designed capacity of 1,475 MW_e and the ARIES-RS is designed at 1,000 MW_e. All comparisons are normalized to 1,000 MW_e (or 1 GW_e).

The data for the energy requirements for power plant materials is listed in Table 4.3 and the CO_2 emissions from materials is listed in Table 4.16. The energy requirements and CO_2 emissions from the UWMAK-I and ARIES-RS DT-fusion power plants were calculated in the same manner as that described in section 3.3.1 for the ARIES-III D^3He-fusion power plant.

The fuel requirements for each reactor are listed in Table E.2. The results listed here are not normalized per GW_e.

Table E.3 is the summary of construction costs for UWMAK-I[1]. The data listed excludes those sectors that are strictly for materials, since materials data was

Table E.1: DT-Fusion Parameters

	UWMAK[1]	ARIES-RS[2]
Designed Output (MW_e)	1,475	1,000
Reactor Lifetime (years)[3]	40	40
Operating Capacity (%)	75%	75
Designed Output (MW_{th})	5,000	2,614
Reactor Lifetime (Full-Power Years)	30	30
Lifetime Electrical Output (MW_eh)	387,895,500	262,980,000
Efficiency of Reactor (%)	30%	30%
D Mass per Reaction	2	2
T Mass per Reaction	3	3
Energy per Reaction (MeV)	20.08	20.08
Mass of Magnets (tonnes - TF Coils only)	13,078	4,588

[1] Design parameters are from ref. [1], except where noted.

[2] Design parameters are from ref. [2], except where noted.

[3] Assumed lifetime.

calculated separately. Likewise, the construction costs of ARIES-RS are listed in Table E.4. Table E.5 lists the ARIES-RS construction costs excluding those sectors that are strictly for materials.

Table E.2: Energy Requirements for Fusion Fuels

UWMAK-I	**Tonne/30 FPY**	**GJ/Tonne**	**Total GJ/30 FPY**
Deuterium[4]	4.89	140,400	686,103
Lithium	1,153	853	982,728
			1,668,831
ARIES-RS			
Deuterium	3.31	140,400	465,155
Lithium	507	853	432,573
			897,727

[4] Energy requirements for Deuterium are from ref. [3].

Table E.3: Summary of Energy Required for the Construction of UWMAK-I[1], (Adjusted to Exclude Materials)

Account number	Account Description	Cost (1974 M$)	Inflation index	Cost (1967)	I/O Sector #	MJ_{th}/ $	TJ_{th}	MJ_e/ $	TJ_e	TJ_{th} (tot)
21	Structures & Improvements	20	1.73	12	1103	67.27	792	6.91	81	1,064
22	Boiler Plate Equipment									
	227-Instrumentation	12	1.49	8	5301	27.31	214	3.56	28	308
	(rest of 22)	30	1.49	20	AV1	49.47	1,008	6.94	141	1,482
23	Turbine Plant Equipment									
	236-Instrumentation Control	2	1.49	1	5301	27.31	37	3.56	5	53
	(rest of 23)	51	1.49	34	AV2	45.6	1,569	6.36	219	2,302
24	Electric Plant Equipment									
	241-Switchgear	4	1.26	3	5303	54.07	183	8.01	27	274
	245-6, Electric wiring	10	1.26	8	5503	54.07	418	8.01	62	625
	(rest of 24)	129	1.49	86	AV3	44.12	3,810	5.61	484	5,433
25	Mise Plant Equipment									
	251-Transportation and Lift Equipment	3	1.31	2	6107	71.23	166	10.92	25	251
	(rest of 25)	6	1.49	4	AV4	47.28	202	6.58	28	296
26	Special Materials	0	1.73	0	2704	156.7 5	0	12.75	0	0
91	Construction Services	24	1.65	15	AV6	50.92	752	4.29	63	964
92	Home Office Engineering	49	1.56	31	7301	24.63	766	2.32	72	1,008
93	Field Office Engineering	77	1.56	49	7301	24.63	1,210	2.32	114	1,591
										0
	Total	417		275			11,126		1,351	15,652
	total per 1000 MW_e	283		187			7,554		917	10,626

Table E.4: Summary of Energy Required for the Construction of ARIES-RS (LSA=1) Verbatim from ARIES Team Web-site[2]

Account number	Account Description	Cost (1992M$)	Inflation index	Cost (1967)	I/O Sector #	MJ_{th}/ $	TJ_{th}	MJ_e/$	TJ_e	TJ_{th} (tot)
21	Structures & Improvements	250.226	4.93	51	1103	67.27	3,413	6.91	351	4,588
22	Reactor Plant Equipment	*1195.572*								
22.1.01	FW/blanket/reflector	70.355	4.24	17	5301	27.31	453	3.56	59	651
22.1.02	shield	159.167	4.24	38	AV1	49.47	1,857	6.94	260	2,729
22.1.03	magnets	259.593	4.24	61	AV1	50.47	3,089	7.94	486	4,717
22.1.04	supplemental-heat./CD syst.	148.489	4.24	35	AV1	51.47	1,802	8.94	313	2,851
22.1.05	primary struct. & support	48.331	4.24	11	AV1	52.47	598	9.94	113	977
22.1.06	reactor vacuum vessels	143.981	4.24	34	AV1	53.47	1,815	10.94	371	3,059
22.1.07	power supply, switching, energy storage	50.025	4.24	12	AV1	54.47	642	11.94	141	1,114
22.1.08	impurity control	12.307	4.24	3	AV1	55.47	161	12.94	38	287
22.1.09	direct energy conversion syst.	0	4.24	0	AV1	56.47	0	13.94	0	0
22.1.10	ecrh breakdown equip.	3.919	4.24	1	AV1	57.47	53	14.94	14	99
22.1	Reactor Equipment	896.167								
22.2	main heat transf. & trnspt.	154.96	4.24	37	AV1	58.47	2,136	15.94	582	4,087
23	Turbine Plant Equipment	284.446	4.24	67	AV2	45.6	3,058	6.36	427	4,487
24	Electric Plant Equipment	98.754	3.60	27	AV3	44.12	1,210	5.61	154	1,726
25	Misc Plant Equipment	53.045	3.72	14	AV4	47.28	674	6.58	94	988
26	Special Materials	11.073	4.93	2.2	2704	156.75	352	12.75	29	448
90	Direct Cost (not incl. contingency)	1903.553								
91	Construction Services	215.102	4.68	46	AV6	50.92	2,338	4.29	197	2,998
92	Home Office Engineering	98.985	4.44	22	7301	24.63	549	2.32	52	723
93	Field Office Engineering	98.985	4.44	22	7301	24.63	549	2.32	52	723
	Total per 1000 MW_e	5,261		500			24,751		3,732	37,253
	(b) 92/76 = 140.3/56.9 =	*2.46573*								

Data concerning the O&M of both DT-fusion power plants is described in section 3.3.1 and the results are listed in section 4.1.4. Data for the energy requirements of decommissioning both DT-fusion power plants was calculated in the same manner as the D^3He-fusion, ARIES-III power plant as described in section 3.3.1.

The results for the UWMAK-I energy requirements are in Table E.5. ARIES-RS energy requirements are listed in Table E.6. Lifetime emissions of CO_2 are listed in Table E.7 for UWMAK-I and Table #.8 for ARIES-RS.

Table E.5: Lifetime and Annual Energy Investments for UWMAK-I D-T Fusion

		Total Energy per Installed GW_e	Annual Energy per GW_ey
Process	**Source**	**GJ/GW_e**	**GJ/GW_ey**
Embodied Energy of Materials and Equipment	See Table 4.3	8,063,222	268,774
Deuterium	[3]	465,155	15,505
Lithium		982,728	32,758
Fuel Cycle Subtotal		1,447,883	48,263
Construction - Power Plant	See Table E.3	10,044,432	334,814
Operation - Station Use	See Table 4.11	13,039,158	434,639
Decommissioning	Normalized	1,664,139	55,471
Radioactive Waste Disposal	[4]	484,019	16,134
Total Required Energy		34,742,853	1,158,095

Table E.6: Lifetime and Annual Energy Investments for the ARIES-RS D-T Fusion Power Plant

Process	Source	Total Energy per Installed GW_e GJ/GW_e	Annual Energy per GW_ey GJ/GW_ey
Embodied Energy of Materials and Equipment	See Table 4.3	16,892,811	563,094
Deuterium	[3]	465,155	15,505
Lithium		432,573	14,419
Fuel Cycle Subtotal		897,727	29,924
Construction - Power Plant	See Table E.4	10,911,269	363,709
Operation - Station Use	See Table 4.11	9,549,821	318,327
Decommissioning	Normalized	1,344,437	44,815
Radioactive Waste Disposal	[4]	184,610	6,154
Total Required Energy		39,780,675	1,326,023

Table E.7: Lifetime and Annual Emissions of CO_2 for UWMAK-I D-T Fusion Power Plant

Process	Source	Total Emissions per Installed GW_e **Tonne CO_2/GW_e**	Annual Emissions per GW_ey **Tonne CO_2/GW_ey**	Annual Emissions per GW_eh **Tonne CO_2/GW_eh**
Embodied Energy of Materials and Equipment		734,893	24,496	2.79
Deuterium		34,111	1,137	0.13
Lithium	incl. w/ materials	61,109	1,381	0.16
Fuel Cycle Subtotal		95,220	2,518	0.29
Construction - Power Plant		702,025	23,401	2.67
Operation - Station Use		818,513	31,873	3.11
Decommissioning		116,622	3,887	0.44
Radioactive Waste Disposal		10,201	340	0.04
Total CO_2 Emitted		2,477,473	86,516	9.3

Table E.8: Lifetime and Annual Emissions of CO_2 for the ARIES-RS D-T Fusion Power Plant

		Total Emissions per Installed GW_e	Annual Emissions per GW_ey	Annual Emissions per GW_eh
Process	**Source**	**Tonne CO_2/GW_e**	**Tonne CO_2/GW_ey**	**Tonne CO_2/GW_eh**
Embodied Energy of Materials and Equipment		1,247,562	41,585	4.74
Deuterium		34,111	1,137	0.13
Lithium	incl. w/ materials	26,899	897	0.10
Fuel Cycle Subtotal		61,010	2,034	0.23
Construction - Power Plant		762,258	25,409	2.90
Operation - Station Use		599,475	23,344	2.28
Decommissioning		94,217	3,141	0.36
Radioactive Waste Disposal		3,891	130	0.01
Total CO_2 Emitted		2,768,413	95,642	10.5

References – Appendix E

[1] Badger, B., et al., "UWMAK-I: A Wisconsin Toroidal Reactor Design", Univ. of Wisconsin-Madison, UWFDM-68 Vol. II (May 1975).

[2] Miller, R., "ARIES-RS Engineering and Economic Parameters," , A. Team, Ed.: UCSD (1998).

[3] Bünde, R., "The Potential Net Energy Gain from DT Fusion Power Plants", *Nuclear Engineering and Design/Fusion*, **3**(1985), pp. 1-36.

[4] Tsoulfanidis, N., "Energy Analysis of Coal, Fission, and Fusion Power Plants", *Nuclear Technology/Fusion*, **1**(2), (1981), pp. 238-254.

Appendix F - Wind Power Plant

The wind power plant analyzed for this thesis is a 25 MW_e facility that is in operation in Southwestern Minnesota along the Buffalo Ridge near the town of Lake Benton. The wind farm provides electric power for Northern States Power utility of Minnesota and is operated by LG&E, Inc. in Costa Mesa, California. This wind farm was the first of at least three phases of wind turbines that will eventually be built on the Buffalo Ridge. For the purpose of this paper, it is referred to as the Buffalo Ridge Phase-I (BR-I) wind farm.

Table F.1 lists the relevant parameters of the wind farm. While the entire power plant is designed to produce a maximum of 25 MW_e, individually, each of the 73 wind turbines has a rated power of 342.5 kW_e. It is expected that each nacelle (wind turbine) will last for 25 years. The expected capacity factor for the turbines, according to the manufacturers quote was 33%. Thus far, with 4 years of operation, the BR-I wind farm has only maintained a capacity factor of 24%.

Table F.1: Parameters for Buffalo Ridge Phase-I Wind Farm Parameters[1]

Turbine Manufacturer & Model	Kenetech
Turbine Model	KVS-33
Rated Power per turbine (kW_e)	342.5
Gross Rated Power per turbine (kW_e)	410.0
Number of Turbines per Power Plant	73
Rated Power Plant Output (MW_e)	25
Expected Life of Turbine (years)	25
Capacity Factor (Predicted)	33%
Capacity Factor (Actual)[2]	24%
Tower Height (feet)	120
Rotor Diameter (feet)	108

[1] From Ref. [1].

[2] See Table H.7.

Table F.2 lists the mass of both individual wind turbines and the wind farm as a whole. All of this data was collected from private conversations with a representative of LG&E, Inc.[1]. The energy requirements and emissions from materials were calculated in the same manner as described for the D^3He-fusion power plant in Chapter 3. Table F.2 also lists the type of material used for each component.

The type and length of wire and cable used in each turbine was also obtained from LG&E[1]. The total mass was calculated by multiplying the length of wire by the weight per unit length of each type of wire, as obtained in ref. [2]. The results are in Table F.3.

In the analysis, the energy requirements for wind farm construction includes both transporting the components to the construction site and the actual onsite construction. The distances and related data for transporting the wind turbine components from the manufacturing site to Lake Benton, Minnesota are listed in Table F.4. The manufacture site data for each component was obtained from LG&E[3]. The distances between these sites were calculated using the Mapquest™ map-generating program[4], which can determine the distances between

Table F.2: Buffalo Ridge Phase-I Wind Project

Component	Material	Mass/ Turbine (lbs.)[3]	Mass/ Turbine (tonnes)	Total Mass for Wind Farm - 73 turbines (tonnes)
Nacelle	Cast Iron	20,500	5.9	430
Rotor/Blades[4]	Fiberglass	7,500	6.8	497
Towers	Steel	43,360	19.7	1,435
Foundation	Concrete	84.78 yds^3	136.1	9,937
Electrical Wire	Copper	-	0.073	5
Control Cabinet	Steel	1,000	0.5	33

[3] Ref. [1].

[4] Totals include 2 sets of blades per turbine. The fiberglass blades are designed to last for the lifetime of the nacelle, but due to a design flaw in the case of BR-I, it was estimated that all blades will have to be replaced once over the lifetime of the plant[1].

Table F.3: Type, Length and Mass of Wire & Cable

Function	Type[5]	Length[6]	Number	Weight per 1000', (lb.)[7]	Total Mass, kg
Power (turbine to inverter)	3-0 awg	130 ft	6	163	57.67
Grounding Cable	1-0 awg	107 ft	1	258	12.52
Auxiliary Power Cable	10 awg	130 ft	1	31.4	1.85
Tachometer cable	20 awg	100 ft	7	3.09	0.98
		Total Mass of Wire/Turbine (kg)			**73.0**

Table F.4: Data for the Transportation of Wind Turbine Components

Origin/Destination[8]	Method	Mass	Miles	Energy (GJ)
Nacelle - (Turbine w/o blades)				
Milwaukee, WI to Livermore, CA	Truck	430	2,190	2,630
Livermore, CA to Lake Benton, MN	Truck	430	1,920	2,306
Total				4,935
Rotors/Blades				
Kent, WA to Lake Benton	Truck	497	1,605	2,224
Towers				
El Paso, TX to Lake Benton	Truck	1,435	1,480	5,928
Concrete				
Sioux Falls, SD to Lake Benton	Truck	9,937	66	1,830
Control Cabinet				
Livermore, CA to Lake Benton	Truck	33	1,920	177
	Total Transportation Energy			**15,094**

5 Ref. [1].
6 Ref. [1].
7 Ref. [2].
8 Ref. [3].

two towns or addresses. The energy requirements per transportation mode are listed in Appendix A. To calculate the CO_2 emissions from component transportation it was assumed that all energy requirements were from diesel fuel. The diesel fuel emission factor was then multiplied by the amount of fuel that would be needed to provide this energy. Heating values diesel and other fuels are also listed in Appendix A.

Data on the energy requirements to construct the BR-I wind farm was not available. The data used for this analysis was scaled from data to construct a two-turbine wind farm in DePere, Wisconsin. The data for this project is located in Table F.5. The energy requirements for BR-I were scaled from the DePere data by a factor of 12 based on the ratio:

$$\left(\frac{\text{\# of turbines BR-I}}{\text{\# of turbines DePere}}\right)*\left(\frac{\text{Mass of 1 BR-I turbine}}{\text{Mass of 1 DePere turbine}}\right)=\frac{73}{2}*\frac{169}{517}=11.9$$

Table F.5: The Energy Requirements to Construct the Two Turbine Wind Farm at DePere, Wisconsin[9]

	1997$	I/O Sector[10]	Btu/77$[11]	BTU	GJ_{th}/ 2 turbines
Craning	$75,000	Hoists, cranes	30,233	8.56E+08	903
Labor	$25,000	Misc. Business Services	10,000	9.44E+07	100
Local Equipment Rental	$3,000	Construction machinery	34,534	3.91E+07	41
Lodging and Food for Employees	$8,000	AV1[12]	28,780	8.69E+07	92
Electrical Grounding	$12,000	NC, Elect. util.	30,648	1.39E+08	147
					1,283

[9] All data from Ref. [7].

[10] I/O sector data is from Spreng, ref. [8].

[11] 1997$ were calculated from the consumer price index by the scale 1977/1997=60.6/160.5=0.3776, ref. [9].

[12] Sector AV1 is an average of the I/O sectors Eat & Drink Places and Hotels.

The turbines at the DePere site are both significantly larger in mass than those at BR-I as well as having a higher rating (600 kW_e) than those at BR-I. Details on the DePere wind farm can be found in a separate report[5]. In calculating the CO_2 emissions for construction, it was assumed that all energy came from diesel fuel.

The energy requirements for operation and maintenance were calculated using the I/O method. Total revenue for LG&E[6] is based on a fixed cost of $7500 per year per turbine and a variable cost of 0.75¢/kWh generated. Of the total revenue generated, 55.6% goes towards O&M. Table F.5 lists the yearly revenue from BR-I, from 1995 through 2019, a 25-year period. All costs were translated into 1995 dollars, using the Consumer Price Index[9]. In Table F.6 is a worksheet used to calculate the energy requirements of O&M for BR-I. The lifetime energy requirements are shown at the bottom. In calculating the CO_2 emissions, it was assumed that all O&M energy requirements were from diesel fuel.

Table F.6: Yearly Revenue for Buffalo Ridge Phase-I

Year	MWh	Fixed Costs 1995$/ yr. /turbine	Variable Costs 1995$/ kWh	CPI #	1995$/ year
1995	54,765	7500	$0.0075	152.4	$958,240
1996	50,419	7500	$0.0075	156.9	$899,095
1997	53,522	7500	$0.0075	160.5	$901,023
1998	53,522	7500	$0.0075	168.5	$858,117
1999	53,522	7500	$0.0075	177.0	$817,254
2000	53,522	7500	$0.0075	185.8	$778,337
2001	53,522	7500	$0.0075	195.1	$741,274
2002	53,522	7500	$0.0075	204.8	$705,975
2003	53,522	7500	$0.0075	215.1	$672,357
2004	53,522	7500	$0.0075	225.8	$640,340
2005	53,522	7500	$0.0075	237.1	$609,848
2006	53,522	7500	$0.0075	249.0	$580,807
2007	53,522	7500	$0.0075	261.4	$553,150
2008	53,522	7500	$0.0075	274.5	$526,809
2009	53,522	7500	$0.0075	288.2	$501,723
2010	53,522	7500	$0.0075	302.6	$477,832
2011	53,522	7500	$0.0075	317.8	$455,078
2012	53,522	7500	$0.0075	333.7	$433,407
2013	53,522	7500	$0.0075	350.4	$412,769
2014	53,522	7500	$0.0075	367.9	$393,113
2015	53,522	7500	$0.0075	386.3	$374,394
2016	53,522	7500	$0.0075	405.6	$356,565
2017	53,522	7500	$0.0075	425.9	$339,586
2018	53,522	7500	$0.0075	447.1	$323,415
2019	53,522	7500	$0.0075	469.5	$308,015
					$14,618,524

There wasn't any available data on the energy requirements to decommission a wind plant. For this reason, an assumption was made that it would take approximately the same amount of energy to completely dismantle the turbines as it would to construct it. At the same time, it is assumed that while the nacelles with all their moving parts will only last 25 years, the towers that support the nacelles will last longer than that. For this analysis, it is assumed that a tower will last for the life of two wind turbines. Therefore, the total energy required to dismantle one turbine will be half the energy required to construct it, since the energy required for dismantlement can be amortized for two turbines. It is also assumed that the fuel used to dismantle the turbines will be diesel, the emission factor of which was used to calculate the CO_2 emissions.

Table F.8 is the actual electricity generation data from Buffalo Ridge Phase-I from March 1994 through July 1998. To calculate the average amount of electricity produced per year at the 25 MW_e wind farm, the average over a four-year period was taken. The four-year

Table F.7: Operation & Maintenance Energy Requirements Worksheet

Total Revenue, 1995-2019 (1995$)	$14,618,524	
Cost to repair one set of blades[13] (95$)		$16,000
Number of sets to replace[13]		x 7
Total Cost to Repair blades (95$)	-$112,000	
Adjusted Revenue, less cost of blade repair (95$)	$14,506,524	
Inflation Adjustment (1977/1995:60.6/152.4)		x 0.3976
Adjusted Cost of O&M (77$)	$5,768,342	
Share of Revenue towards O&M (%)		x 55.6%
Share of Revenue toward O&M (95$)	$3,207,200	
I/O Auto Repair Sector energy intensity (GJ/77$)[14]		x 0.0233
Lifetime Energy Requirements of O&M (GJ)		74,625

[13] Ref. [10]. Full blade replacement was not anticipated in the original O&M costs expenditures, but it was anticipated that 10% of the blades could fail.

[14] From I/O Table in ref. [8].

period extends from June 1994 through May 1998. The capacity factor is calculated by dividing the yearly average of electricity (53.5 GW_eh) by the amount of electricity that would be generated if the power plant produced at its rated capacity for a full year (25 MW_e*8760 hrs./year =219 GW_eh). The actual capacity factor of BR-I is 24%.

The energy requirements for BR-I are listed in Table F.9 and the total CO_2 emissions for the power plant are listed in Table F.10.

Table F.8: Production History of Buffalo Ridge Phase-I[15]

Month	Actual Production (kWh)	Budget Production (kWh)	Monthly Actual as a % of Budget	Cumulative Actual as a % of Budget	Actual % Production per Month	Budget % Production per Month	Design Projected Output (kWh)	Monthly Actual % of Design Projected Output	Cumulative Design Projected Output (kWh)	Cumulative Actual % of Design Projected Output	Average Availability
Mar-94	1,139,000	1,162,000	98%	98%							88%
Apr-94	1,921,000	3,244,000	59%	69%							78%
May-94	3,075,000	7,028,000	44%	54%							67%
Jun-94	3,362,000	5,790,000	58%	55%							83%
Jul-94	2,228,449	4,371,000	51%	54%							86%
Aug-94	2,344,085	4,371,000	54%	54%							85%
Sep-94	4,082,009	6,047,000	68%	57%							87%
Oct-94	6,072,747	5,318,000	114%	65%							93%
Nov-94	7,418,257	6,047,000	123%	73%							97%
Dec-94	5,578,133	6,047,000	92%	75%							82%
	37,220,680	49,425,000	75%				49,245,000	76%	49,245,000	76%	85%
Jan-95	4,448,911	6,419,000	69%	75%	8%	9%	6,556,860	68%	55,801,860	75%	96%
Feb-95	4,673,482	4,993,000	94%	76%	9%	7%	5,099,780	92%	60,901,640	76%	95%
Mar-95	5,754,084	7,208,000	80%	77%	11%	10%	7,285,400	79%	68,187,040	76%	98%
Apr-95	5,541,625	7,285,000	76%	77%	10%	10%	7,285,400	76%	75,472,440	76%	92%
May-95	3,910,756	7,285,000	54%	75%	7%	10%	7,285,400	54%	82,757,840	74%	99%
Jun-95	3,845,611	5,828,000	66%	74%	7%	8%	5,828,320	66%	88,586,160	74%	97%
Jul-95	3,524,385	4,371,000	81%	74%	6%	6%	4,371,240	81%	92,957,400	74%	94%
Aug-95	2,927,136	4,371,000	67%	74%	5%	6%	4,371,240	67%	97,328,640	74%	96%
Sep-95	4,432,344	5,828,000	76%	74%	8%	8%	5,828,320	76%	103,156,960	74%	98%
Oct-95	5,637,984	5,828,000	97%	75%	10%	8%	5,828,320	97%	108,985,280	75%	97%
Nov-95	5,964,761	5,828,000	102%	77%	11%	8%	5,828,320	102%	114,813,600	77%	98%
Dec-95	4,104,244	7,288,000	56%	75%	7%	10%	7,285,400	56%	122,099,000	75%	94%
	54,765,323	72,532,000	76%		100%	100%	72,854,000	75%	122,099,000	75%	96%

15 From LG&E operational data, Ref. [11, 12].

Table F.8 Continued

Month	Actual Production (kWh)	Budget Production (kWh)	Monthly Actual as a % of Budget	Cumulative Actual as a % of Budget	Actual % Production per Month	Budget % Production per Month	Design Projected Output (kWh)	Monthly Actual % of Design Projected Output	Cumulative Design Projected Output (kWh)	Cumulative Actual % of Design Projected Output	Average Avail-ability
Jan-96	4,690,750	5,533,990	85%	76%	9%	9%	6,556,860	72%	128,655,860	75%	86%
Feb-96	6,931,063	4,304,214	161%	79%	14%	7%	5,099,780	136%	133,755,640	77%	92%
Mar-96	5,561,090	6,148,878	90%	79%	11%	10%	7,285,400	76%	141,041,040	77%	96%
Apr-96	5,770,304	6,148,878	94%	80%	11%	10%	7,285,400	79%	148,326,440	77%	97%
May-96	5,473,300	6,148,878	89%	80%	11%	10%	7,285,400	75%	155,611,840	77%	96%
Jun-96	3,567,000	4,919,102	73%	80%	7%	8%	5,828,320	61%	161,440,160	77%	93%
Jul-96	1,820,199	3,689,325	49%	79%	4%	6%	4,371,240	42%	165,811,400	76%	77%
Aug-96	2,629,102	3,689,325	71%	79%	5%	6%	4,371,240	60%	170,182,640	75%	75%
Sep-96	2,594,120	4,919,102	53%	78%	5%	8%	5,828,320	45%	176,010,960	74%	73%
Oct-96	5,398,598	4,919,102	110%	79%	11%	8%	5,828,320	93%	181,839,280	75%	72%
Nov-96	1,873,602	4,919,102	38%	78%	4%	8%	5,828,320	32%	187,667,600	74%	78%
Dec-96	4,109,898	6,148,878	67%	78%	8%	10%	7,285,400	56%	194,953,000	73%	72%
	50,419,026	61,488,774	82%		100%	100%	72,854,000	69%	194,953,000	73%	84%
Jan-97	4,282,699	5,901,174	73%	77%	8%	9%	6,556,860	65%	201,509,860	73%	84%
Feb-97	4,313,402	4,589,802	94%	78%	8%	7%	5,099,780	85%	206,609,640	73%	90%
Mar-97	5,999,699	6,556,860	92%	78%	11%	10%	7,285,400	82%	213,895,040	73%	91%
Apr-97	4,049,398	6,556,860	62%	78%	7%	10%	7,285,400	56%	221,180,440	73%	96%
May-97	5,740,078	6,556,860	88%	78%	11%	10%	7,285,400	79%	228,465,840	73%	97%
Jun-97	3,644,625	5,245,488	69%	78%	7%	8%	5,828,320	63%	234,294,160	73%	100%
Jul-97	3,192,188	3,934,114	81%	78%	6%	6%	4,371,240	73%	238,665,400	73%	96%
Aug-97	1,769,900	3,934,116	45%	77%	3%	6%	4,371,240	40%	243,036,640	72%	97%
Sep-97	4,107,788	5,245,488	78%	77%	8%	8%	5,828,320	70%	248,864,960	72%	96%
Oct-97	7,775,000	5,245,488	148%	79%	14%	8%	5,828,320	133%	254,693,280	74%	96%
Nov-97	5,055,125	5,245,488	96%	79%	9%	8%	5,828,320	87%	260,521,600	74%	96%
Dec-97	4,568,875	6,556,860	70%	79%	8%	10%	7,285,400	63%	267,807,000	74%	99%
	54,498,777	65,568,598	83%		100%	100%	72,854,000	75%	267,807,000	74%	95%

Table F.8 Continued

Month	Actual Production (kWh)	Budget Production (kWh)	Monthly Actual as a % of Budget	Cumulative Actual as a % of Budget	Actual % Production per Month	Budget % Production per Month	Design Projected Output (kWh)	Monthly Actual % of Design Projected Output	Cumulative Design Projected Output (kWh)	Cumulative Actual % of Design Projected Output	Average Availability
Jan-98	3,318,125	5,245,488	63%	79%	12%	15%	6,556,860	51%	274,363,860	73%	96%
Feb-98	3,919,000	4,079,824	96%	79%	14%	12%	5,099,780	77%	279,463,640	73%	98%
Mar-98	5,995,398	5,828,320	103%	80%	21%	17%	7,285,400	82%	286,749,040	73%	95%
Apr-98	4,984,199	5,828,320	86%	80%	17%	17%	7,285,400	68%	294,034,440	73%	84%
May-98	5,100,800	5,828,320	88%	80%	18%	17%	7,285,400	70%	301,319,840	73%	95%
Jun-98	3,311,500	4,662,656	71%	80%	12%	13%	5,828,320	57%	307,148,160	73%	96%
Jul-98	2,055,402	3,496,990	59%	79%	7%	10%	4,371,238	47%	311,519,398	72%	96%
Aug-98							4,371,240				
Sep-98							5,828,320				
Oct-98							5,828,320				
Nov-98							5,828,320				
Dec-98							7,285,400				
	28,684,424	34,969,918					43,712,398	66%	311,519,398	72%	94%

Four year average for 6/94-5/98	53.52	(GW_eh/yr.)
Max. elect. produced / year (at full capacity)	219	(GW_eh/yr.)
Capacity Factor over 4 year period	24%	

Table F.9: Lifetime and Annual Energy Investments for a Wind Power Plant (Buffalo Ridge Phase I)

Process	Source	Total Energy per Installed 25 MW_e Power Plant **GJ_{th}/ Power Plant**	Total Energy per GW_eh produced **GJ_{th}/ GW_eh**
Turbine Materials			
Blades		6,363	4.76
Nacelles		17,499	13.08
Inverter		12,385	9.26
Wiring		696	0.52
Tower		49,431	36.94
Foundations		13,694	10.23
Materials subtotal	See Table 4.3	100,067	75
Transportation	See Table F.4	15,094	11
Construction	See Table F.5	15,305	11
Construction Subtotal		30,399	22
Operation and Maintenance	See Table F.7	74,625	56
Decommissioning (g)		7,652	6
Total Required Energy per Plant		212,744	159
Total per 1000 MW_e installation		8,509,760	
Total per 30 GW_ey			41,784,359

Table F.10: Lifetime and Annual Emissions of CO_2 for a Wind-farm (Buffalo Ridge Phase I)

Process	Source	Total Emissions per Installed 25 MW_e **Tonne CO_2/plant**	Total Emissions per Installed GW_e **Tonne CO_2/ GW_e**	Emissions per GWh_e **Tonne CO_2/ GW_eh**	Emissions per GW_ey **Tonne CO_2/ GW_ey**
Turbine Materials					
Blades	Various	399	15,978	0.30	2,615
Nacelles	Various	1,179	47,151	0.88	7,717
Inverter		778	31,100	0.58	
Wiring		40	1,588	0.03	
Tower		3,547	141,891	2.65	
Foundation		5,166	206,630	3.86	33,820
Materials subtotal		11,108	444,337	8.30	72,726
Construction		1,106	44,220	0.83	7,238
Transportation		1,090	43,613	0.81	7,138
Construction subtotal		2,196	87,833	1.14	14,376
Maintenance		5,390	215,617	4.03	35,291
Decommissioning		553	22,110	0.41	3,619
Total Emissions		19,247	769,898	14	126,011

References - Appendix F

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