Energy Balance and Lifetime Emissions from Fusion, Fission and Coal Generated Electricity

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ENERGY BALANCE AND LIFETIME EMISSIONS FROM FUSION, FISSION AND COAL GENERATED ELECTRICITY

by

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1.0 Introduction

Nuclear fusion has been touted as the electrical power source of the future. It is a technology that has vast fuel reserves and is believed to have less of a harmful impact on the environment than existing sources of baseload electrical power. However, the first generation of fusion reactors, which will use the hydrogen isotopes deuterium and tritium (D-T) as fuel, could have masses of high-level radioactive waste that are similar to those of current fission reactors (hundreds of tons per year). The mass of radioactive material that is associated with handling tritium and replacing the first wall of the reactor may not be viewed as a satisfactory alternative to our current nuclear fission reactors in the eyes of the public. While these issues of radioactivity, engineering, and physics problems of fusion are being solved, and before D-T fusion reactors become commercially feasible, other key issues such as the net energy investment in each technology and the overall environmental impact of fusion needs to be considered. This paper will address these issues by accounting for the energy expended and pollutants emitted during the lifetime of a fusion power plant.

There have been a few studies that addressed the net energy output of a D-T fusion power plant [1-3], but none have thoroughly analyzed the environmental impact of generating base load electricity with fusion. An analysis of fusion's environmental impact is important to ensure inclusion of the technology in future policy making and long-range planning. Also, an extensive comparison of fusion to coal-fired and fission power plants, which will probably be fusion's primary competition to provide baseload electric power in the 21st century, is important for accurate interpretation of the data.

There have been several studies which address the net energy investment in coal and fission plants [1, 3-10]. Only refs.[1, 3] have included fusion. There have also been several studies

[6, 11-21] that have dealt with various environmental impacts of electric power generated from coal and fission power plants, but none of these studies have included fusion. The lack of studies that adequately compare fusion's net energy and environmental impact with those of coal and fission, make this an important topic to address.

This paper will approach both the net energy balance and environmental impacts of the three types of power plants from the cradle-to-grave. It is recognized that the impact of an electricity generating power plant on the environment, and the energy that is expended to produce electric power, is not limited to the operating lifetime of a power plant alone. Energy is consumed and pollutants are emitted during all phases of the power plants' lifetime. These phases include:

- acquiring and processing materials,
- acquiring and processing fuels,
- power plant construction,
- power plant operation,
- and power plant decommissioning, including the storage and safe disposal of waste.

To thoroughly analyze the net energy and environmental impact of power plants it was necessary to use material requirements from generic power plants. The bill of materials for coal and fission plants are for model power plants that come from studies that analyzed the energy investments of the technologies. The tonnage for each material was based on a standard for the technology or were averages for multiple plants. The coal plant model is based on an 800 MW(e) plant from ref. [6] while the fission plant is for a 1,000 MW(e) pressurized water reactor (PWR) from ref. [6]. The fusion power plant data is for the 1,475 MW(e) UWMAK-I tokamak reactor [22], which has published the most detailed bill of materials available for a fusion power plant. The bill of materials for each power plant as they were used in this report can be found in section 2.1.

Two methods of net energy analysis were considered for the power systems; the process chain analysis (PCA) and input-output (I/O) methods. In the PCA method, the energy consumed in each phase of the power plant's lifetime is analyzed and summed to determine the overall energy investment. For construction materials, the mass of each material is determined and these values are multiplied by the total energy input per unit mass of the assembled product. The energy intensity of the total mass is then determined by breaking the power plant's life into a chain of production steps which begins with mining the raw materials, and ends with the decommissioning of the plant. The use of actual operating data for specific processes to determine energy expenditures characterizes the PCA method.

The I/O method on the other hand is based on a detailed analysis of the economic costs for all materials, equipment, services and utilities other than fuels and electricity of a power plant [7]. Each of the individual parts are multiplied by the energy intensity of the monetary unit, which in turn is dependent on the industry or sector from which they are produced. The sum of the energy intensities of all materials, equipment, services and non-fuel or electricity utilities gives the energy intensity of the entire power plant.

The process chain analysis (PCA) was used in this study to determine the energy expenditures of the power plants instead of the input-output (I/O) method. Most of the energy investment data comes directly from previously published sources and was used directly, except for normalizing the units into gigajoules (GJ) per giga-watt (10^9 watts) of installed electric capacity (GW(e)). It is likely that some of this data was generated by using the I/O method.

The PCA method is the best method to use in determining the energy intensity for fusion because of the complex technology and the fact that some of the reactor's components are not sufficiently covered in I/O sectors. Bünde [1] states that multipliers in the I/O method are not accurate enough in the case of nuclear power because the technologies required for construction are much more sophisticated than the average commodity. There evidently is not a strong relationship between the energy intensity in some individual sectors, such as engineering, and their economic costs. Construction technologies for nuclear fusion are not only more complex than those of fission, some of them are not yet developed. Although authors such as Perry, et. al. [9], state that while neither the PCA nor I/O methods are entirely adequate by themselves, the I/O method yields energy input values that are much too high for nuclear power plants and therefore are not directly used here.

The method used to determine the energy payback, E_G, is shown in the equation below:

$$E_G = \frac{E_{n,L}}{\left(E_{MAT,L} + E_{CON,L} + E_{OP\,P,L} + E_{F,L} + E_{DEC,L}\right)}$$

The net energy produced over the lifetime of the power plant, $E_{n,L}$ or 30-GW(e)-yrs, is divided by the total energy invested in the power plant, as found in the denominator, which includes the energy invested in materials acquisition ($E_{MAT,L}$), construction ($E_{CON,L}$), plant operation ($E_{OP\,P,L}$), fuel gathering ($E_{F,L}$), and power plant decommissioning ($E_{DEC,L}$). A flow chart of the energy investment of each power plant is provided in figure 1.1. The total energy investment in this figure corresponds with the denominator of the above equation.

Much like with the energy analysis, a cradle-to-grave method was used in analyzing the environmental impact of each power plant. The analysis was limited to easily quantifiable environmental impacts such as resource use, pollutant emissions and waste production. A

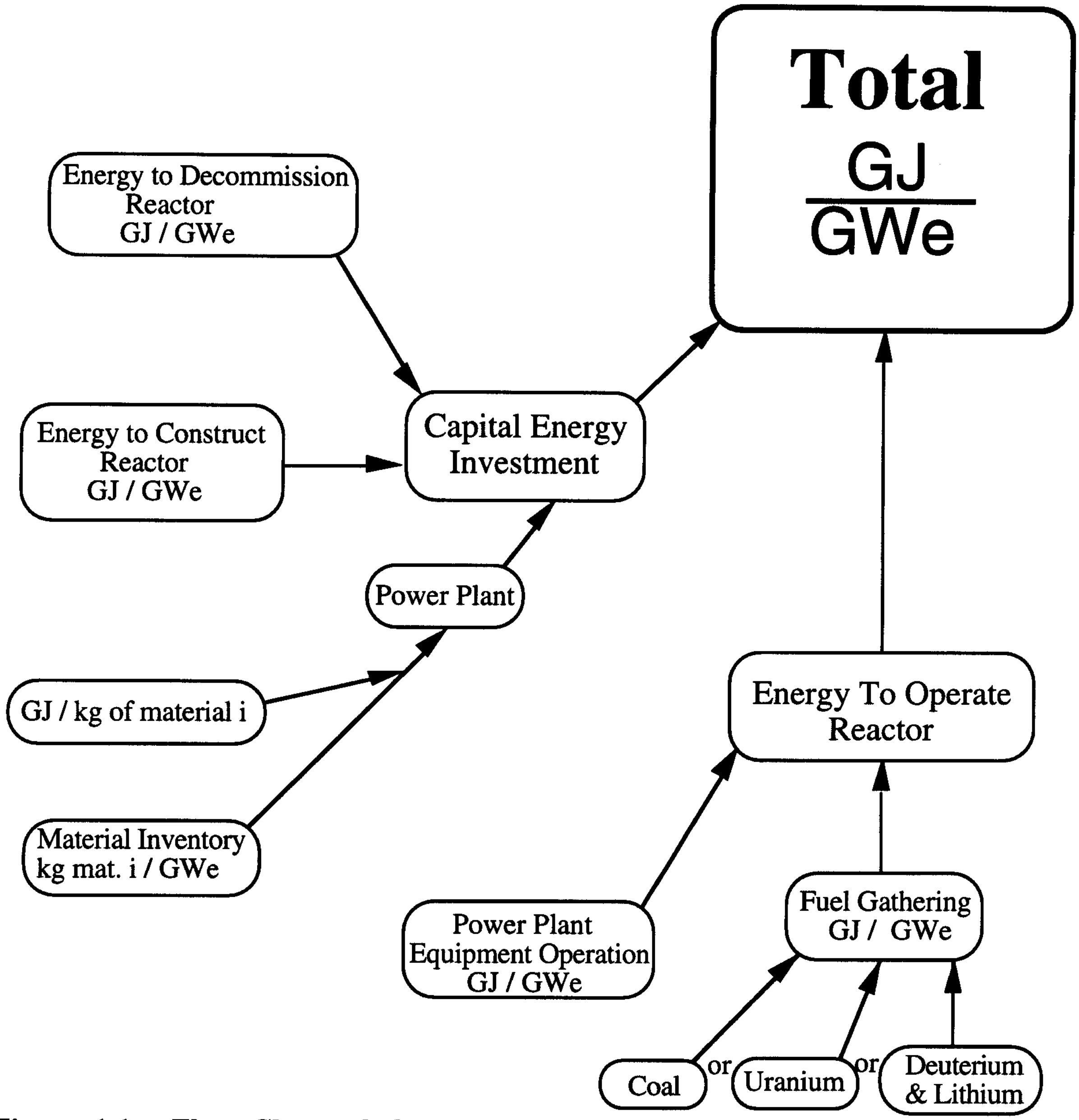

Figure 1.1: Flow Chart of the Energy Investment of Power Plants.

method similar to the process-chain analysis for net energy accounting, was employed to quantify the environmental impacts of all energy production processes from which data was available or derivable. For this paper, the impacts were broken down into the following categories:

- gaseous emissions,
- aqueous emissions,
- radioactive emissions,
- solid waste,
- and land use.

Gaseous emissions include carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_X), carbon monoxide (CO) and particulate matter (PM). Every attempt was made to use actual data whenever possible and for the material acquisition phase, emissions were calculated by breaking down the energy consumed by individual materials into specific fuels using refs. [23-26] and assigning a value for individual pollutants to each fuel. Ample data on emissions from the operation of coal and fission powered plants is available, while data on fusion is understandably scarce.

2.0 Energy Expenditures

The energy investment in coal, fission and fusion plants are analyzed from cradle-to-grave for the purpose of determining the net energy balance of each. Net energy analysis is a method of energy accounting that has been used since the mid-1970's to compare the lifetime energy investments and the expected lifetime energy output of a power plant [1]. The operating lifetime of the power plants were standardized to a 40-year life at 75% capacity, or 30 full-power years (FPY). In sections 2.1 to 2.5, the energy investment will be analyzed individually for each phase of the three power plants. The lifetime of a power plant has been broken down into five phases; material processing, fuel gathering, construction, operation, and decommissioning. In section 2.6, the energy balance of each power plant will be discussed and analyzed. The direct and indirect energy consumption are both taken into account beginning with the mining of power plant materials all the way through the decommissioning of the plant. Thermal and electrical energy were appropriately combined in most cases to determine the total energy use.

2.1 Material Processing

Material processing is considered an indirect energy input to a power plant because the energy required to process materials is not consumed at the site of the power plant. Every material used in a power plant requires energy to transform it from its most basic state (e.g. ore) to a usable finished form. The bill of materials for each generic power plant are found in tables 2.1 - 2.4. Table 2.2 lists the alloy requirements for the fusion power plant.

Only the non-fuel materials required throughout the operating lifetime of a power plant are considered in this section. Replacement materials, such as those for the fusion power plant's first wall, and materials used in the electrical production process, such as turbines and generators, are also included in this section, though they could have been included as indirect energy investments in the operation section. Two non-fuel materials which were not included in this section include: lime for coal scrubbing and lithium for tritium breeding. Though the coal plant in this analysis is assumed to burn low-sulfur coal, which does not require lime for scrubbing, lime would normally be included in the operational energy investments for a conventional coal plant because it is a material that is not fundamental to the structure or operation of a plant and has a primary function during the operational process of scrubbing the exhaust air stream of sulfur oxides. Lithium serves the dual function of 1) a heat transfer fluid and 2) a breeder for tritium fuel. An arbitrary decision was made to include the energy invested in lithium procurement in the analysis of fuel gathering. The mass of lithium is, however, listed in the bill of materials for the fusion power plant.

Several studies have been conducted to analyze the energy requirements to produce different materials [5, 23-29]. Table 2.5 lists the energy required for individual materials, which came from a variety of sources [1, 5, 23, 26, 27, 30-34]. All energy data was normalized to megajoules (MJ) per metric tonne of finished product.

The materials for each power plant, as found in tables 2.1, 2.3 and 2.4, are listed in the quantities for which energy investment calculations were made. The tonnage of several materials listed here differs slightly from those found in their original paper. The mass of elements used as alloying agents were included with the alloys rather than being listed separately. For example, the fusion power plant bill of materials [22] included 15,500 tonnes of chromium and 1,000 tonnes of molybdenum. Because the entire mass for both elements was used in alloys such as 316 stainless steel (316 SS) and Croloy 2 1/4, neither are listed separately in the fusion power plant's bill of materials as found in table 2.1. The mass of other materials listed in the bill of materials found here may also vary from their original sources for similar reasons.

The data, compiled on Microsoft® Excel spreadsheets, compares the total mass of each type of material included in the specific power plants. For many of the materials, the energy investment per unit mass varied substantially in the literature. When data for a specific material was found in multiple studies, the value used either fell within the range of the other data, took into account recent technological advances, or had greater background detail for the energy investment per unit mass of the material. Because the majority of materials studies were performed soon after the 1973 energy crisis, it is likely that the actual energy investments for some materials are slightly lower now due to improvements in energy efficiency.

The energy content of each material includes all of the energy required to process the material from its most basic form into a usable state. The energy required for material gathering includes mining, refining, smelting, transporting and final finishing stages. For example, the energy requirement for one kilogram of aluminum requires bauxite to be mined from the earth, transported, crushed and concentrated, smelted, refined and possibly rolled. Different materials require different processes to manufacture a finished product.

The fusion power plant chosen for this study (UWMAK-I) has the greatest mass per GWe of the three power plants as can be seen in figure 2.1 because of the large amount of concrete

Table 2.1: Fusion Power Plant Bill of Materials[1]

Materials	Total Mass (Metric Tonnes)	Normalized[2] Mass (Tonnes/GW(e)-Installed)
Aluminum	476	323
B_4C[3]	2,026	1,374
Copper	10,252	6,951
Helium	138	94
Carbon Steel	66,957	43,395
Stainless Steel	83,902	56,883
Unalloyed Steels[4]	8,025	5,441
Lead	20,500	13,898
Lithium	1,700	1,153
Mercury	3	2
Nickel (as Inconel)	1,045	708
Niobium-Titanium (Nb-Ti)[5]	212	144
Sodium	17,826	12085
Yttrium	5	3
Zirconium	100	68
Concrete	746,054	505,799
TOTAL	959,148	650,270

[1]Based on the UWMAK-I fusion tokamak reactor, ref. [22] p. IV-2,5,7.
[2]The UWMAK bill of materials is based on a 1,475 MW(e) power plant. The material masses were normalized linearly to a 1,000 MW(e) power plant.
[3]B_4C is comprised of 78% B and 22% C.
[4]Includes Low Alloy Steel, Croloy-2 1/4 and the iron not accounted for in other alloys (2,596 tonnes).
[5]Nb-Ti is comprised of 66% Nb and 34% Ti.

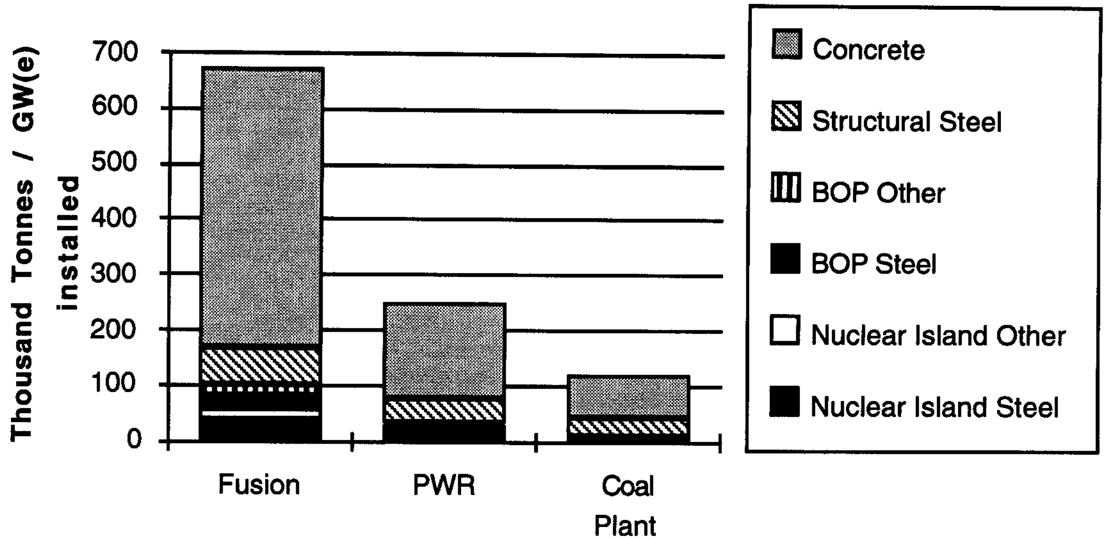

Figure 2.1: The Fusion Power Plant has the greatest Mass of the Three Power Plants. Fuel Mass is not Included.

Table 2.2: Summary of Alloy Requirements for the Fusion Power Plant[1]

Alloy or Compound	Total Mass (Metric Tonnes)
316 SS[2]	53,095
304 SS[3]	30,807
Low Alloy Steel[4]	4,227
Carbon Steel	66,957
Croloy - 2 1/4[5]	197
Nb-Ti[6]	212
B_4C[7]	2,026
Inconel - 600[8]	1,045

[1]Ref. [22] p. IV-8.
[2]316 SS is comprised of 62% Fe, 18% Cr, 14% Ni, 2% Mn, 2% Mo, 1% Al and 1% Cu.
[3]304 SS is comprised of 66% Fe, 20% Cr, 12% Ni and 2% Mn.
[4]Low Alloy steel is comprised of 97% Fe, 2% Ni and 1% Cr.
[5]Croloy - 2 1/4 is comprised of 96.25% Fe, 2.25% Cr, 1% Mo, and 0.5% Mn.
[6]Nb-Ti is comprised of 66% Nb and 34% Ti.
[7]B_4C is comprised of 78% B and 22% C.
[8]Inconel - 600 is comprised of 77.65% Ni, 15% Cu, 7% Fe and 0.35% Mn.

Table 2.3: Bill of Materials for generic PWR[1]

Material	Total Mass (range) (Metric Tonnes)	Average Mass (Metric Tonnes)
Aluminum	18-45	32
Asbestos	90-138	114
Cadmium	<1	1
Chromium	150-415	283
Concrete	170,000	170,000
Copper	726-2,000	1,363
Lead	8-47	27
Magnesium	783	783
Manganese	400-467	434
Molybdenum	3-164	83
Nickel	100-484	292
Silver	<1	1
Steel	10,000-54,000	32,000
Tin	0.05-2	1
Zinc	2-100	51
TOTAL	182,281 - 228,647	205,464

Table 2.4: Bill of Materials for Generic Coal Plant[2]

Material	Normalized Mass (Metric Tonnes/GW(e)-Installed)
Aluminum	255
Chrome	122
Copper	454
Concrete[3]	77,584
Unalloyed Steel[4]	39,681
Stainless Steel	612
Manganese	112
Molybdenum	42
Nickel	10
Cobalt	trace
Silicon	trace
Tungsten	trace
Vanadium	4
TOTAL	118,877

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[1]Ref. [6] p 135.
[2]Ref. [6], p 275.
[3]Based on 37,000 yds^3.
[4]Includes pipe & tubes and forgings.

used. The concrete adds to the total mass of the plant, but does not have as big an impact in the energy embedded in the construction materials, as can be seen in figure 2.2. The fusion power plant still requires the most capital energy for construction materials, because of the large

Table 2.5: Energy Costs of Power Plant Materials.

Element or Alloy	Reference	Total (GJ/Tonne)
Aluminum	[34]	182
B_4C	[1]	270
Brass[1]		99
Bronze[2]		99
Calcium (lime)	[24]	10
Carbon (Graphite)	[26]	187
Chromium	[23]	395
Concrete	[31]	1
Copper	[31]	99
$CuZn_{28}Sn$	[31]	99
Earth Work (m^3)	[1]	0.06
Helium (tonne)	Estimate	30
Helium (m^3)	[1]	13
Insulation Materials	[1]	97
Iron		
Carbon Steel	[30]	26
Stainless Steel[3]	[34]	40
High Alloyed Steels	[1]	65
Unalloyed Steels[4]	[1]	39
Lead	[23]	34
Lithium	[1]	970
Manganese	[5]	49
Mercury	[23]	87
Molybdenum (ferromolybdenum)	[23]	378
Inconel[5]	[23]	184
NbTi	[1]	270
Sand & Gravel	[1]	0.02
Silver	[23]	16,809
Sodium Metal	[30]	97
Tin	[32]	118
Titanium	[34]	460
Vanadium	[23]	3,711
Yttrium	[26]	1,471
Zinc	[34]	73
Zirconium	[26]	1,387

[1]Based on the ref. [31] value for copper.
[2]Based on the ref. [31] value for copper.
[3]Includes 304 SS and 316 SS.
[4]Includes low-alloy steel and croloy-2 1/4
[5]Based on the value for electrolytic nickel in ref. [23].

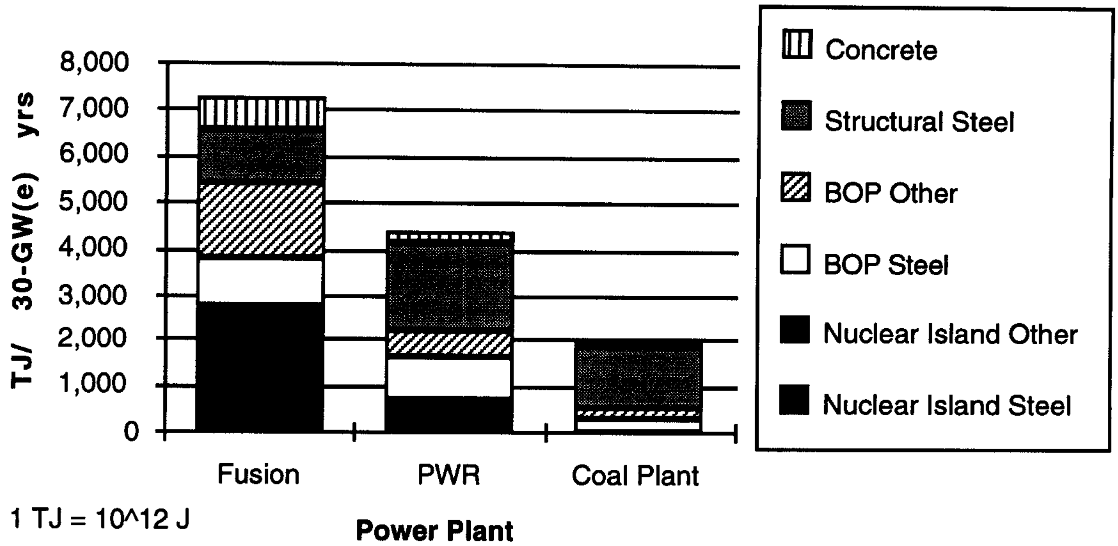

Figure 2.2: The Fusion Power Plant Requires a Greater Energy Investment for Construction Materials of the Three Power Plants. The Energy Content of the Fuels is not Included here.

amounts of non-ferrous metals that are needed for both the nuclear island and in the balance of the plant. When the mass and energy content include the inner core and fuel, the coal plant and PWR have the greatest mass and energy content respectively.

2.2 Fuel Acquisition

In this section, all energy invested in mining, transporting and refining the fuels for each power plant is analyzed. The three fuel types are analyzed individually in sections 2.2.1 through 2.2.3 and collectively in section 2.2.4.

2.2.1 Coal

The energy investment in coal is considerable due to the large quantities of coal required. Over 95 million tonnes of coal are required over the 40 year lifetime of a coal plant with a 75% load factor. The energy investment of the coal fuel cycle was broken down into four categories: mining, processing, storage, and transportation. It was assumed that the coal plant burned low sulfur coal, which usually only requires minimal preparation in the form of crushing and screening. Because the coal processing multiplier is based heavily on coal cleaning, it is not included in the fuel energy totals. When coal processing is involved it uses the greatest amount of energy for the fuel acquisition stage. When processing is not included, transportation, which is primarily by railroad, uses the most energy, followed by mining. Data was not found for energy invested in coal storage, though it is believed to be small. Table 2.6 lists the energy requirements for each category.

2.2.2 Uranium

The processes involved in producing uranium fuel rods for the pressurized water reactors are more energy intensive than similar processes for coal and fusion power plants (see figure 2.6). Enrichment and conversion processes are the most energy intensive of all the fuel cycle processes while milling, mining and fuel fabrication processes also require significant amounts of energy. The lifetime energy requirements of the uranium fuel cycle for a 1,000 MW(e) Pressurized-Water Reactor (PWR) are shown in table 2.7. Enrichment and conversion

Table 2.6: Lifetime Fuel Energy Requirements for a 1,000 MW(e) Conventional Coal Plant.[1]

	Source	Total Energy GJ/GWe	Annual Energy GJ/GWe-yr
Coal Mining	[6] p 249	7,409,212	246,974
Coal Transportation[2]	[24] p 20	15,126,186	504,206
Total		22,535,398	751,180
Coal Processing[3]	[29]	16,176,570	539,219

[1]Based on 1,000 MW(e) generated at 31.5% efficiency over 30 full power years.
[2]Based on an average haul of 200 miles and 780 KJ per net tonne-mile.
[3]Included only as a reference, but is not included in the totals. Most U.S. coal requires some sort of preparation, though for this section it is assumed that low sulfur, western coal, which generally only requires crushing and screening, is used. Coal Processing requires 46.28 kWh/tonne.

processes are the most energy intensive of the fuel cycle processes while milling, mining and fuel fabrication processes also require significant amounts of energy.

2.2.3 Deuterium and Tritium

Deuterium and tritium are needed as fuels for fusion. Tritium is not listed in table 2.8 because it is not acquired independently, but rather bred from a lithium breeder/coolant in UWMAK-I. Therefore, only the energy invested in deuterium and lithium are listed below. Lithium requires significantly more energy to procure than deuterium. However, the combined total is still much less than that required for either the uranium or coal fuel cycles.

Table 2.7: Lifetime Energy Requirements for a 1,000 MW(e) PWR with No Recycle. Based on 0.30% Tails from Conventional Ore and 262,800,000 MWh Lifetime Output.[1]

Process	Electricity	Fuels	Total
	MWh(e)	MWh(th)[(2)]	GJ(th)/ GW(e)
Mining	122,213	977,839	4,916,943
Milling	139,333	970,416	5,085,879
Conversion	92,120	2,497,532	10,043,915
Enrichment[3] [6]	1,560,000	280,269	18,837,540
Fuel Fabrication	329,867	823,916	6,736,002
Transportation of U.			
5682 MT Nat. U.	663	26,655	103,532
822 Tonnes of fuel	2,481	99,972	388,256
Waste Storage	6,680	71,570	333,995
Total Required Energy	2,253,357	5,748,169	46,446,063[(4)]

[1]From ref. [35], p 83. Based on a 40 year reactor lifetime at 75% (30 full power years). The numbers include both direct and indirect energy consumption in each subcategory.
[2]Not including fuels used to generate electricity.
[3]Enrichment is via gas centrifuge. Based on 215.8 MTSWU per year.
[4]A 31.5% efficiency was assumed for electrical generation in the GJ column to account for energy consumed to produce the electricity.

2.2.4 Fuel analysis

The lifetime mass of fuel required for each technology is listed in table 2.9 and compared in figure 2.3. The coal plant requires by far the greatest mass of the three power plants. The

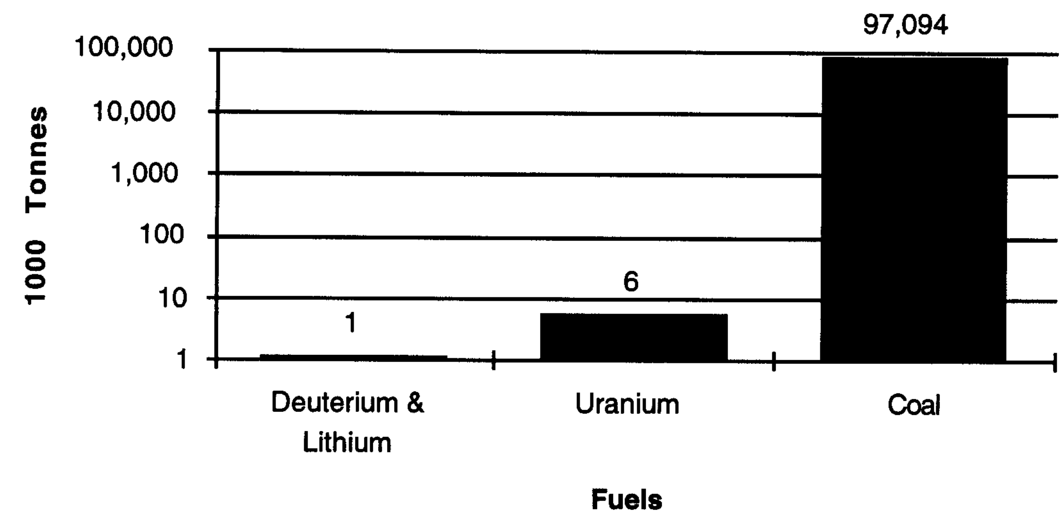

Figure 2.3: Coal Power Plants Handle the Largest Fuel Mass over a 30 FPY Lifetime.

Table 2.8: Fuel Lifetime and Annual Energy Requirements for a 1,000 MW(e) Tokamak Fusion Reactor.[1]

Fuel	Source	Total Energy GJ/GWe	Annual Energy GJ/GWe-yr
Deuterium	[1] p 12	421,200	14,040
Lithium	[1] p 10	1,118,451	37,282
Total		1,539,651	51,322

Table 2.9: Lifetime Fuel Masses for Power Plants.

Type of Fuel	Lifetime Mass (Tonnes per 30 GW(e)-yrs
Coal	97,093,596
Uranium	5,682
Deuterium & Lithium	1,156

[1]Based on 1,000 MW(e) generated at 31.5% efficiency over 30 full power years.

fusion power plant requires 3 tonnes of deuterium over the lifetime of the plant and just over 1,000 tonnes of lithium as a breeding medium for 4 tonnes of tritium. Figure 2.1 showed that the fusion plant had the greatest mass of the three power plants, when fuel was not included. In figure 2.4, the mass of the plants is compared, including fuels. The inclusion of the coal mass makes the total mass more than 100 times that of the fusion plant. The fusion plant still has a greater mass than that of the fission plant when fuel is included.

Despite the huge difference in fuel mass, uranium requires more energy than coal to procure for 1,000 MW(e) power plants. The fuel gathering stage extends throughout the operating lifetime of the plant and includes all the fuel that is required for normal operation and output. Figure 2.5 compares the energy required for the three individual fuel cycles. The energy invested in the deuterium-tritium fuel cycle is significantly less than coal or uranium.

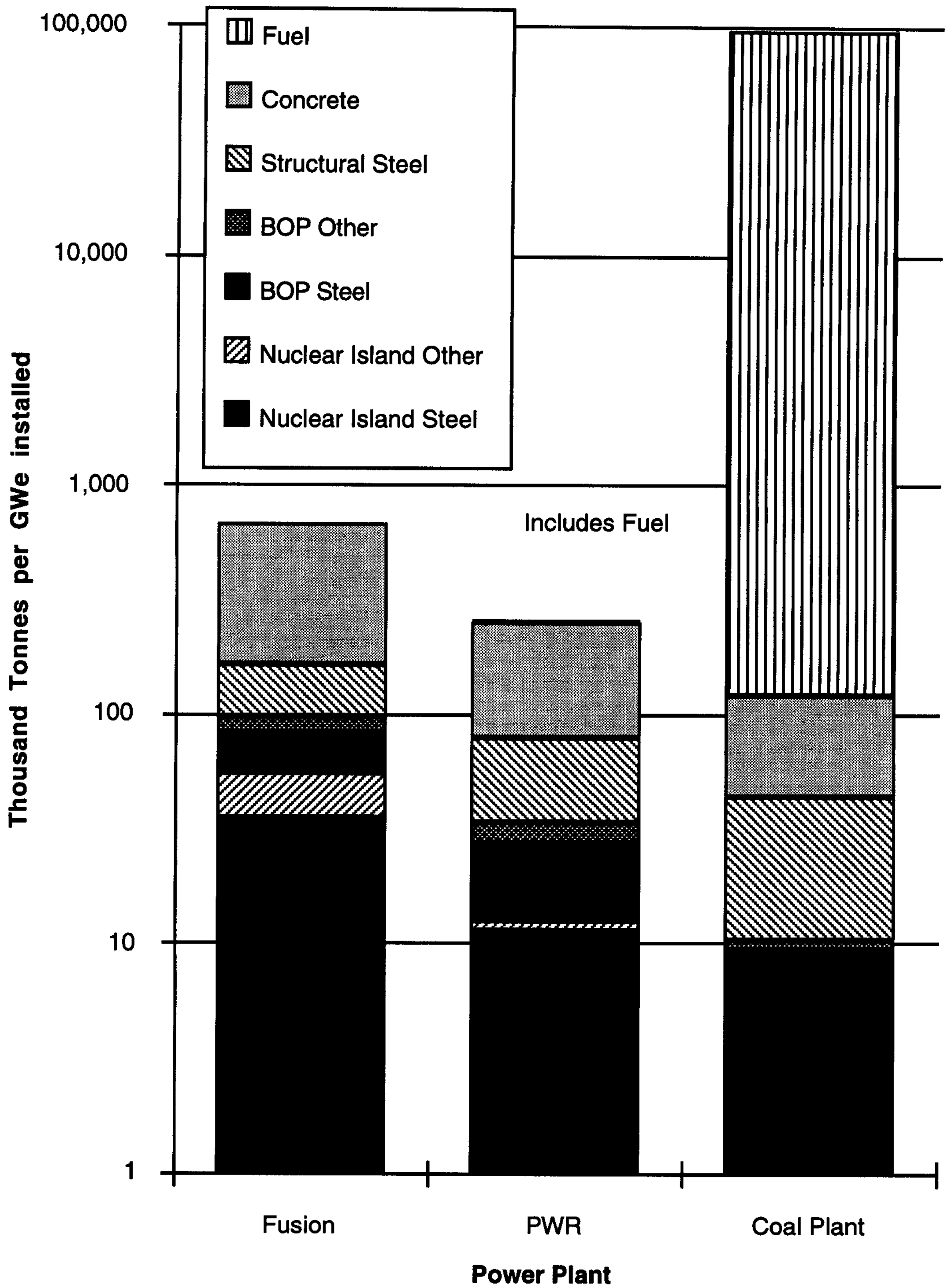

Figure 2.4: The Total Lifetime Mass Required to Produce 30 GW(e)-yrs of Electricity is Largest for Coal Plants.

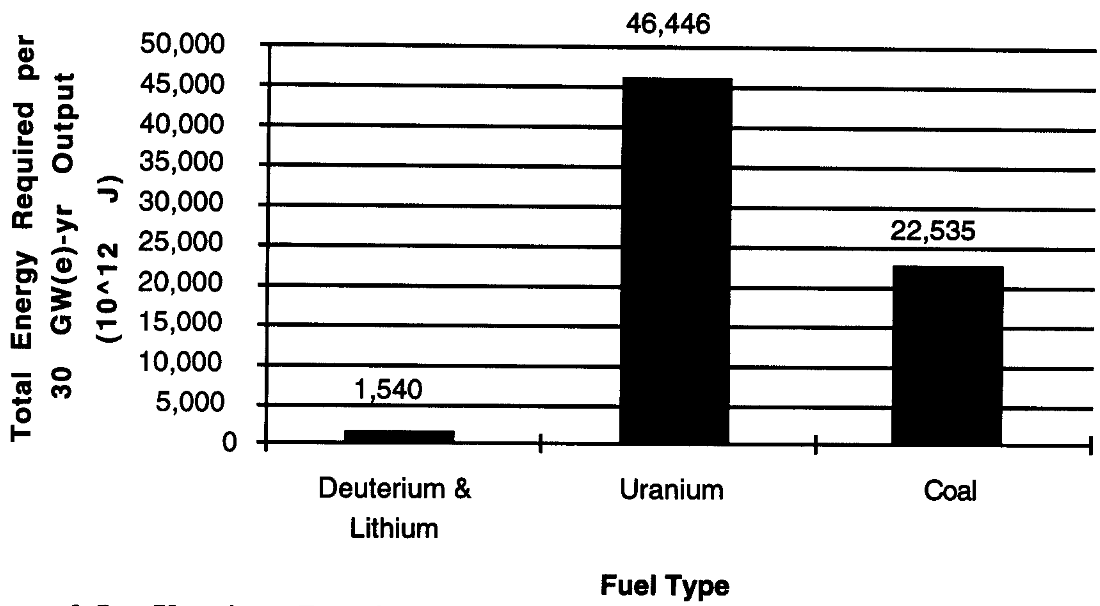

Figure 2.5: Uranium Requires the Most Energy to Gather and Process over a 30 GW(e)-yr Lifetime. (Standardized for 1000 MW(e) Power Plant)

2.3 Construction

For this paper, construction energy expenditures are defined to only include direct energy requirements, such as diesel fuel for machinery and electricity to operate tools, etc. Indirect energy requirements, such as the energy required to mine, manufacture and transport construction materials were included in the material acquisition section (section 2.1).

Figure 2.6 compares the construction energy requirements for each power plant. This figure shows that the fusion power plant requires more than 3 times the energy required to construct the PWR and around 5 times as much as the requirement for the coal plant. Though it is expected that the fusion plant will require more energy to construct due to its greater mass, than the PWR, this difference may actually be too large. The large differences between the data is likely due to the methods used in the corresponding sources. There was only one source for

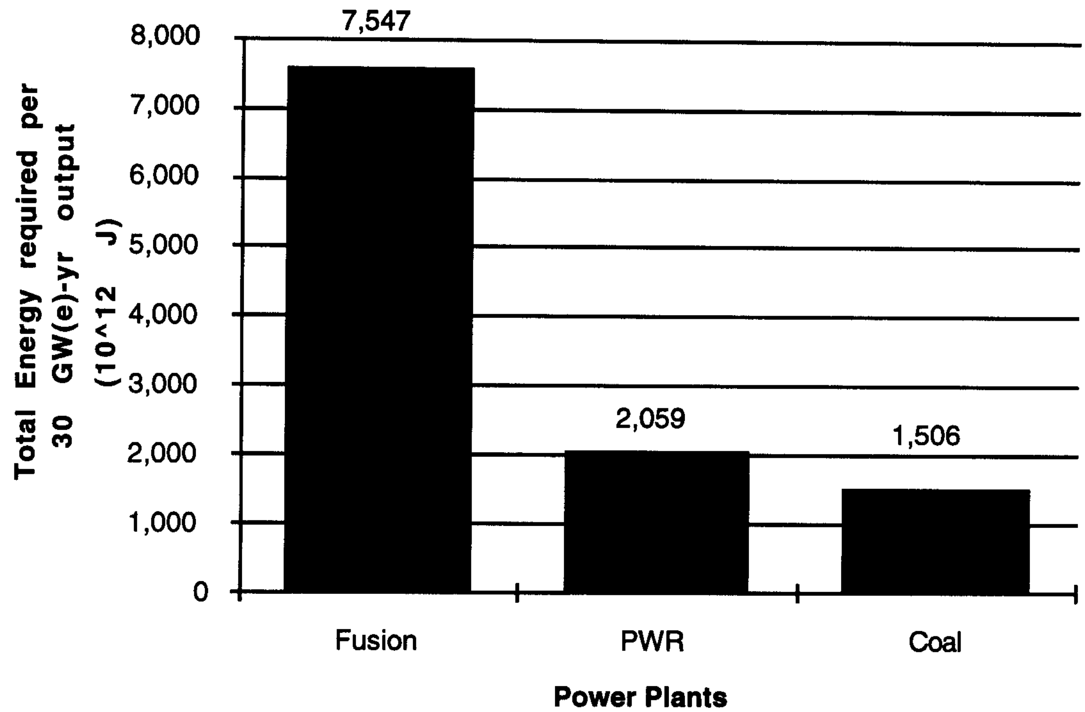

Figure 2.6: The Fusion Power Plant Requires More Energy to Construct than either the Fission or Coal Power Plant.

the fusion data [1], which used the input-output (I/O) method of energy accounting to determine the energy investment. The I/O method is known to generate numbers that are too high for highly sophisticated technologies such as fusion. This method also includes the energy invested in construction materials, which was subtracted out for this paper. Therefore, the 7,547 terrajoules (1 TJ = 10^{12} J) required to construct the fusion power plant does not reflect the 7,400 TJ invested in construction materials. The PWR data is from Rotty [35] who determined the energy investment by first accounting for the amount and types of fuels used. The accuracy of the PWR number is not known, though it may be less precise in comparison to the coal number. In general, the order of ranking of the three technologies as shown if figure 2.6 was as expected. The construction energy requirements for each power plant are listed in tables 2.9 through 2.11.

2.4 Operation

Operation energy expenditures, also known as station use, consists of the energy that is required for operation and maintenance of the power plant once it is producing electricity. This includes the direct energy requirements of fuels used for backup generators that supply fission and fusion plants during repairs. Neither the energy content of the power plants' fuel nor the thermal losses from electrical generation were included due to the differences of the fuels used.

The operating lifetime of the power plants have been standardized to a 40-year lifetime at 75% capacity, or 30 full-power years (FPY). Some of the original data used here was based on 30 years at 75% capacity factor [6, 35]. The differences between this data and the assumptions made in this report primarily effects the amount of fuel required over the plants lifetime and the energy needed for operation. To be consistent, this data was normalized to 30 FPY.

Figure 2.7 shows that a conventional coal-fired power plant consumes considerably more energy for station use than fission or fusion. The primary differences between the operational energy requirements for coal and nuclear plants include the direct energy needs for pollution abatement, such as sulfur scrubbing, particulate removal, moving large quantities of waste air through pollution abatement devices, and transporting coal from in-house storage to the burners would also be a difference. It was assumed for this paper that the coal plant uses low sulfur coal and does not require SO_2 scrubbing. Total station use is based on 5% of the plants gross electrical production, which is equivalent to nearly 53 MW(e) [36]. Other indirect energy requirements, such as the those embodied in lime or limestone production, would normally be included here, also. This paper does not include data for lime, because of the assumed use of low sulfur coal. The operational energy requirements for fusion are considerably less than those for fission or coal and are detailed in tables 2.9 - 2.11.

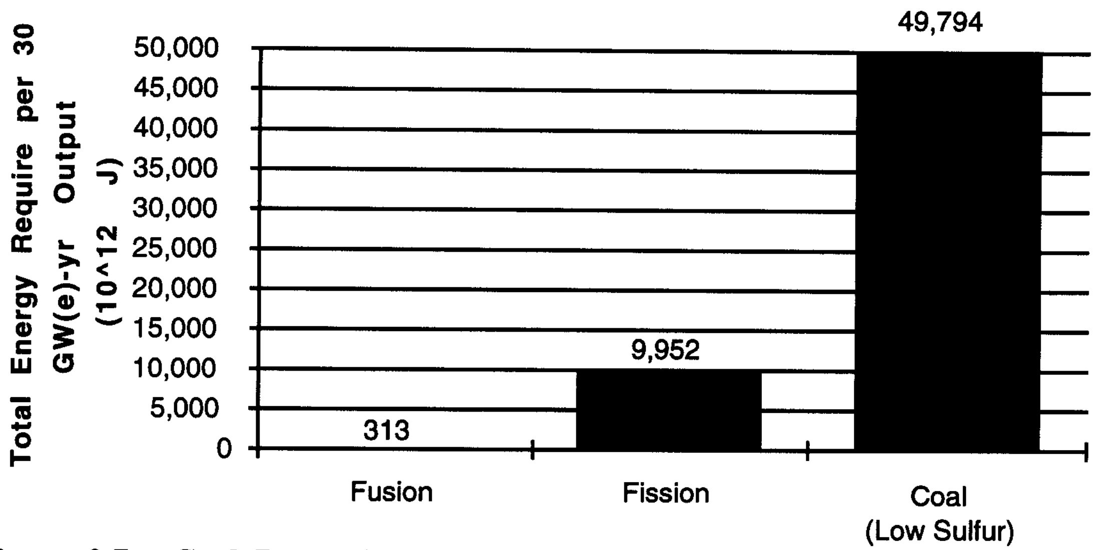

Figure 2.7: Coal Power Plants Require More Energy to Operate than Fission or Fusion Power Plants.

2.5 Decommissioning

Decommissioning a power plant includes all the energy necessary to close down and dismantle the power plants in a safe manner, including waste disposal and site cleanup. Ideally, an assessment of the energy requirements for decommissioning would account for all of these processes. Unfortunately, data for this area is lacking. The only decommissioning data found for this paper [6] included estimates for "immediate dismantlement" and the "safe storage and subsequent dismantlement" of a PWR. The latter only accounts for the preparation of the facility for safe storage and does not consider the energy consumed in deferred dismantlement. The author assumed that the total energy required for both scenarios was basically the same with "immediate dismantlement" requiring 3 GWh more than "preparation for safe storage"[1].

[1]"Immediate Dismantlement" requires 1.4 x (10^{12}) Btu of petroleum products and 2.33 x (10^5) MWhe. "Safe Storage and Subsequent Dismantlement" requires 1.4 x (10^{12}) Btu of petroleum products and 2.3 x (10^5) MWhe[6].

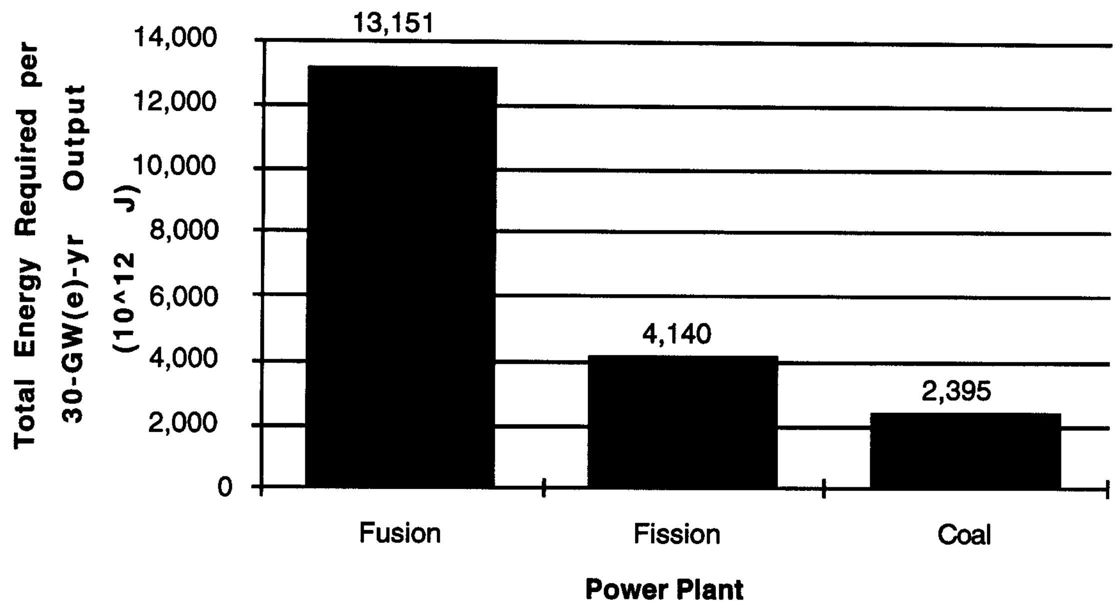

Figure 2.8: Fusion Requires the Most Energy for Decommissioning due to its Larger Mass.

For both scenarios, the energy from petroleum products was assumed by the author to be roughly 75% of the construction energy requirements.

The data for each power plant in figure 2.8 was based on the energy needed for the "immediate dismantlement" of a PWR [6]. For this paper, the data for fusion and coal were scaled linearly from the PWR "immediate dismantlement" totals based on the mass of the plants. This method increases the chances for error, but accounts for the different sizes of the plants. Because of a lack of fissile materials in a coal plant, it is possible that less energy than is listed in this paper will be needed to safely decommission the plant.

2.6 Overall Energy Payback

Tables 2.10 through 2.12 detail the energy investments for coal, fission, and fusion respectively. For the coal plant, the greatest amount of energy investment is required for the power plant's operation, as is shown in table 2.10. The amount of energy invested in operational station use varies between power plants. Station use can consume from 4% of gross electrical production for plants using low sulfur coal [36], to 9.2% of the plants net electrical production when sulfur dioxide (SO_2) scrubbing is required [37]. Figure 2.9 shows a comparison of the station use of 1,000 MW(e) coal plants that require 9.2% of net electrical production and 5% of gross electrical production (5.3% of net) respectively. It is the energy required for pollution abatement technologies, such as SO_2 scrubbers or electrostatic precipitators (ESP), which consume the greatest amount of energy in coal power stations. The private utility, Wisconsin Power and Light (WPL), recently analyzed its coal-fired power plants to assess the energy consumed for station use. The analysis found that the power plants, all of which use low-sulfur, western coal and do not require the use of SO_2 scrubbers (only electrostatic precipitators are used), use 4-6% of gross electrical generation for operational station use [36]. For this paper it was assumed that coal station use requires 5% of gross electrical output. Processes involved in gathering coal also require a significant percentage of the coal plants lifetime energy investment.

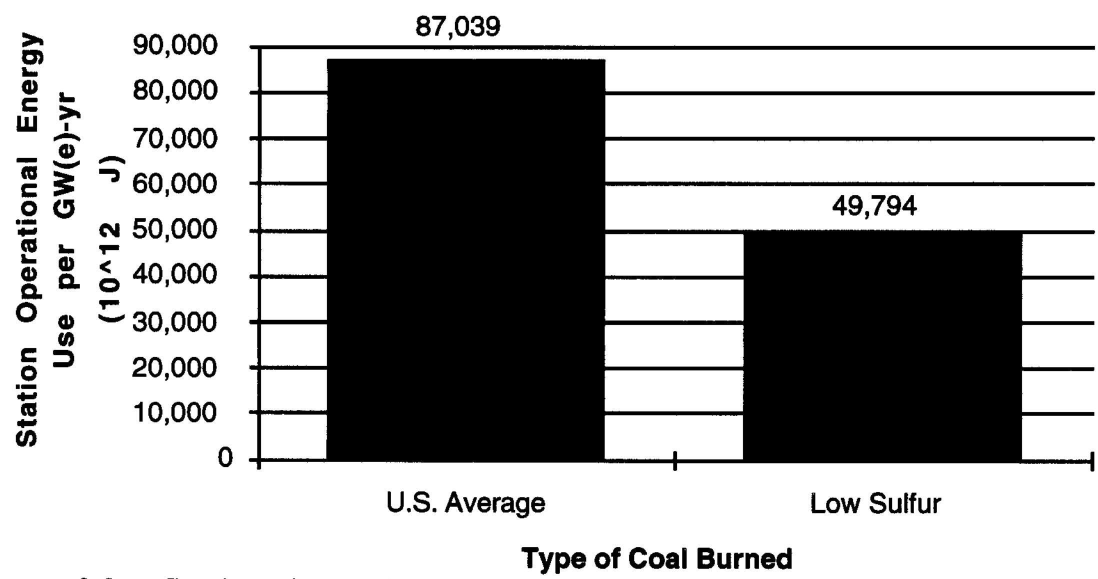

Figure 2.9: Station Operating Energy Use Can Vary Greatly According to the Type of Coal Used and the Corresponding Energy Needed to Meet Air Quality Standards.

Table 2.11 lists the energy investment for different stages of a fission pressurized-water reactor (PWR). The uranium fuel cycle requires the greatest energy investment for the PWR and is larger than similar processes for coal and fusion. The conversion and enrichment stages require over 60% of the total fuel cycle energy investment. The total energy required for construction and station use are also significantly large.

Table 2.10: Lifetime and Annual Energy Investments for a 1,000 MW(e) Conventional Coal Plant.[1]

Process	Source	Total Energy per Installed GW(e) GJ/GW(e)	Annual Energy per GW(e)-yr GJ/GW(e)-yr
Acquisition of Materials and Equipment	See Table 2.5	1,864,302	62,143[2]
Coal Mining	[6] p 249	7,409,212	246,974
Coal Transportation[3]	[24] p 20	15,126,186	504,206
Fuel Cycle Total		22,535,398	751,180
Construction[4]	[6] p 278	1,505,529	50,184
Operation - Station Use[5]	[36]	49,793,684	1,659,789
Decommissioning or land reclamation[6]	[6] p 137	2,395,237	79,841
Total Required Energy		78,094,074	2,603,136

[1]Based on a 1,000 MWe coal plant operated at 31.5% efficiency over 30 full-power years.
[2]Amortized over 30 full power years.
[3]Based on an average haul of 200 miles and 780 KJ per net tonne-mile.
[4]Normalized to 1,000 MW(e). Original data was for a 747 MW(e) system.
[5]Based on 5% of gross electrical output, which equates to roughly 53 MW(e). This is from a utility, Wisconsin Power & Light and is based on an internal study of their own coal plants, which use low-sulfur, western coal and require no scrubbers.
[6]Based on data for the PWR reactor, normalized to account for the difference in the plant's mass.

Construction, material acquisition and decommissioning all require significant amounts of energy for the fusion plant as shown in table 2.12. A fusion power plant will be much more complex, than either the coal or fission plants, requiring more materials and a longer time to construct. Similarly, the large mass will demand more energy for decommissioning. The energy required for operational station use and fuel gathering are relatively small compared to similar processes in the other technologies.

Figure 2.10 compares the total energy invested in the three standardized 1,000 MW(e) power plants. The coal plant has the largest energy investment with large amounts of energy required for operation, while the PWR follows with large investments in fuel cycle processes. As the figure shows, the majority of the fusion plants energy investment comes during plant decommissioning and construction and has low energy requirements in fuel gathering and operation, the two largest consumption processes for coal and fission.

Figure 2.11 illustrates how the energy payback ratio was determined. The energy output for all of the power plants is the same, based on their 1,000 MW net electrical generation. The input for each is based on the total required energy as shown at the bottom of tables 2.9 to 2.11. As can be seen in table 2.13, the fusion power plant has the highest net energy payback, more than twice that of nuclear fission and coal. The fusion plant, with an energy payback ratio of nearly 32, generates more than thirty times as much energy than was invested in material acquisition, construction, fuel acquisition, operation and decommissioning processes. Likewise, the coal plant produces over twelve times as much energy than was expended in its processes. The pressurized water reactor produces nearly 15 times the energy that was originally invested in it.

Table 2.11: Lifetime and Annual Energy Investments for a 1,000 MW(e) PWR with No Recycle.[1]

Process	Source	Total Energy per Installed GW(e) GJ/GW(e)	Annual Energy per GW(e)-yr[(2)] GJ/GW(e)-yr
Acquisition of Materials and Equipment [3]	See Table 2.5	2,155,400	71,847[(4)]
Mining	[35] p 83	4,916,943	163,898
Milling	"	5,085,879	169,529
Conversion	"	10,043,915	334,797
Enrichment[5]	[6] p 110	18,837,540	627,918
Fuel Fabrication	"	6,736,002	224,533
Transportation of U.			
(5,682 MT Nat. U.)	"	103,532	3,451
(822 Tonnes of fuel)	"	388,256	12,942
Waste Storage	"	333,995	11,133
Fuel Cycle Total		46,446,063	1,548,202
Construction	[35] p 66	2,059,047	68,635
Operation			
Auxiliary Diesel Fuels and energy in process materials	[35] p 66	9,951,978	331,733
Cooling Tower		NA[6]	NA
Decommissioning	[6] p 137	4,139,857	137,995
Total Required Energy[7]		64,752,345	2,158,412

[1]Based on a 40 year reactor lifetime at 75% (30 full power years) and 262,800,000 MWh lifetime output. The numbers include both direct and indirect energy consumption in each subcategory.
[2]Averaged over 30 GW(e) years.
[3]Values are based on the average mass from table 2.3.
[4]Amortized over 30 full power years.
[5]Enrichment is via gaseous centrifuge. Based on 215.8 MTSWU per year.
[6]NA = Not Available
[7]The energy of fuels to generate electricity were not included in the total MWh needed for each stage, though a 31.5% efficiency was assumed for electrical generation in the GJ column to account for energy consumed to produce the electricity.

Table 2.12: Lifetime and Annual Energy Investments for a 1,000 MW(e) Tokamak Fusion Reactor.[1]

Process	Source	Total Energy per Installed GW(e) GJ/GW(e)	Annual Energy per GW(e)-yr[(2)] GJ/GW(e)-yr
Acquisition of Materials and Equipment	See Table 2.5	7,428,906	247,630[(3)]
Fuel Acquisition			
Deuterium	[1] p 12	421,200	14,040
Lithium	[1] p 10	1,118,451	37,282
Fuel Cycle Total		1,539,651	51,322
Construction			
Power Plant Construction	[1] p 11	7,266,294	242,210
Fuel Installations Construction	[1] p 11	280,800	9,360
Construction Total		7,547,094	251,570
Operation	[1] p 11	313,200	10,440
Cooling Tower		NA	NA
Decommissioning	[6] p 137	13,151,427[(4)]	434,750
Total Required Energy		29,871,360	995,712

[1]Based on 1,000 MW(e) generated at 31.5% efficiency over 30 full power years.
[2]Averaged over 30 full power years.
[3]Amortized over 30 full power years.
[4]Based on data for the PWR reactor, normalized to account for the difference in the plant's mass.

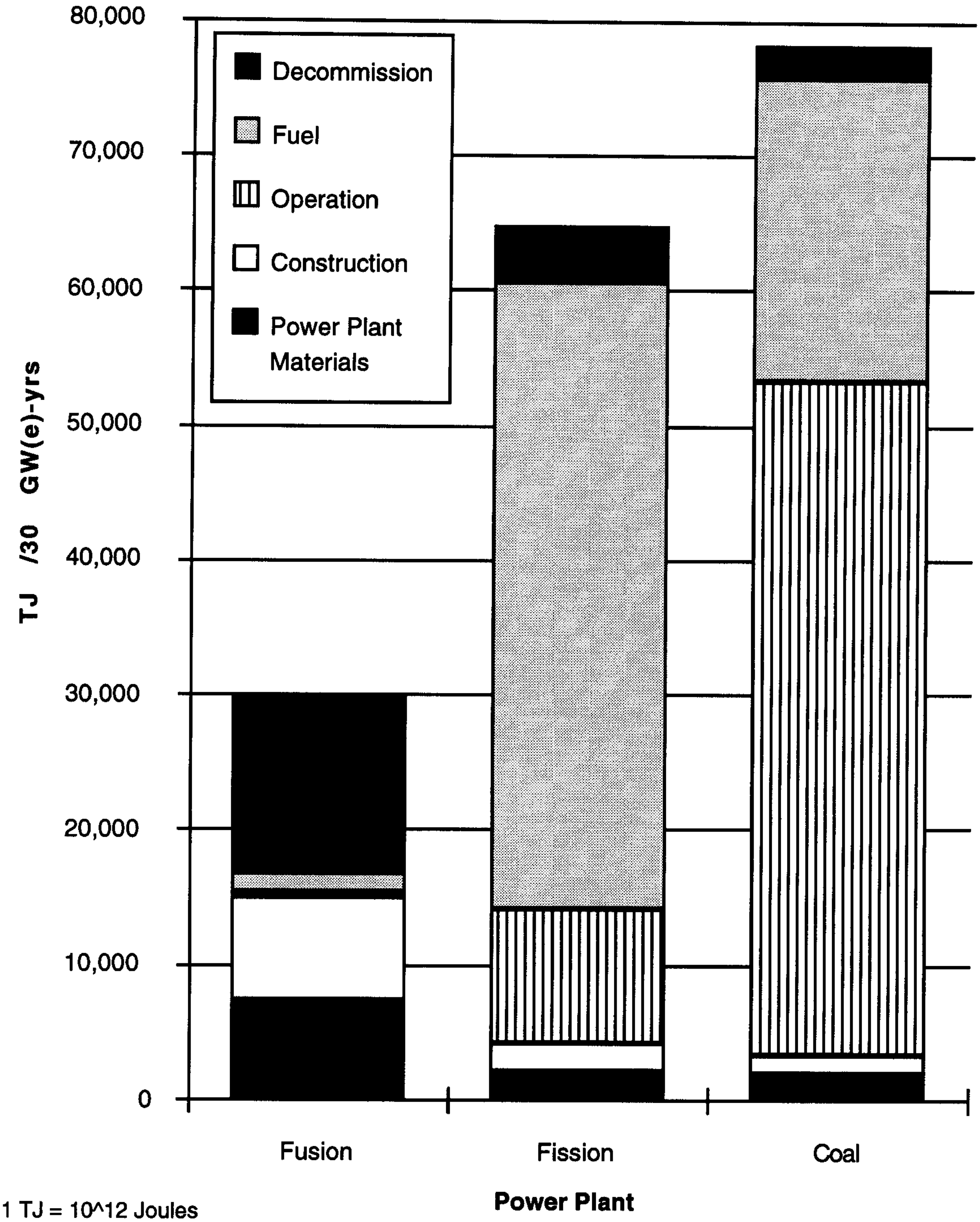

Figure 2.10: The Coal Power Plant Requires the Greatest Lifetime Energy Investment of the Three Power Plants.

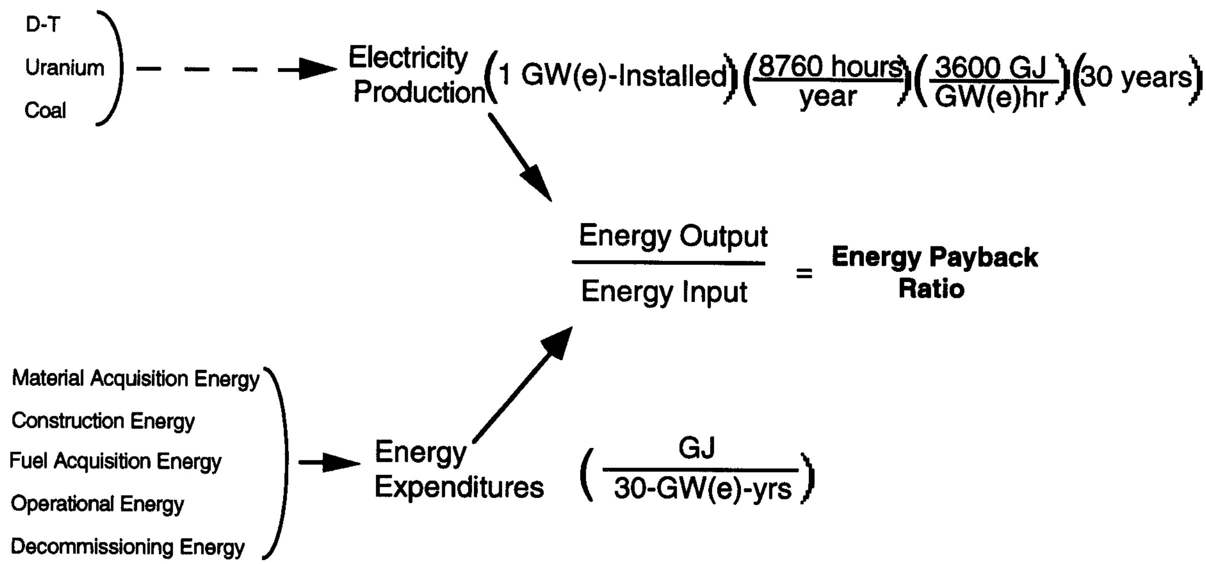

Figure 2.11: The Energy Payback Ratio

Table 2.13: The Energy Balance Ratio of 1,000 MW(e) Power Plants.

Power Plant	Energy Payback
Coal	12
Fission	15
Fusion	32

3.0 Environmental Considerations

Every phase of an electric power plant has an impact on the environment. This section analyzes all environmental impacts that can be quantified with current information. Subsections are broken down by individual pollutants and natural resources rather than by the phases of a power plant like the Energy Expenditures section. It is the individual impact of the pollutants from power production that are unique rather than the phase from which they were emitted.

Under each subsection, the impact of coal, fission and fusion plants is analyzed from cradle-to-grave for the purpose of determining the net emissions of each. In sections 3.1 to 3.4 the gaseous, liquid, radioactive and solid waste emissions respectively will be analyzed for each of the three power plants. The land use requirements of each power plant are examined in section 3.5.

3.1 Gaseous Emissions

The gaseous emissions that are analyzed include carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter (PM). Of the five air pollutants analyzed in this section, CO_2 is the only one that is neither considered a criteria pollutant by the Clean Air Act nor has a National Ambient Air Quality Standard (NAAQS). Table 3.1 summarizes the NAAQ Standards for the pollutants mentioned in this paper. A coal-fired power plant obviously releases the greatest quantity of air pollutants of the three electric power technologies during its operation. For fission and fusion power plants, the greatest amount of emissions are produced during the materials acquisition and fuel processing stages.

The criteria pollutant lead (Pb) was not analyzed here because initial data did not show significant emissions of the pollutant from any stage of power production.

It is well known that SO_2, NO_x, CO and PM all have adverse effects on human health, while SO_2 and NOx are the primary pollutants responsible for acid rain. Nitrogen oxides are also precursors for tropospheric ozone, a criteria pollutant that is not emitted directly, but formed from photochemical reactions involving NO_x as well as organic compounds.

The data for the air emissions from coal plants are based on plants operating in the late 1970's and early 1980's. It is likely that the operational emissions from new coal plants, especially those sited in areas that currently have air pollution problems, may be lower due to improved technology and more stringent legislation for new stationary sources.

Table 3.1: National Ambient Air Quality Primary (Health-Related) Standards[1]

Pollutant	Averaging time	Maximum concentration (approximate equivalent)
Particulate matter (PM_{10})	Annual arithmetic mean 24-hour	50 $\mu g/m^3$ 150 $\mu g/m^3$
Sulfur dioxide (SO_2)[2]	Annual arithmetic mean 24-hour	80 $\mu g/m^3$ (0.03 ppm) 365 $\mu g/m^3$ (0.14 ppm)
Carbon monoxide (CO)[3]	8-hour 1-hour	10 $\mu g/m^3$ (9 ppm) 40 $\mu g/m^3$ (35 ppm)
Nitrogen dioxide (NO_x)	Annual arithmetic mean	100 $\mu g/m^3$ (0.053 ppm)

[1]From ref. [38], p 2-1.
[2]Secondary standard for; averaging time of 3 hours, concentration of 1300 $\mu g/m^3$ (0.50 ppm).
[3]There is no secondary standard for CO.

3.1.1 Carbon Dioxide

It is because of the purported role of CO_2 in global warming that makes it a concern and warrants its inclusion here. The build-up of CO_2 in the atmosphere has been well documented since 1958 when Charles D. Keeling made the first accurate and precise measurements of atmospheric CO_2 [39] and has received recent international political attention, such as at the Framework Convention on Climate Change in May 1992, produced by the United Nations Intergovernmental Committee [40], concerning anthropocentric emissions and potential abatement solutions.

Carbon dioxide is created by the oxidation of carbon during the combustion of carbonaceous materials. The combustion of fossil fuels contributed 49% of all anthropogenic emissions of CO_2 in 1992 [41]. Every phase of operation in a power plant which requires fossil fuel combustion will have CO_2 emissions. Data was primarily available for those stages with significant CO_2 emissions.

The lifetime emissions of carbon dioxide for the power plants were determined for each stage in the lifetime of a power plant. The CO_2 emitted during the material gathering stage for each power plant was determined by first computing a CO_2 emission factor for each type of material found in the power plants. This was done by breaking the energy investment of each material down into specific types of fuels, when possible, and using CO_2 emission factors for each fuel type. The emission factors for the fuels are from references [42-45] and are listed in Appendix A. Information for the quantity and types of fuel consumed in processing a tonne of each material was obtained from references [1, 23-26, 33]. Emission factors for specific materials are listed in Appendix A

The emissions from the material gathering stage are most likely to be slightly lower than in reality, since only fossil fuels and electricity are factored into the material CO_2 emission factor. Other materials used to mine and process the materials, which likely discharge CO_2, such as explosives, were ignored because the emission factors were not found.

Table 3.2 shows the CO_2 emissions from various stages of the three power plants lifetimes. The greatest CO_2 emissions of the three plants occurs during the operation of the coal-fired plant. The production of lime (if it is used) also contributes significant amounts of CO_2 to the atmosphere for the coal plant. This can be attributed to the large mass of the mineral that is required in the scrubbing of SO_x from the power plants waste stream.

The largest CO_2 emissions for fusion come from the acquisition and production of power plant materials. Emissions from the production of materials seems to correlate with the total mass of the plant. Operational CO_2 emissions for the fission plant comes from the use of auxiliary diesel fuel [6]. The fusion plant was assumed to have the same operational emissions as fission for CO_2 as well as the other air pollutants analyzed in following sections.

Overall, the coal plant had the greatest emissions of CO_2, which was eighty times more than those of the fission power plant. The overwhelming majority of CO_2 emissions from the coal plant come from operational coal combustion. The most significant contribution of a fission plant to the emission of CO_2 comes from mining, milling and centrifuge enrichment. Figure 3.1 compares the lifetime emissions of coal to those of fission and fusion.

The data is not complete for any of the power plants. This is true for all the other pollutants as well because of a lack of sufficient data for certain stages. Carbon dioxide emission data was not found for the construction or decommissioning stages for any of the power plants. For the fusion plant, only data for materials acquisition was found. Later versions of this paper will be more detailed.

Table 3.2: The Carbon Dioxide Emissions for Electrical Power Generation Technologies.

Process	References	Annual Emissions (1000 tonnes / GWe-yr)	Lifetime Emissions (1000 tonnes / 30-GWe-yr)
Coal			
Materials[1]	see Appendix A	1.5	44.1
Coal Mining		NA[2]	NA
Construction		NA	NA
Lime Production	see Appendix A	141.9	4,256.2
Power Generation	[41]	2,814.9	84,447.1
Decommission		NA	NA
Total		2,958.3	88,747.4
Fission			
PWR Materials	see Appendix A	2.95 - 6.55	88.47 - 196.56
Uranium Mining	[35]	7.73	232.02
Uranium Milling	[21]	7.84	235.3
Conversion	[21]	3.32	100
Enrichment[3]	[6]	5.87	170.08
Fuel Fabrication	[35]	5.4	161.92
Pumping Water	[21]	0.01	0.19
Construction		NA	NA
Operation[4]	[6]	0.98	39.26
Decommission		NA	NA
Total		34.1 - 37.7 (35.9)	1,027.24 - 1,135.33 (1,081.29)
Fusion			
Materials	see Appendix A	17.44	523.17
Fuel Gathering - Lithium	see Appendix A	1.69	50.7
Construction		NA	NA
Operation[5]		0.98	39.26
Decommission		NA	NA
Total		20.11	613.13

[1]References and emission factors for each material are listed in Table A-1 in Appendix A.
[2]Not Available
[3]Based on centrifuge enrichment.
[4]Based on auxiliary diesel fuel requirements of 12,607(10^6) Btu per year and 73.8 g CO_2/MJ diesel fuel.
[5]Assumed to be the same as that for nuclear fission.

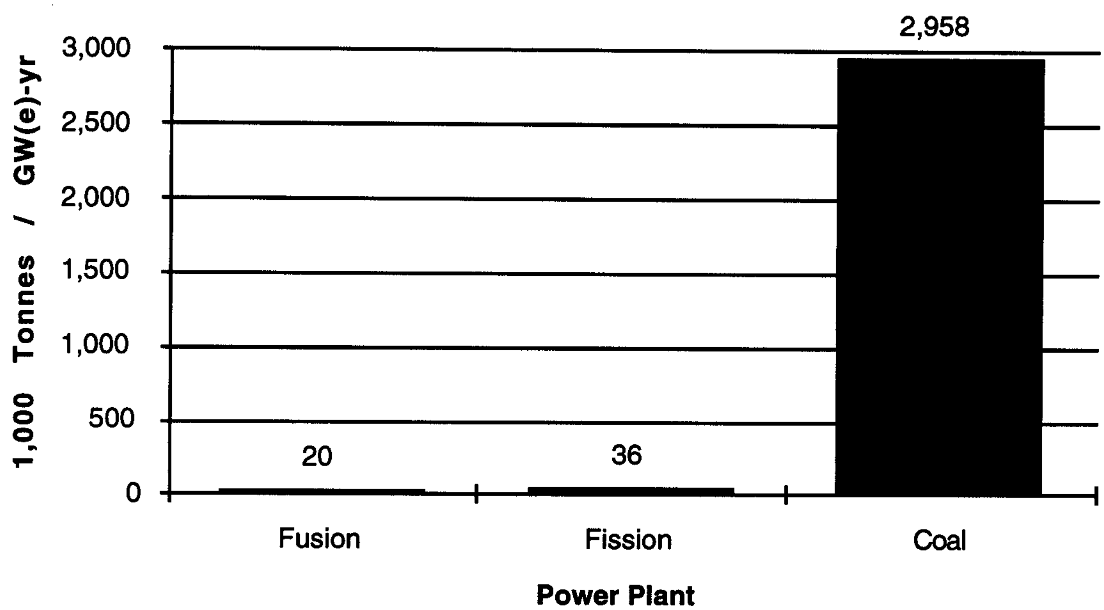

Figure 3.1: The Coal Plant has the Greatest Annual Emissions of Carbon Dioxide.

3.1.2 Sulfur Dioxide

Sulfur dioxide is a product of the combustion of sulfur, which is present in coal and oil and from the roasting of metal sulfide ores. United States coal generally contains between 0.6 and 2.45% sulfur [46], while the sulfur content of fuel oil is between 0.6 and 4.0% by mass [47]. It is estimated that fossil fuel burning is the direct cause of over half of global sulfur emissions [48].

Sulfur dioxide is a toxic agent which can cause respiratory problems, especially in the upper respiratory tract. Human health problems such as pulmonary edema, bronchitis, massive destruction of lung tissue and asphyxiation have been attributed to the criterion pollutant [49]. In high enough concentrations permanent lung damage is also possible. Epidemiological studies have shown that concentrations above 0.25 ppm are usually associated with adverse health effects [46].

Sulfur dioxide is also an ingredient of acid aerosols, which can combine with moisture to become acid rain, which has deleterious effects on vegetation, lakes and soils. Alone, acid aerosols can reduce visibility and erode stone used in buildings, statues and other architecture [50].

The emissions of sulfur oxides over the lifetime of power plants are attributable to the combustion of fossil fuels such as coal and fuel oil as well as the roasting of metal sulfide ores. Coal power generation is responsible for the largest amounts of SO_2 emissions of the three power plants. The range in SO_2 emissions from coal electricity generation are due to the differences in control technology efficiencies, which can remove 85% of SO_x emissions [37], and the sulfur content of the coal used. Western coal, such as that found in Wyoming, has a lower sulfur content then that originating from the eastern and midwest United States.

As shown in table 3.3, the greatest emissions of SO_2 come from the combustion of coal for power production. Other significant amounts of SO_2 are emitted during fission's uranium during the uranium milling stage of fission fuel and the materials acquisition stages of both fission and fusion. The SO_2 emissions from the materials acquisition stage are closely linked with the amount of metal (ferrous and non-ferrous) included in the plant. The production of the fusion power plant materials is responsible for the emission of more than twice as much SO_x as the fission plant and ten times more than the coal plant. These differences are related largely to the larger mass of the fusion plant, which is three times larger than the fission plant and five times larger than the coal plant, and the greater amounts of high alloy, energy intensive metals. Emission factors for individual power plant materials can be found in Appendix A. Small amounts of SO_2 are also emitted during stages of the uranium fuel cycle, lime production and coal materials acquisition. Figure 3.2 compares the annual emissions of SO_2 per GW(e)-year for the three technologies.

Table 3.3: The Sulfur Oxide Emissions for Electrical Power Generation Technologies.

Process	References	Annual Emissions (1000 tonnes / GWe-yr)	Lifetime Emissions (1000 tonnes / 30-GWe-yr)
Coal			
Materials[1]	see Appendix A	0.08	2.33
Coal Mining		NA[2]	NA
Construction		NA	NA
Lime Production	see Appendix A	0.09	2.6
Power Generation	[6, 51]	13.2[3] - 65.7[4]	396 - 1,970
Decommission		NA	NA
Total		13.37 - 65.87 (39.62)	401 - 1,975 (1,188)
Fission			
PWR Materials	see Appendix A	0.19 - 0.72	5.7 - 21.5
Uranium Mining	[6]	0.01	0.26
Uranium Milling	[6]	0.09	2.55
Conversion	[52]	0.03	1.03
UF_6 Production	[21]	0.04	1.16
Enrichment	[6]	0.02	0.65
Fuel Fabrication	[21]	0.03	0.92
Construction		NA	NA
Operation[5]	[6]	0.2	6
Decommission		NA	NA
Total		0.61 - 1.14 (0.87)	18.27 - 34.07 (26.17)
Fusion			
Materials	see Appendix A	1.4	42
Fuel Gathering - Lithium	see Appendix A	0.01	0.4
Construction		NA	NA
Operation[6]		0.2	6
Decommission		NA	NA
Total		1.61	48.4

[1]References and emission factors for each material are listed in Table A-3 in Appendix A.
[2]Not Available
[3]From ref. [6], which assumed the use of uncleaned western coal, a 99.5% ESP efficiency and 85% flue gas desulfurization (FGD).
[4]From ref. [34].
[5]Based on auxiliary diesel fuel requirements of 12,607(10^6) Btu per year and 0.097 g SO_x/MJ diesel fuel.
[6]Assumed to be the same as that for nuclear fission.

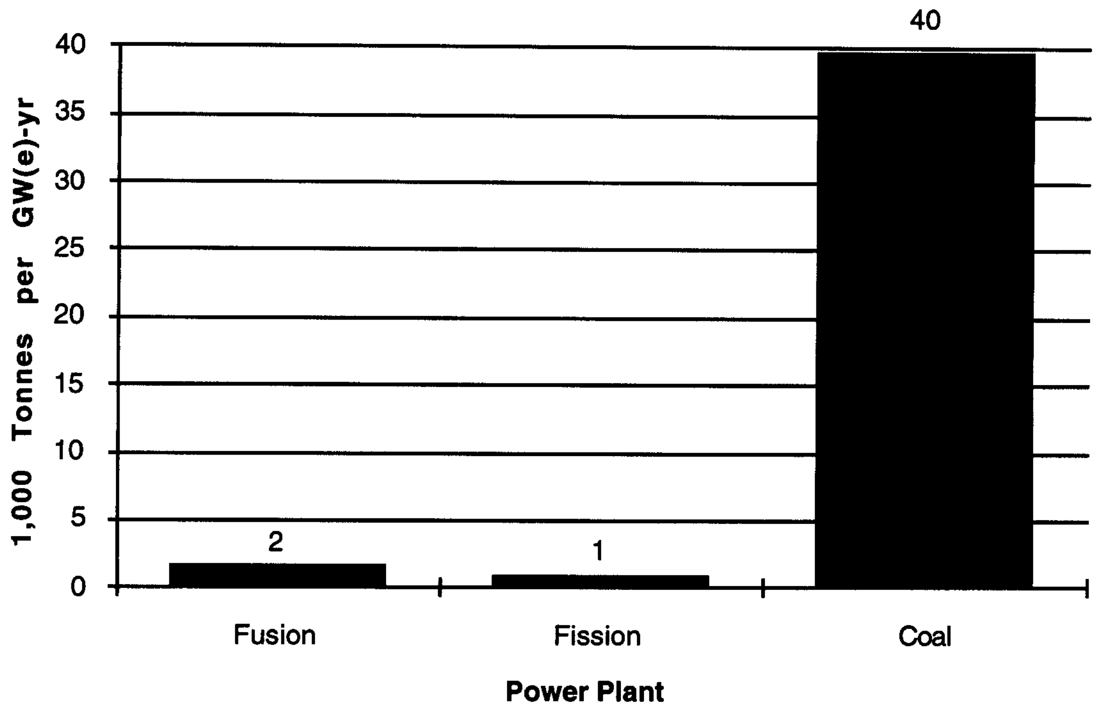

Figure 3.2: The Coal Plant has the Greatest Annual Sulfur Dioxide Emissions of the Three Technologies.

3.1.3 Nitrogen oxides

Nitrogen oxides (NO_x) are produced by the oxidation of both organically bound nitrogen in fossil fuels (particularly coal) and atmospheric nitrogen during combustion at high temperatures and/or pressures. Most emissions of NO_x are in the form of nitrogen monoxide (NO) and nitrogen dioxide (NO_2). Though the primary form of NO_x emissions are as NO, this relatively innocuous gas oxidizes readily to NO_2, a known irritant of the lungs, once it reaches the atmosphere.

Nitrogen dioxide is not only a toxic that has deleterious effects on human health, it also is a precursor for the formation of ozone and is an ingredient in acid rain. Through a photochemical reaction, NO_2 is converted to ozone (O_3) and peroxyacyl nitrates (PAN). Ozone is the principal component of smog and is responsible for breathing problems, reduced lung function, asthma, eye irritation, reduced resistance to colds and infection, nasal congestion and may also speed up the aging of lung tissue. PAN is a known eye irritant [50].

NO_2 is also an ingredient of acid aerosols, which damage lakes, trees and soils as acid rain, as well as reduce visibility and damage stone. Ozone can damage plants and trees, while the subsequent smog can reduce visibility.

Control technologies can usually remove 40% of NO_x produced [37]. The reduction of NO_x emissions often consists of the reduction of peak temperatures, gas residence time, and oxygen concentrations in the flame zone [39]. The tradeoff for such modifications, however, is often an increase in the emissions of carbon monoxide.

Table 3.4 lists the emissions of nitrogen oxides during different stages of the power plants' lifetimes. The primary source of NO_x emissions comes from the combustion of coal for power generation in the coal-fired power plant. Uranium mining and milling as well as the operation of the nuclear fission power plant also contribute sizable quantities of NO_x. Emissions of NO_x during the operation of the fission power plant are associated with oil and diesel support systems. NO_x emissions associated with the production of materials are relatively small for each power plant. A comparison of the NO_x emissions per GW(e)-year is shown in figure 3.3.

Table 3.4: The Nitrogen Oxide Emissions for Electrical Power Generation Technologies.

Process	References	Annual Emissions (1000 tonnes / GWe-yr)	Lifetime Emissions (1000 tonnes / 30-GWe-yr)
Coal			
Materials[1]	see Appendix A	0.005	0.14
Coal Mining		NA[2]	NA
Construction		NA	NA
Lime Production	see Appendix A	0.53	16
Power Generation	[6, 20]	21[3] - 25.04[4]	630 - 751
Decommission		NA	NA
Total		21.54 - 25.58 (23.56)	646.14 - 767.14 (706.64)
Fission			
PWR Materials	see Appendix A	0.01	0.2 - 0.39
Uranium Mining	[6]	0.11	3.52
Uranium Milling	[6]	0.09	2.55
UF_6 Production	[21]	0.01	0.40
Enrichment	[6]	0.02	0.52
Fuel Fabrication	[21]	0.01	0.24
Fuel Transportation	[21]	neg.	0.10
Construction		NA	NA
Operation[5]	[6]	0.24	7.2
Decommission		NA	NA
Total		0.49	14.73 - 14.92 (14.83)
Fusion			
Materials	see Appendix A	0.04	1.3
Fuel Gathering - Lithium	see Appendix A	0.01	0.16
Construction		NA	NA
Operation[6]		0.24	7.2
Decommission		NA	NA
Total		0.29	8.66

[1]References and emission factors for each material are listed in Table A-3 in Appendix A.
[2]Not Available
[3]From ref. [20].
[4]From ref. [6].
[5]Based on auxiliary diesel fuel requirements of 12,607(10^6) Btu per year and 1.45 g NO_x/MJ diesel fuel.
[6]Assumed to be the same as that for nuclear fission.

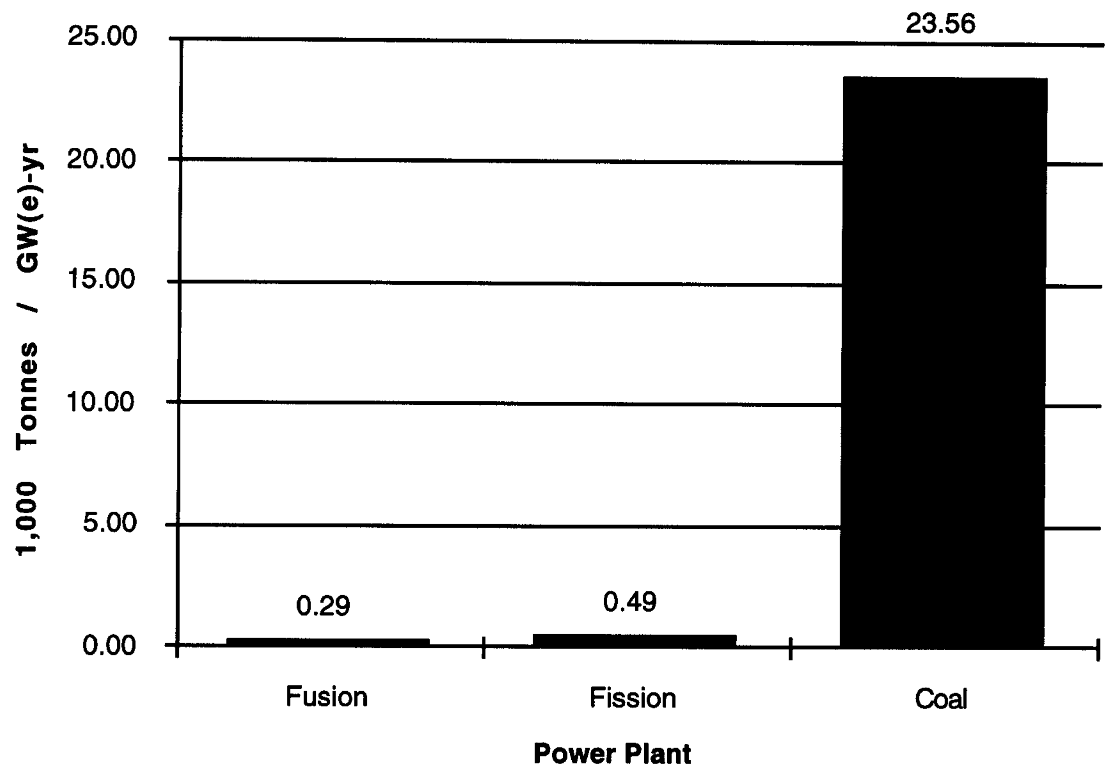

Figure 3.3: The Coal Plant has the Greatest Annual Emissions of Nitrogen Oxides of the Three Technologies.

3.1.4 Carbon Monoxide

Carbon monoxide (CO) is a product of the incomplete or low temperature combustion of carbonaceous materials, such as fossil fuels, and is likely to appear when a concerted effort is made to control NO_x emissions. Though motor vehicles are the source of over half of the global CO emissions, coal combustion and industrial processes that pertain to both the production of energy and the production of power plant materials also contribute a significant amounts of the pollutant [53].

Carbon monoxide has an affinity for hemoglobin, with which it combines to form carboxyhemoglobin (COHb), which impairs bloods ability to carry oxygen which is necessary for cells and tissue to work, slowing down the persons reflexes and motor functions in the process [53]. People who have heart or circulatory problems or damaged lungs are particularly susceptible to the danger of CO. Carbon monoxide has no known effects on the environment outside of its impact on human and mammalian health.

Table 3.5 lists the emissions of carbon monoxide from various stages of electrical production from the three power plants. The amount of CO emissions from coal-fired power generation can vary widely. The higher value of CO emissions from this stage is significantly higher than any other stage of electrical power generation of the three power plants, while the lower value would be lower than several other stages. Carbon monoxide emissions from uranium mining are significantly high and are the likely result from diesel fuel combustion in land movers and other heavy machinery. Materials processing accounts for the greatest emissions of CO for the fusion plants lifecycle. The CO emissions of each technology are compared in figure 3.4 .

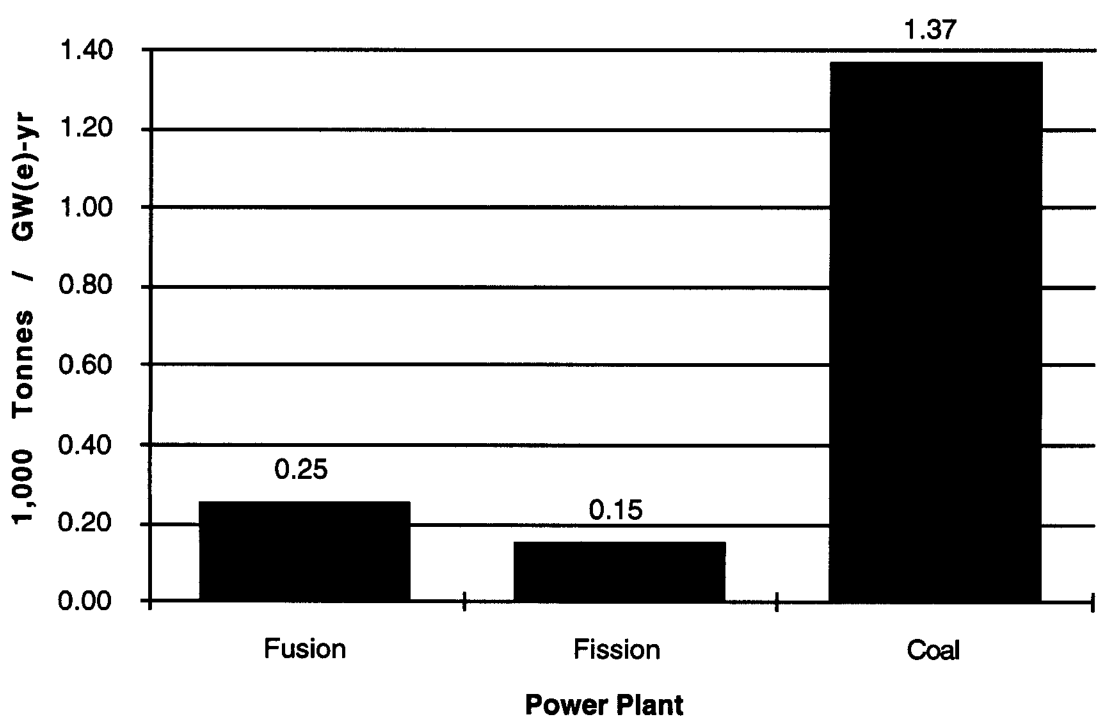

Figure 3.4: The Coal Plant has the Greatest Annual Emissions of Carbon Monoxide of the Three Technologies.

Table 3.5: The Carbon Monoxide Emissions for Electrical Power Generation Technologies.

Process	References	Annual Emissions (1000 tonnes / GWe-yr)	Lifetime Emissions (1000 tonnes / 30-GWe-yr)
Coal			
Materials	see Appendix A	0.08	2.33
Coal Mining		NA[1]	NA
Construction		NA	NA
Lime Production	see Appendix A	0.14	4.34
Power Generation	[6, 34]	0.1[2] - 2.19[3]	3.11 - 65.70
Decommission		NA	NA
Total		0.32 - 2.41 (1.37)	9.78 - 72.37 (41.08)
Fission			
PWR Materials	see Appendix A	0.02 - 0.1	0.61 - 3.04
Uranium Mining	[6]	0.07	2.14
Uranium Milling	[21]	neg.	0.01
UF_6 Production	[21]	neg.	0.01
Enrichment	[6]	neg.	0.10
Fuel Fabrication	[21]	neg.	0.01
Construction		NA	NA
Operation[4]	[6]	0.01	0.16
Decommission		NA	NA
Total		0.1 - 0.18 (0.14)	3.14 - 5.57 (4.36)
Fusion			
Materials	see Appendix A	0.25	7.44
Fuel Gathering - Lithium	see Appendix A	neg.	0.02
Construction		NA	NA
Operation[5]		0.01	0.16
Decommission		NA	NA
Total		0.26	7.62

[1]Not Available
[2]From ref. [6].
[3]From ref. [34].
[4]Based on auxiliary diesel fuel requirements of 12,607(10^6) Btu per year and 0.41 g CO/MJ diesel fuel.
[5]Assumed to be the same as that for nuclear fission.

3.1.5 Particulate Matter

Particulates are very small diameter solids or liquids that remain suspended in air in exhaust gases. There are three basic processes by which particulates are released into the air. One is from the crushing and grinding of ores which can create fine dusts. Combustion processes, especially those involving fossil fuels, are a second process, which can emit small particles of noncombustible ash or incompletely burned soot. A third process occurs once pollutants enter the atmosphere, where they can undergo gas conversion reactions which can create aerosols and other particles [39].

Though particulate matter (PM) can come in a wide range of sizes, it is those particles smaller than 10 microns (μm), which are of concern to human health because of their ability to penetrate deep into the lungs. These particles, referred to as PM_{10}, are monitored by the Environmental Protection Agency (EPA) and have national ambient air quality standards (NAAQS), which can be found in table 3.1.

Particulate matter can carry heavy metals and other toxic elements such as lead, mercury and arsenic, as well as known carcinogens, such as nickel and chromium. Such trace elements can have negative impacts on human health as well as aquatic and terrestrial ecosystems. Human health can be directly impacted by trace elements emitted into the air as well as indirectly by those that end up in the food or water supply via particulate deposition on the soil and water bodies.

Emissions data for the acquisition and production of materials is less complete for particulates than for the other pollutants. The correlation of particulate emission factors between different metals is more difficult to make and therefore was not attempted in this paper. It is standard for pollution control technologies on larger industrial processes, which normally include cyclones and electrostatic precipitators (ESP), to remove 99.5% of uncontrolled particulate emissions [37].

Table 3.6 lists the particulate matter emissions from various stages of electrical production from the three power plants. For a coal plant, the largest amounts of particulate emissions come from power generation and coal cleaning, though low sulfur coal does not normally require cleaning. Most particulate emissions for a fission plant are emitted during the operation and in material acquisition processes. Emissions during operation of a fission plant primarily result from oil or diesel support systems [6]. Materials acquisition processes account for the majority of the fusion tokamak particulate emissions. A comparison of the power plants' emissions per GW(e)-year is shown in figure 3.5.

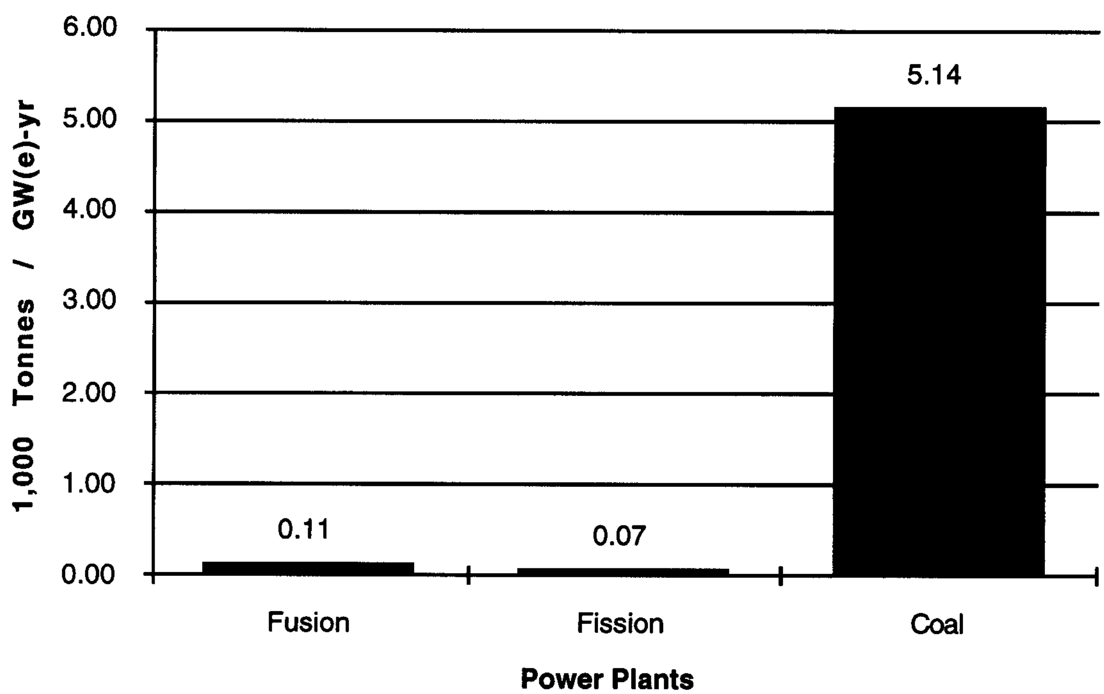

Figure 3.5: The Coal Plant has the Greatest Annual Emissions of Particulate Matter.

Table 3.6: The Particulate Matter Emissions for Electrical Power Generation Technologies.

Process	References	Annual Emissions (1000 tonnes / GWe-yr)	Lifetime Emissions (1000 tonnes / 30-GWe-yr)
Coal			
Materials	see Appendix A	0.01	0.43
Coal Mining		NA	NA
Coal Cleaning	[37]	3.17(1)	95
Construction		NA	NA
Lime Production		NA	NA
Power Generation	[6],[37]	0.6(2) - 3.33	17.87 - 99.96
Decommission		NA	NA
Total		3.78 - 6.51 (5.14)	113.3 - 194.99 (154.15)
Fission			
PWR Materials	see Appendix A	0.01 - 0.03	0.3 - 0.89
Uranium Mining	[6]	neg.	0.08
Uranium Milling	[21]	0.01	0.39
UF_6 Production	[21]	0.01	0.30
Enrichment	[6]	neg.	0.03
Fuel Fabrication	[21]	0.01	0.24
Construction		NA	NA
Operation	[6]	0.02	0.52
Decommission		NA	NA
Total		0.06 - 0.13 (0.07)	1.86 - 2.45 (2.16)
Fusion			
Materials	see Appendix A	0.1	2.89
Fuel Gathering - Lithium	see Appendix A	neg.	0.04
Construction		NA	NA
Operation[3]		0.02	0.52
Decommission		NA	NA
Total		0.12	3.45

[1]Based on the mean of a range of 18,000 - 29,500 MT/yr. A control efficiency of 90% was assumed.
[2]From ref. [6], which assumed a 99.5% ESP efficiency and the use of uncleaned coal.
[3]Assumed to be the same as that for nuclear fission.

3.1.6 Total Air Pollutants

The coal-fired power plant generates more air emissions over its lifetime than either the fission or fusion power plants. The lifetime amounts of each pollutant from the various power plants are listed in table 3.7 and collectively compared in figure 3.6. Figure 3.6 excludes carbon dioxide because the quantity of this pollutant dwarfs the total emissions of the other pollutants. For pollutants that have a range of values in the tables, the mean value was used for the

Table 3.7: Total Lifetime Air Pollutants for Electricity Generation.

Pollutant	Annual Emissions (1000 Tonnes / GW(e)-yr)	Lifetime Emissions (1000 Tonnes / 30-GW(e)-yrs)
Coal		
Carbon Dioxide	2,958	88,747
Sulfur Dioxide	40	1,188
Nitrogen Dioxide	24	707
Carbon Monoxide	1	41
Particulate Matter	5	154
Total	3,028	90,837
Total exl. CO_2	70	1,790
Fission		
Carbon Dioxide	366	10,986
Sulfur Dioxide	0.9	26
Nitrogen Dioxide	0.5	15
Carbon Monoxide	0.1	4
Particulate Matter	0.1	2
Total	367	11,033
Total exl. CO_2	1.6	48
Fusion		
Carbon Dioxide	20	613
Sulfur Dioxide	1.6	48
Nitrogen Dioxide	0.3	9
Carbon Monoxide	0.3	8
Particulate Matter	0.1	3
Total	22	683
Total exl. CO_2	2.3	70

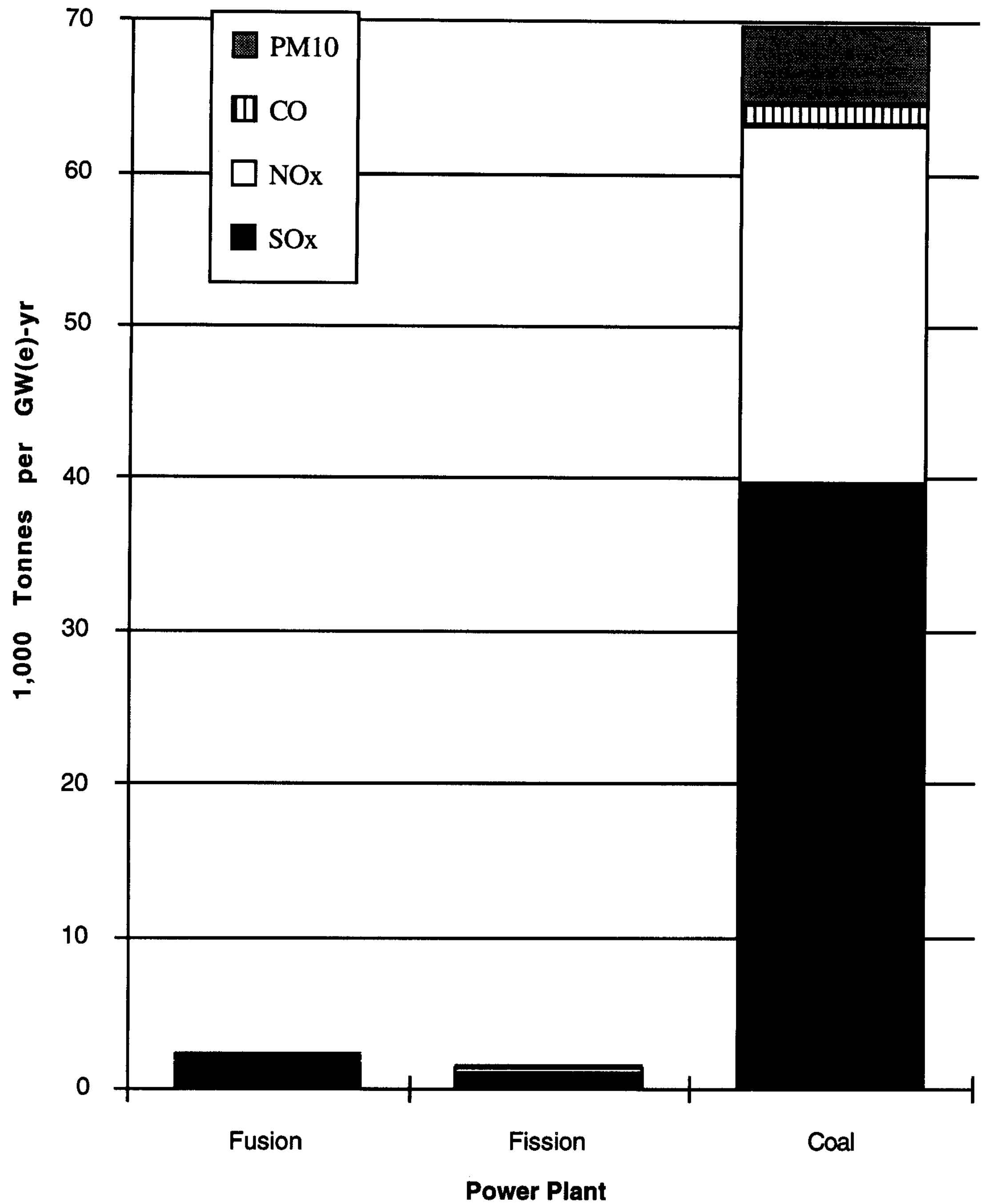

Figure 3.6: The Coal Plant has the Greatest Annual Emissions of Criteria Air Pollutants. Carbon Dioxide is Excluded in this Figure.

purpose of graphing. As mentioned earlier, the totals do not include all phases of the power plants' lifetimes due to a lack of sufficient data. Notable are omissions of pollutants from the construction and decommissioning stages for all three plants.

3.2 Aqueous Emissions

Water consumed in the industrial processes involved in generating electricity is quantified in this section. Data that deserves inclusion in this section includes: water emitted from power plant cooling processes, fuel acquisition processes, and water used to suppress fugitive dust during mining and the storage of materials and fuels. Water emissions data was not found for material acquisition, power plant construction and decommissioning stages, but should be included in future versions of this paper.

Water degraded or contaminated from non-industrial processes, such as acid mine drainage, which is rain and groundwater contaminated by elements exposed from mining processes, would ideally be quantified here as well, but is not due to a lack of available data. Acid mine drainage potentially exposes millions of people to toxic elements through the food chain and groundwater. It's impact is of greatest concern in places where water treatment facilities or alternative sources of water do not exist [46].

There are three primary means of releasing industrial water to the environment: evaporation to the air, discharging to the ground and discharging to natural bodies of water. Not all of the water used in power production is discharged polluted. Much of the water is treated before it is discharged and in circumstances where wet draft cooling towers are used, evaporation accounts for the primary usage of the resource.

To dissipate heat, power plants can use dry cooling towers, wet cooling towers or hybrids. It was assumed for this paper that each power plant uses a wet-cooling tower to dissipate sensible heat. Cooling towers are closed-loop systems which take in make-up water to replace water that is lost to evaporation, drifting or blowdown processes. Drift is unevaporated water that becomes entrained in air and is carried from the system as drizzle or fine mist. Blowdown, also known as bleed, is water that is intentionally discharged from the system and replaced by fresh water [54]. In contrast to closed-loop systems, once-through systems discharge heated cooling water directly into bodies of water. These systems are becoming less common in the United States due to concerns about the impact of heated discharge water on aquatic ecosystems [37].

Tables 3.8 through 3.10 detail the water effluents from a coal-fired plant, PWR and fusion plant respectively. For the coal-fired power plant, the only data available was from the operational stage and most of that comes from cooling processes. The PWR uses the most water of the three power plants, with significant differences due to the water required during uranium enrichment. Though not stated in the original data, it is assumed that the enrichment cooling processes use the once-through method of cooling, which is much more water intensive then cooling towers. Also, this data is for gaseous diffusion enrichment, which is much more energy intensive than centrifuge and therefore requires more water for cooling. Future versions of this paper should use gas centrifuge data, which was not available for this one. Because the PWR and fusion tokamak have a smaller thermal efficiency than the coal power plant, 33% compared to 40%, the water required to dissipate sensible heat is greater. Figure 3.3 compares the annual water requirements for the three technologies. For a more precise comparison of these technologies, more information is needed for both the coal and deuterium-tritium fuel cycles.

Table 3.8: Annual Water Effluents for Electrical Production from a Coal-Fired Power Plant.

Process	Source	Discharged To Air	Discharged To Water Bodies	Discharged To Ground
		10^6 m^3 /GW(e)-yr	10^6 m^3 /GW(e)-yr	10^6 m^3 /GW(e)-yr
Material Acquisition	NA[1]	-	-	-
Coal Mining	NA	-	-	-
Power Plant Construction	NA	-	-	-
Operation[2]				
Evaporation	[54]	10.1	0	0
Blowdown[3]	[54]	0	1.3 - 9.8	0
Drift[4]	[54]	0.2 - 0.27	0	NA
Solid Waste Handling[5]	[37]	0	1.86 - 6.05	NA
Decommissioning	NA	-	-	-
TOTAL		10.3 - 10.4	3.2 - 15.9	NA

[1]Not Available

[2]Based on a 1,000 MW(e) coal plant and 40% thermal efficiency.

[3]The low number is based on a cooling range of 45° F and 13.4% of evaporation; the high number is based on a cooling range of 15° F and 97% of evaporation.

[4]The low number is based on a cooling range of 45° F and 2% of evaporation; the high number is based on a cooling range of 15° F and 2.67% of evaporation.

[5]The numbers are based on 16% and 30% of the cooling tower requirements respectively.

Table 3.9: Annual Water Effluents for Electrical Production from a PWR.

Process[1]	Source	Discharged To Air	Discharged To Water Bodies	Discharged To Ground
		10^6 m^3 /GW(e)-yr	10^6 m^3 /GW(e)-yr	10^6 m^3 /GW(e)-yr
Uranium Mining	[21]	0	0	0.47
Uranium Milling	[21]	0.25	0	NA
Uranium Hexafluoride production	[21]	0.013	0.09	NA
Uranium Enrichment	[21]	0.32	41.64	NA
Fuel Fabrication	[21]	0	0.02	NA
Power Plant Construction	NA[2]	-	-	-
Material Acquisition	NA	-	-	-
Operation[3]				
Evaporation	[54]	15.1	0	0
Blowdown[4]	[54]	0	2 - 14.7	0
Drift[5]	[54]	0.3 - 0.4	0	NA
High-level Radioactive Waste Management	[21]	0.001	0.001	NA
Decommissioning	NA	-	-	-
TOTAL		15.99	43.75 - 56.45	0.47

1Normalized to the annual fuel requirements of a 1,000 MW(e) LWR.
2Not Available
3Based on a 1,000 MW(e) PWR and 33% thermal efficiency.
4The low number is based on a cooling range of 45° F and 13% of evaporation; the high number is based on a cooling range of 15° F and 97.3% of evaporation.
5The low number is based on a cooling range of 45° F and 2% of evaporation; the high number is based on a cooling range of 15° F and 2.67% of evaporation.

Table 3.10: Annual Water Effluents for Electrical Production from a Nuclear Fusion Tokamak Power Plant.

Process	Source	Discharged To Air	Discharged To Water Bodies	Discharged To Ground
		10^6 m^3 /GW(e)-yr	10^6 m^3 /GW(e)-yr	10^6 m^3 /GW(e)-yr
Fuel Acquisition	NA[1]	-	-	-
Material Acquisition	NA	-	-	-
Power Plant Construction	NA	-	-	-
Operation[2]				
Evaporation	[54]	15.1	0	0
Blowdown[3]	[54]	0	2 - 14.7	0
Drift[4]	[54]	0.3 - 0.4	0	NA
Decommissioning	NA	-	-	-
TOTAL		15.4 - 15.5	2 - 14.7	0

[1]Not Available
[2]Based on a 1,000 MW(e) power plant and 33% thermal efficiency.
[3]The low number is based on a cooling range of 45° F and 13% of evaporation; the high number is based on a cooling range of 15° F and 97.3% of evaporation.
[4]The low number is based on a cooling range of 45° F and 2% of evaporation; the high number is based on a cooling range of 15° F and 2.67% of evaporation.

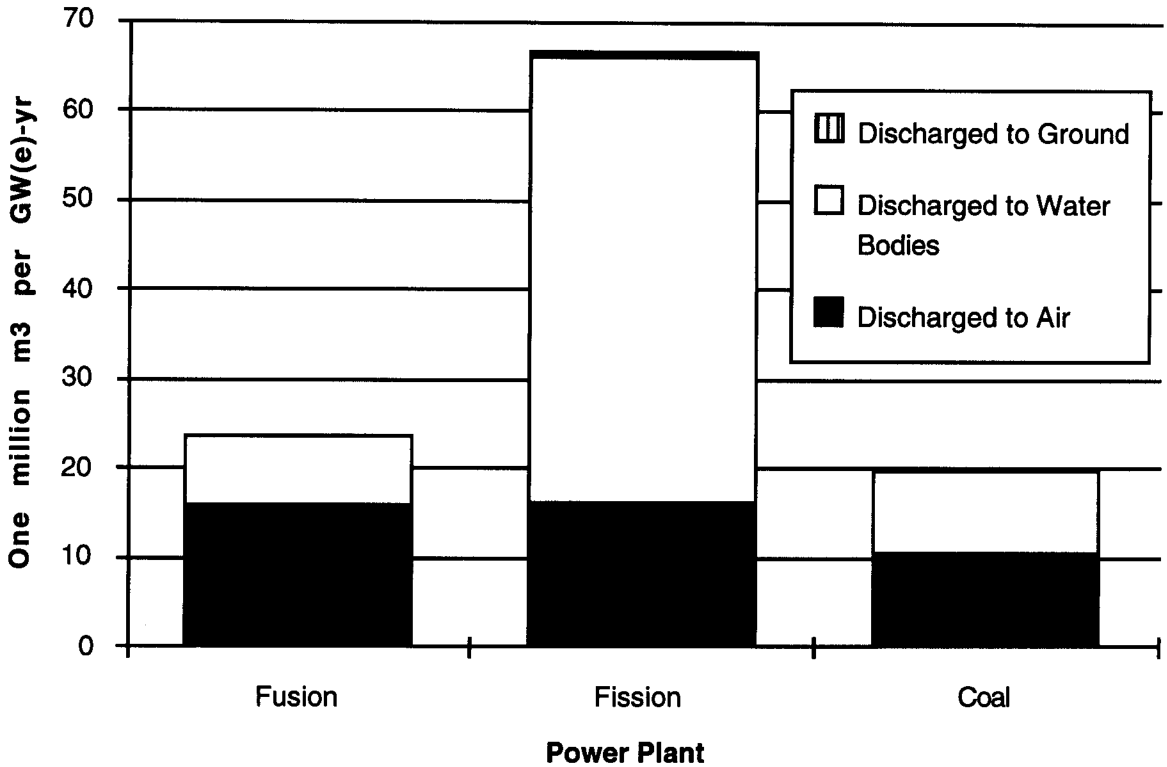

Figure 3.7: Electricity Generated from Fission Requires a Greater Amount of Water per GW(e)-yr than Coal or Fusion.

3.3 Radioactive Emissions

The radioactive emissions include radioactive isotopes that are expelled into the environment by combustion activities and radioactive reactions as well as radioactive waste. Some distinction between high-level radioactive waste and low-level radioactive waste will be made.

The primary channel of radioactive emissions from coal plants is in the fly ash. Radioactivity in fly ash emissions may negatively impact public health in three ways: 1) inhalation of fly ash particles, 2) ingestion of contaminated food grown in the vicinity of the plant, and 3) direct exposure to radiation emanating from particles deposited on the ground [37].

In order for the radioactive emissions of power plant technologies to be fairly analyzed, they need to be done under similar parameters. Ideally, the comparison would involve the routine emissions measured in terms of biological hazard instead of curies. This would determine the negative impact the emissions have on living beings. As it is now, studies of the radioactive emissions of fusion plants are for accident scenarios [55-58], while the most detailed data for radioactive coal emissions are measured in curies [6, 14-17, 20, 46, 59-62].

Tables 3.11 to 3.13 list the radioactive emissions from coal, fission and fusion power plants respectively. The fusion data is based on normal releases of 10.1 Ci of tritium per day from the 1500 MW(e) UWMAK-I [22], which corresponds to 2,460 Ci/GW(e)-yr. The occupational dose to workers who remove the first wall is not known and therefore, not included here. Similarly, the cumulative occupational dose to coal miners was not found. Due to limitations of data, the units for coal and fission, though similar, do not correspond accurately. The data, as presented, implies that the processes involved in the lifetime of a fission reactors produce a greater amount of radioactive emissions than either coal and fusion, which would seem to be correct. What still needs to be shown is by how much does the radioactive emissions from fission exceed either coal or fusion. The cumulative occupational dose to coal miners also needs to be included in this section. More complete data for coal and fusion is needed for future comparisons.

Table 3.11: Estimates of the Cumulative Radiological Early Dose from a Coal-Fired Power Plant (whole body mrem/year)

Process	References	Dosage
Plant Operation[1]	[37] p 45	1.9

[1]Assumes coal characteristics of 1.7 ppm U-228, -235, 4.5 ppm Th-232, and 16 ppm K-40. The worst case assumes that all particles are completely soluble and 100% of diet is from the area with the highest level of contamination to yield 18.2 mrem/yr to bone.

3.4 Solid Waste

Solid waste is a broad category. In power plants, solid waste can vary from plant to plant and within an individual plant in toxicity, radioactivity and chemical composition. It is impossible to fairly compare the mass or volume of solid waste between two completely different types of power plants. Fission and fusion plants have a greater amount of radioactive waste, which

Table 3.12: Estimates of 50-year Cumulative Dose from Light-Water Reactor Fuel-Cycle Components (whole-body person-rem per GW(e)-yr)

Fuel Cycle Component	Light Water Reactor[63]	
	General Population	Occupational
Mining	628	256
Milling	122	119
Conversion	9.5	1
Enrichment	0.02	0.7
Fabrication, UO_2	0.6	11.6
Reactor Operation	75.8	562
Fuel Storage	0.009	3.6
Transportation	0.1	0.36
Waste Management	0.002	0.35
Foreign Exposure from U.S. Releases	52	0
	888	954
TOTAL	1842	

Table 3.13: Estimates of the Cumulative Radiological Early Dose from a Fusion Tokamak Reactor. (whole body mrem/GW(e)-yr)

Process	References	General Population[1]
Plant Operation	[22]	2.21

[1]Based on an estimated release of 10.1 Ci of tritium per day. Does not include the exposure of workers who remove the first wall or who do routine maintenance. Based on $9.01(10^{-7})$ whole body mrem/Ci [64].

require years of safe storage and monitoring, than coal-fired plants. Coal plants on the other hand have greater volumes (and mass) of ash waste, some of which is considered hazardous, some of which can be used as a filler in highway construction and some of which is landfilled with normal household waste. Because of the differences, the wastes from each type of power plant will be looked at individually, instead of comparatively. Also, because of a lack of data, this paper will only deal with waste generated from the operational stage of power plants.

3.4.1 Coal

The solid wastes generated by a coal-fired electrical generation plant come from the combustion of coal and the pollution abatement processes. The bottom ash is the dry ash which is too heavy to be entrained in the flue gas, while fly ash is that ash which is carried out with the flue gas. It is assumed that pollution abatement equipment recovers 99.5% of the fly ash [62]. Precipitator sludge, or scrubber sludge, is the waste material created by flue gas desulfurization processes. These processes usually use lime or limestone scrubbing and result in a sludge composed mainly of calcium sulfite, calcium sulfate and water [46]. Sludge is only produced at those coal plants that exceed the National Ambient Air Quality Standards for SO_2 and varies with the sulfur content of the coal and efficiency of the abatement equipment. Power plant using low sulfur coal often do not have any scrubber sludge.

The major impacts of ash disposal arise from the chemical nature of the ash. The chemical composition, in turn, depends upon the particular coal and boiler operating conditions [62]. Trace metals can be leached from the vitrified ash in acid solutions and even in distilled water. Precautions must be taken in ash disposal. The use of clay caps and liners in ash ponds and FGD stabilization are necessary. Without such precautions, the leaching of toxic and carcinogenic metals (like nickel, chromium, arsenic, lead and selenium), could end up in drinking water and food chains via root uptake and potentially lead to long-term, chronic exposure problems [20]. A good assessment of the environmental impacts of solid waste on terrestrial and aquatic ecosystems can be found in ref. [62].

The values for solid wastes from coal, as shown in table 3.14, vary widely. Possible explanations for the differences include: varying ash contents in different types of coal, varying assumptions in the percentage of ash that remains as bottom ash or becomes fly ash, differing processes in burning the coal (e.g.. pulverized-coal burners or cyclone boilers), varying sulfur contents of the coal, and contrasting assumptions made by the authors in regards to pollution abatement efficiencies. The amount of solid waste generated will effect the amount of land required for settling ponds, though this is not reflected in this paper due to the different sources used for the two sections.

3.4.2 Fission

The solid wastes generated by a pressurized water reactor consist primarily of high level radioactive waste, consisting of irradiated fuel, and low level waste that includes ion-exchange demineralizers and solidified concentrates from the treatment of liquids containing small

Table 3.14: Solid Wastes from a 1,000 MW(e) Coal-Fired Power Plant (10^6 kg).

Waste Type	Source	Annual	Lifetime
Bottom Ash[1]	[46], [6]	13 - 101	536 - 4,030
Recovered Fly Ash[2]	[46], [6]	52 - 397	2,086 - 15,867
Precipitator Sludge	[6]	79 - 703	3,154 - 28,109

[1]The ranges vary primarily due to coal ash content. The low number is based on Pittsburgh seam coal which has a coal ash content of 3.6% and assumes bottom ash constitutes 20% of the total ash for dry-bottom pulverized coal [46], while the high number is from [6], which did not list its assumptions.
[2]The ranges vary primarily due to coal ash content. The low number is based on Pittsburgh seam coal which has a coal ash content of 3.6% and assumes fly ash constitutes 80% ash of the total for dry-bottom pulverized coal, 99.5% is captured in an ESP [46], while the high number is from [6], which did not list its assumptions.

amounts of radioactivity [65]. This section consists primarily of low-level radioactive waste. Such waste must be packed and transported according to government specifications Federal and State-licensed burial grounds. Currently, high level waste is stored on site at the power plant and is considered a decommissioning waste, which is not analyzed here. This may change in future versions of this paper once nuclear waste depositories are used for long-term storage of spent fuel rods. The volumes of solid waste listed in table 3.15.

3.4.3 Fusion

The solid waste generated by the fusion power plant is mainly associated with radiation damage to first wall materials. Most of the first wall in UWMAK-I will consist of 316 stainless steel, which will need to be replaced 14 times (every 2 years), over a 30 year plant lifetime, resulting in the replacement of 327.3 metric tonnes of 316 stainless steel each time. The rest of the blanket, which includes the reflector and header, will need to be replaced every 10 years. This results in the replacement of an additional 7,682 tonnes. Data for low-level radioactive waste, which will undoubtedly be generated, is not available at this time. Table 3.16 lists the solid waste from the fusion power plant.

3.5 Land Use

One of the natural resources that all power plants use is land. Land is used not only to site the power plant, but also to excavate fuel and materials as well as to store waste. There are, however, differences in how land is used and disrupted and distinguishing between temporary and permanent land commitments can be difficult. Budnitz [66] suggests that when analyzing and comparing land use of different technologies it is useful to distinguish between inventory commitments ("land committed for the duration of facility's operation, e.g. the land on which the plant sits"), temporary commitments ("km^2-years per MWe-yr of delivered electricity, e.g. km^2 strip-mined per MW(e)-yr, multiplied by the mean number of years required to restore the land to other uses), and permanent commitments (e.g. repositories for radioactive waste or strip mined land that is not restored). For the most part, this method was used here. The units

Table 3.15: Solid Wastes from a 1,000 MW(e) PWR (m^3).

Material Category	Annual Disposal Volume	Lifetime Disposal Volume
Operational [65][1]		
Power Plant Low-Level Solids	57 - 113	1,700 - 3,400

Table 3.16: Solid Wastes from a 1,000 MW(e) Fusion Power Plant (m^3).

Material Category	Annual Disposal Mass[22] (kg/GW(e)-yr)
Power Plant with 316 SS First Wall[2]	
First Wall	163,333
Reflector	325,333
Corrosion Products	1,667
Sputtering	167
Total Mass	490,500
Total Volume (7.8 gm/cm^3) =	94 m^3

[1]Based on a 40 year plant lifetime.
[2]SS = stainless steel.

for inventory were changed to km^2 per GW(e)-installed, while the temporary commitments are for km^2-years per GW(e)-installed. It was assumed that there were no permanent commitments of land, since most data did not specify this. Also, it is assumed that all temporary land commitments will use different parcels of land each year and require ten years from the year of use to restore to some other function.

Tables 3.17 and 3.19 detail the land used for the three power plant technologies. Overall, a coal plant uses more land than a PWR due, in part, to the extensive amount of land required for coal-mining purposes. The majority of land required for both coal and fission are due to the mining of fuels. Waste disposal can also involve significant amounts of temporary land commitments. Data for fusion waste storage was unavailable.

Table 3.17: Land Use for the Coal-Fired Power Plant.

Process	Source	Inventory[1]	Temporary Commitment[2]
		km^2/GW(e)-installed	km^2-yrs / 30 GW(e)-years
Mining[3]	[37]	-	46.11[(4)]
Power Plant	[37]	1.22 - 2.03[5]	-
Coal Storage Areas	[46]	0.02 - 0.03	-
Cooling Tower	[37]	0.04	
Ash Ponds	[46]	0.81 - 1.22	
Ash Disposal[6]	[46]	-	2.6 - 7.81
Scrubber Sludge Disposal[7]	[46]	-	0
TOTAL		2.09 - 3.32	48.71 - 53.92

[1]Includes facilities for processing and transport, but not transmission.
[2]Assumes a 10-yr mean time for restoration to other use and a 30 year lifetime for plant.
[3]Based on the following percentages for 1990 U.S. coal output: surface mining - 59%, underground mining - 41%. Adapted from ref. [67], p 46-47.
[4]Based on 121.5 acres/year for surface mining and 288 acres/year for underground mining for a 1,000 MWe coal plant. It's assumed that each over 30 years each annual requirement is for different land and a 10-year mean time is needed for restoration to another use.
[5]Site specific. Does not include land required for solid waste disposal.
[6]Assumes that the disposal site contains 25-acre feet per acre of waste material (refuse and ash).
[7]There is no scrubber sludge for plants using low-sulfur, western coal. However, for plants that use high-sulfur coal from the Appalachians or Illinois, the preempted land can range from 6-14 acres annually.

Table 3.18: Land Use for the PWR.

Process	Source	Inventory	Temporary Commitment[1]
		km^2/GW(e)-installed	km^2-yrs / 30 GW(e)-years
Mining	[52]	NA[2]	19.44
Milling	[52]	0.007	NA
Conversion	[52]	0.008	NA
Isotope Separation	[52]	0.004	NA
Nuclear Plant	[52]	0.65	-
Short term Storage	[52]	NA	0.24 - 1.94
Long term Storage	NA	-	-
TOTAL		0.67	19.68 - 21.38

Table 3.19: Land Use for the Fusion Reactor.

Process	Source	Inventory	Temporary Commitment[3]
		km^2/GW(e)-installed	km^2-yrs / 30 GW(e)-years
Power Plant[4]	[22]	1.94	-
Deuterium & Lithium	NAppl.[5]	-	-
TOTAL		1.94	

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[1]Assumes a 10-yr mean time for restoration to other use and a 40 year lifetime of plant.
[2]NA = Not available
[3]Assumes a 10-yr mean time for restoration to other use and a 40 year lifetime of plant.
[4]Based on $1,200,000 capital costs for land at $2,500/acre.
[5]Not Applicable. Deuterium is derived from water and lithium is derived from brines, neither of which requires significant areas of land.

4.0 Discussion

This discussion will deal with the energy payback of the power plants and the environmental considerations as detailed above.

4.1 Energy Payback

The energy payback ratio was calculated as a tool to analyze the total energy investment of each power plant. This ratio is the energy output divided by the total energy investment. The energy output for each of the plants is 30 GW(e)-years, based on 1 GW(e) output over 40 years with an assumed load factor of 75%. The primary calculations in determining the energy payback were in computing the energy investment. The energy investment was broken down into several phases that typified a power plants lifetime. These phases, several of which overlap chronologically, include:

- acquiring and processing materials,
- acquiring and processing fuels,
- power plant construction,
- power plant operation,
- and decommissioning the plant, including the storage and safe disposal of waste.

The energy invested in acquiring and processing materials is strongly correlated with the mass of the plant. The fusion power plant had the greatest mass, 650,000 metric tonnes, of the three plants analyzed which was three times larger than the mass of the fission pressurized water reactor (PWR) (210,000 tonnes) and five times greater than that of the coal plant (120,000 tonnes). When concrete is excluded, the fusion plant's total mass of 145,000 tonnes is 4 times greater than the PWR's 35,000 tonnes and 3.5 times greater than the coal plant (41,000 tonnes). The energy invested in fusion materials totaled 7 million GJ per GW(e)-installed, compared to fission's 2.2 million and coal's 1.8 million GJ per GW(e)-installed. The ratio's of material processing energy investment are 3.2:1 for fusion to fission and 3.9:1 for fusion to coal. This suggests a correlation between the energy invested in the power plants and the non-concrete mass. This correlation is stronger for coal than fission, which may be due to the fact that a higher percentage of the PWR's mass is concrete (83%) than fusion (68%) or coal (66%).

The PWR requires a greater investment in acquiring and processing fuels than coal or fusion. The uranium fuel cycle energy investment is 46 million GJ per 30-GW(e)-years when the uranium is enriched via the gas centrifuge process and more than 150 million GJ per 30-GW(e)-years when enriched via gaseous diffusion. It was assumed that gas centrifuge enrichment was used for the PWR analyzed in this paper. The procurement of coal is also energy intensive requiring more than 22 million GJ per 30-GW(e)-years, while only 1.4 million GJ per 30-GW(e)-years is needed to procure deuterium and lithium for the fusion plants fuel. The lithium requires 1.1 million GJ per 30-GW(e)-yrs of the fusion total.

The direct energy invested in power plant construction is dependent on the mass and sophistication of the plant. The fusion power plant requires more than 3 times the energy required to construct the PWR and around 5 times as much as the requirement for the coal plant. Around 7 million GJ/GW(e)-installed will be required to construct the fusion power plant, compared to the 2 million GJ per GW(e)-installed for fission and 1.5 million GJ per GW(e)-installed. Though it is expected that the fusion plant will require more energy to construct due to its greater mass, than the PWR, this difference may actually be too large. The large differences between the data is likely due to the methods used in the corresponding sources. The fusion data came from Bünde[1], who used the input-output (I/O) method of energy accounting to determine the energy investment. The I/O method is known to generate numbers that are too high for highly sophisticated technologies such as fusion. This method also includes the energy invested in construction materials, which for this paper, was subtracted out for this section. Therefore, the 7,547 terrajoules (1 TJ = 10^{12} J) required to construct the fusion power plant does not reflect the 7,400 TJ invested in construction materials. The PWR data is from Rotty [35], who determined the energy investment by first accounting for the amount and types of fuels used. The accuracy of the PWR number is not known, though it may be less precise in comparison to the coal number.

Coal had the greatest operational use of the three power plants, requiring more than 1.7 million GJ per GW(e)-yr. It was assumed that low sulfur coal was burned and lime scrubbers were not used. When scrubbers are used, around 2.8 million GJ per GW(e)-yr are required for station use. The PWR requires 331 thousand GJ per GW(e)-yr , while the fusion plant requires the smallest amount of operational energy at 10 thousand GJ per GW(e)-yr. The large differences between coal's station use and those for fission and fusion are due to the energy required for air pollution abatement, such as the electrostatic precipitator. The lowest station use energy investment data available was used for the coal plant. This was based on a study of one utilities coal-fired power plants, all of which burn low sulfur coal [36]. The energy consumed by cooling towers was factored into the coal station use data, but was not available for fission or fusion. Obviously, the lack of this data for the two nuclear plants slants the data against coal. The inclusion of such data will be important for the accuracy of future versions of this paper.

The data used to determine energy investment in decommissioning power plants was all based on the decommissioning of a light water reactor [6]. There is a serious lack of detailed information for this area. Based on the mass of each plant, the data for fusion and coal were scaled linearly from the "immediate dismantlement" of a PWR data. The use of this method provides a possible source of error, but it does account for the difference in plant sizes, which is a major determinant of the energy needed. Because of a lack of fissile materials in a coal plant, it is likely that the actual energy investment for safe decommissioning is less than that listed in this paper.

Overall, the fusion power plant has the lowest energy investment and the coal plant has the greatest. This is reflected in fusion's energy payback, which is more than twice that of nuclear fission and coal. The fusion plant, with an energy payback ratio of nearly 32, generates more than thirty times as much energy than was invested in material acquisition, construction, fuel acquisition, operation and decommissioning processes. Coal's energy payback is 12, while fission's is 15. When the missing pieces of data are included in later versions of this paper, fusion's energy payback ratio will likely be lessened, though it should still be the highest of the three technologies. Fission's energy payback ratio will drop as well and may actually become lower than that of coal.

4.2 Environmental Considerations

Most of the gaseous emissions for power plant processes were determined with the use of emission factors for each of the fuel types used in the various processes. All of the data for construction materials comes from sources that listed the types and quantities of fuels used for processing. Similarly, some of the processes in the uranium fuel cycle listed the types of fuels used for each. The emissions of CO_2 differ from those of the other criteria pollutants due to the fact that all fossil fuels contain carbon and CO_2 pollution abatement technologies do not exist. To determine the CO_2 emission factor, the relevant information includes the type and quantities of fuel combusted, the carbon content of each fuel and an assumption that the combustion of all fuel is complete. For other emissions, multiple factors influence the quantity of emissions. Sulfur dioxide emissions are dependent on the sulfur content of each fuel as well as the efficiency of lime scrubbers, when used. Emissions of nitrogen oxides and carbon monoxide are largely dependent on the operating conditions of the combustion chamber. Greater amounts of NO_x are produced during high temperature combustion, while CO is the result of the incomplete combustion of carbonaceous materials, which often occurs during low temperature combustion. Particulate emissions are not solely dependent on the combustion of fossil fuels, though are usually produced during operations that involve combustion, such as during smelting operations. Other factors that influence PM emissions include the ash content of the fuel and the collection efficiency of abatement technologies.

Emissions of carbon dioxide from coal are much higher than those of fission or fusion, correlating strongly with the amount of fossil fuels used. Coal plant operations alone produce more than 80 times the CO_2 as all of the processes from either fission or fusion. Overall CO_2 emissions of coal plants are nearly 3 million tonnes per GW(e)-yr, (2.8 million during operation), compared to 36 thousand and 20 thousand tonnes per GW(e)-yr for fission and fusion respectively. The majority of the CO_2 emissions for fusion come during the materials acquisition stage, when 17 thousand tonnes per GW(e)-yr are produced. The PWR, on the other hand, emits between 5 and 8 thousand tonnes of CO_2 per GW(e)-yr during uranium mining, milling, enrichment and fabrication stages, as well as during materials acquisition. Data for the emissions of CO_2, or from any other pollutants, was not found for the construction and decommissioning processes of any of the power plants. Future versions of this paper should include this data or approximations of pollutants from whatever data is available. CO_2 emissions from these processes will not have a significant percentage impact on the coal emissions, though may contribute a larger percentage of the total emissions for fission and fusion.

Emissions of sulfur dioxide are also greatest for coal generated electricity, which produces 40,000 tonnes of SO_x per GW(e)-yr. This amount is significantly higher than the emissions from fission (870 tonnes/GW(e)-yr) and fusion (1,600 tonnes/GW(e)-yr). Processes that burn coal or residual fuel oil, such as ore smelting and steam production, produce the greatest emissions of SO_x due to the higher sulfur contents of these fuels. Emissions of SO_x from fusion are greatest during material production. Fusion SO_x emissions from materials production is disproportionately higher for fusion than from coal. This may be due to the higher percentage of the fusion plant's mass from non-ferrous metals that require greater amounts of energy. Overall, the SO_x emissions from fusion are greater than those of fission with the difference in plant mass providing the best explanation.

Emissions of nitrogen oxides and carbon monoxide often reciprocate each other. It takes opposite combustion chamber conditions for the two pollutants to be formed. The greatest emissions for each pollutant are produced by coal-fired power plants. The coal plant emits 1,400 tonnes of CO per GW(e)-yr and 23,600 tonnes of NO_x per GW(e)-yr. This is compared to 140 tonnes of CO and 490 tonnes of NO_x per GW(e)-yr for fission and 260 tonnes of CO and 290 tonnes NO_x per GW(e)-yr for fusion. For each power plant the emissions of CO are smaller than the other pollutants. This may be attributed to the high temperatures and moderated oven conditions at which fossil fuels are burned in industrial processes. Coal is a common fuel in many industrial processes, and is combusted at high temperatures which provide conditions that are more favorable for the production of NO_x than CO. Carbon monoxide formation results from the incomplete combustion of carbonaceous materials.

Particulate matter (PM) emission data is probably the least accurate of all the air pollutants. Many factors effect the emissions of this pollutant, including the ash content of the fuel, combustion conditions of the oven and the efficiencies of pollution control technologies. Emission factors for specific fuels were not available, while emission factors for the production of materials were only available for the most commonly used materials, such as aluminum, copper and steel. Emission factors were not extrapolated for all materials, due to the difference in production processes. For this reason, data for materials acquisition are not claimed to be precise. As for the data found in this paper, coal has the greatest emissions of PM (5,100 tonnes per GW(e)-yr), while fusion has slightly more than fission (120 to 70 tonnes per GW(e)-yr).

Usage of water resources are primarily determined by the cooling needs of the industry. The method of cooling can have a large effect on the amount of water used. Once-through systems, which use water once before returning it to the river or lake from which it was originally taken have detrimental effects on local ecosystems because of the higher temperature of the returned water. The use of cooling towers has become a more acceptable method of dissipating sensible heat and is assumed to be used on the power plants analyzed in this paper. For plants that produce equal amounts of electric power, these dissipation differences are determined primarily by the efficiencies of the plants. Coal plants often have efficiencies of around 40%, while the efficiencies of fission plants often range around 33%. Fusion was assumed to have the same efficiency as fission and the same operational water usage, 24 million cubic meters of water per GW(e)-yr, which is greater than the requirements of coal, 15 million m^3 per GW(e)-yr. Because of the water requirements during the uranium fuel cycle, the fission plant uses the greatest amount of water, averaging around 65 million m^3 per GW(e)-yr. The data for enrichment was based on gaseous diffusion, an energy intensive process, despite the fact that energy and CO_2 data were based on gas centrifuge enrichment. The cooling needs of gaseous diffusion enrichment require 42 million m^3 per GW(e)-yr. This data may be high, and will likely be replaced by data for gas centrifuge enrichment, when it becomes available.

The data suggests that the radioactive emissions from fission are greater than those from coal or fusion, though data is not currently available for the occupational exposure levels of fusion power. Since workers are exposed to radioactivity through all phases of the uranium fuel cycle and only the operational and decommissioning stages of fusion, it cannot be concluded with great certainty that total exposure rates will be greatest for fission. At this time it is not known what the exposure levels will be for the workers who remove the first wall of the fusion reactor. This wall, which will consist primarily of stainless steel in the UWMAK-I, will need to be replaced up to 14 times in a 30 year lifetime. Each replacement will remove 327.3 tonnes of 316 stainless steel, which will be considered highly radioactive. Methods of removal and potential exposures have not currently been determined, but will need to be included in later versions of this paper or similar studies in the period before the commercial viability of fusion. The current radioactivity data for fusion accounts for routine emissions of tritium, which will total 6.73 Curies/day, with a biological hazard of $9.01(10^{-7})$ whole body mrem/Ci at the plant boundary (1 km) [64]. This equates to a total of 2.21 whole body mrem per GW(e)-yr, which is slightly greater than the 1.9 whole body mrem per GW(e)-yr emitted by the coal plant. Data for the PWR was in the units of whole-body person-rem per GW(e)-yr, which includes a population density not stated in the source of information.

The types and volumes of solid waste vary considerably between the three power plant technologies. Data was not available for each stage of the three power plants, so only the solid waste generated from plant operation was considered in this paper. The large volumes of waste that will need to be disposed of after decommissioning deserves to be considered in this section in later versions, once data becomes available. The solid waste from coal results from combustion and air pollution abatement technologies. Bottom ash and recovered fly ash account for an average of 280 million kilograms annually of coal solid waste, while precipitator sludge contributes another 400 million kgs. Some of this waste is toxic and needs to be handled as hazardous waste, while some can be landfilled.

Operational solid waste from nuclear fission and fusion operations are predominantly radioactive. Waste from fission is primarily in the form of spent fuel, while solid waste from fusion is in the form of radiation damaged steel that is highly radioactive. This paper only includes low-level waste from the PWR, although there will undoubtedly be some low level waste for the fusion reactors. Currently, spent fission fuel is stored safely on the site of the power plant and is not disposed of until after decommissioning. Only the solid wastes are removed from the premises of the plant. Special precautions will be needed to safely remove, transport and store this material at licensed facilities.

Comparing the solid wastes of the three reactors is difficult due to the differences in the waste. The large amounts of toxic ash and sludge that requires disposal from the coal plants differs considerably in handling precautions from the fission plants low-level radioactive waste and the highly radioactive steel from fusion.

The mining of coal and uranium utilize the greatest area of land for coal and fission plants respectively. Over a 30-GW(e)-yr lifetime, coal mining temporarily disturbs 46 km^2-yrs of land. Uranium mining requires 19 km^2-yrs of land to produce the same amount of power. It has been assumed that the temporary land commitments are used during one year and not completely restored to another use for another 10 years. The amount of land required for the production of deuterium or the procurement of lithium is believed to be negligible. Deuterium is obtained from water and lithium from brine. Neither process is expected to use a sizable amount of land for the given amount of material needed. The fusion power plant considered in this study will be sited on approximately 2 square kilometers of land [22], which is larger than the 0.67 km^2 required by the PWR. A coal plant requires between 2 and 3 km^2 of land, which is larger than either fission or coal and includes the area needed for ash and sludge disposal.

Though nuclear fusion is still years away from being a commercial reality, understanding its benefits and costs as compared to its future competing sources of baseload electric power, coal and nuclear fission, are imperative in the period before its viability. The data as it appears in this paper is far from complete and has many gaps which must be filled before the most accurate comparisons can be made. Obviously, the most detailed data will not be available until after the first fusion reactor is in operation, though accurate conclusions can and must be drawn using educated assumptions in the meanwhile.

5.0 Conclusions

This paper has attempted to compare the energy invested in fusion, coal and fission generated electric power as well as the emissions that flow out of each system. The biggest challenge in making such comparisons is overcoming a lack of available data for different processes and especially concerning fusion. Despite the holes in the data, several conclusions can be drawn.

- The fusion power plant has the greatest non-fuel mass of the three technologies. The fusion plants mass is 650,000 metric tonnes per GW(e)-installed, compared to 205,500 tonnes for the PWR and 119,000 tonnes for the coal-fired plant. This equates to ratios of 3:1 for fusion to fission and 5:1 for fusion to coal. Both nuclear plants have large amounts of concrete in their designs to shield radiation. When concrete is not included, fusion has a total mass of 145,000 tonnes compared to fission's 35,000 tonnes and coal's 41,000 tonnes. The ratios of non-fuel mass, excluding concrete, are 4:1 for fusion to fission and 3.5:1 for fusion to coal.

- When the mass of fuels are included, the coal plant has the greatest lifetime mass. More than 97 million tonnes of coal are consumed over the 30-GW(e)-yr lifetime of the plant. This mass alone is more than two orders of magnitude higher than the mass for either the fission or fusion plants. The PWR requires 5,700 tonnes of uranium per 30 GW(e)-yr, while fusion's energy needs are supplied by 1,160 tonnes of deuterium and lithium (mainly lithium).

- Fusion power has a greater lifetime energy payback than coal or fission. This means that less energy is invested into the fusion plant to generate a standard amount of energy, 30-GW(e)-yrs, than into coal or fission. Over a lifetime of 30 GW(e)-years, 30 million GJ are invested into fusion as compared to 78 million GJ for coal and 65 million GJ for fission. The efficiency of these technologies is also reflected in their energy payback ratios; fusion - 32, fission - 15, and coal - 12.

- It is obvious to conclude that electricity generated from coal produces more air pollution than from fission or fusion. Coal produces 2,958,000 tonnes of carbon dioxide and 70,000 tonnes of the criteria pollutants, SO_2, NO_x, CO and particulate matter, annually. Fusion, meanwhile, produces more criteria pollutants than fission (2,280 to 1,570 tonnes annually) and less carbon dioxide than fission (22,400 tonnes for fusion and 35,900 tonnes for fission annually).

- The difference in the lifetime emissions of CO_2 for the fission and fusion plant seems to be related to the amount of energy invested into each. The PWR has a lifetime energy investment that is twice as large as that of fusion, but only produces 1.6 times more CO_2. Though data is lacking for the construction and decommissioning phases, it would seem that CO_2 emissions from these processes will be greater for fusion than from fission.

- The difference in the amount of criteria pollutants emitted by fission and fusion seems to correlate with the difference in mass, though like CO_2, is not exact. Fusion produces around 1.5 times the criteria pollutants as fission, yet has a total power plant mass that is five times larger than of fission. This discrepancy will likely be lessened when emissions data for power plant construction and decommissioning is included.

- The fission power plant uses the greatest amount of water for cooling purposes. Around 67 million cubic meters are needed annually to cool processes related to PWR electrical output. In comparison, the fusion plant consumes around 23 million cubic meters and the coal plant requires around 20 million cubic meters. A large part of the water consumption for the PWR related processes comes from the uranium fuel cycle, including 42 million cubic meters for enrichment.

- The biological hazard associated with the routine release of radioactivity from fission reactors is greater than that from fusion and coal plants. Workers and the public are exposed to radioactivity through all of the stages of the uranium fuel cycle, but only during operation and decommissioning for fusion. Data for occupational doses during operation are not currently available for fusion and will be necessary for accurate future comparisons.

- Coal-fired power plants require a greater amount of land per GW(e)-installed than fission or fusion plants. The land required to site the power plant, ash storage and ash ponds can range between 2 and 3 square kilometers. Also, the temporary commitment of land for coal mining averages around 50 km^2-years per GW(e)-installed. The fusion plant will require nearly 2 km^2 for the power plant, while the PWR requires around 0.7 km^2. Temporary land commitments of coal are dominated by mining and consume around 50 km^2-years of land per 30 GW(e)-years. Fission power requires around 20 km^2-years of temporary land commitments per 30 GW(e)-years. Temporary land commitments for fusion will likely be small.

Recommendations

There are several areas that warrant further research to make studies like this more complete and accurate. These are listed below.

- The energy investment for coal plant construction and the decommissioning of all power plants needs to be studied. Reports by Bünde [1], El-Bassioni [6], and Rotty [35] have included some data on these areas for fission, while only El-Bassioni includes coal. Rotty's data on constructing PWR's may be adequate, but more precise data is still needed for constructing coal and fusion plants. Fusion's data will need to be extrapolated. Any study of decommissioning energy requirements would ideally detail the quantities and types of fuels used in these processes.

- If the types and quantities of fuels used in construction and decommissioning were known, the air pollutants emitted during these processes could also be determined. Emissions data was not found for either of these processes for any effluents. Though it is likely that water use is minimal for these, the amount of air pollution created from the many large diesel machines that move the earth and materials is likely to be greater than negligible.

- This type of study will need to be continually updated as fusion research improves, more is understood about the technology's operation and more accurate data becomes available.

- Ultimately, the goal of nuclear fusion will extend beyond the deuterium-tritium fuel cycle to advanced fuels involving helium-3. Involving power plants that use these advanced fuels in a similar study is the next logical step.

- More research is needed to determine effluents from material procurement processes. Currently, comprehensive data on the air emissions of material acquisition processes exists in a series of U.S. EPA reports [47] and their supplements, though only the most commonly used materials are included. Similar studies are needed to determine the water usage and solid waste of these processes.

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Appendix A: Material Gathering Emissions

The emission factors for gaseous emissions from material acquisition processes, as found in the tables of subsection 3.1, are listed in this appendix. Emission factors for carbon dioxide were all derived from reports [1-6] that listed the types and quantities of fuels used to procure a given unit of the material. The CO_2 emission factor for each fuel type, listed in table A-2, was used to determine the emission factor for each material. The most accurate material acquisition factors are for carbon dioxide, which are listed in table A-1. This is the one pollutant that is not effected by pollution abatement efficiencies.

Many of the other emission factors for individual materials, which are also listed in table A-2, are estimates based on data for similar types of minerals. Particulate emission factors are the least reliable due to a lack of data and wide range of factors that determine these emissions. These factors include the ash content of the fuel, stove conditions, abatement technology efficiencies, and variable other processes that create fine dust. The difference in these factors between each material also make it difficult to extrapolate an emission factor from other materials. For similar reasons particulate matter also does not have a emission factors for specific fuels or electricity. The emission factors for each material are listed in table A-3, while the emission factor for electricity generation are found in table A-4.

Table A-1: The CO_2 Emission Factor for the Procurement of Materials

Material	References	kg CO_2 per Tonne of Material
Aluminum	[6]	10,654
Asbestos	[2]	231
B_4C	[5]	12,675
Cadmium	[6]	1,519
Calcium (quicklime)	[1]	574
Carbon[1]	[3]	1,595
Cement (Portland)	[1]	255
Chromium	[6]	3,889
Coke (Metallurgical)	[2]	3,353
Copper	[6]	4,592
$CuZn_{28}Sn$	[5]	1,943
Earth Work (m3)	[5]	neg.
Helium (m3)	[5]	678
Insulation Materials	[5]	679
Iron		
Carbon Steel[2]	[1]	1,927
Stainless Steel	[5]	2,176
High Alloyed Steel	[5]	2,176
Unalloyed Steel	[5]	424
Lead	[6]	2,412
Lithium	[5]	43,995
Magnesium	[2]	20,726
Manganese[3]	[2]	3,111
Mercury	[6]	2,687
Molybdenum	[2, 6]	8,755
Inconel (electrolytic nickel)	[6]	7,616
Niobium-Titanium	[5]	12,675
Sand & Gravel	[5]	1
Silver	[6]	913,458
Sodium Metal	[2]	6,879
Soderberg Paste	[2]	2,959
Tin	[3]	30,136
Titanium[4]	[2, 4]	31,993
Vanadium	[6]	18,417
Yttrium	[3]	37,065
Zinc	[1]	4,898
Zirconium[5]	[3]	44,838

[1]Based on one tonne of graphite flakes and fines.
[2]Based on one tonne of carbon steel castings.
[3]Based on Ferromanganese produced in an electric arc furnace.
[4]Electricity factors come from [4] and other fuel data comes from [2]. Electricity data is for the basis of titanium ingots, while other fuel's are based on titanium sponge due to limitations of data.
[5]Based on one tonne of zirconium sponge processed via the batch chlorinization process.

Table A-2 : Fuel Emission Factors (grams pollutant per MJ)

Fuel[a]	CO_2[b]	SO_x[c]	NO_x[d]	CO[e]
Butane	61.60[f]	neg.	0.06	0.015
Coal (Subbituminous)	92.77[f]	1.438	0.407	0.039
Coal (Bituminous)	87.27[f]	1.438	0.407	0.039
Diesel	73.80[g]	0.097	1.45	0.41
Distillate fuel oil	73.80[h]	0.267	0.061	0.154
Gasoline	71.20[g]	0.018	0.35	13.55
Kerosene	71.20[g]	NA	NA	NA
LPG[j]	59.65[k]	neg.	0.057	0.14
Metallurgical Coke	96.81[k]	0.455	0.364	0.087
Natural Gas	50.53[m]	0.0003	0.06	0.015
Petroleum Coke	96.81[k]	0.376	0.301	0.072
Propane	59.77[f]	neg.	0.056	0.014
Residual fuel oil	78.00[g]	1.026	0.158	0.014

[a] Heating values for the fuels are: 139,000 Btu/gal diesel, 140,000 But/gal distillate fuel oil, 125,000 Btu/gal gasoline, 135,000 Btu/gal kerosene, 94,000 Btu/gal LPG, 1000 Btu/ft^3 natural gas, 30 (10^6 Btu)/short ton petroleum coke, 95,000 Btu/gal propane, and 150,000 Btu/gal residual oil [3]. Non-utility industrial coal has an average heating value of 22.195 (10^6 Btu)/short ton and metallurgical coke has a heating value of 24.8 (10^6 Btu)/short ton [7]. Butane's heating value was based on LPG's. NA = not available. neg. = negligible.

[b] Assumes complete combustion.

[c] Emission factors were derived from ref. [8] and based on: 0.09 x (sulfur content) lb/ 10^3 gal butane/LPG/propane (a sulfur content of 0.1% was assumed for butane, LPG and propane based on [8]), 17.5 x (sulfur content of coal) kg/tonne (average sulfur content of 2.12% sulfur for U.S. coal derived from [9]), 31.2 lb/ 10^3 gal diesel, 145(sulfur content) lb/10^3 gal distillate fuel oil (sulfur content of 0.6% derived from [8]), 5.31 lb/ 10^3 gal gasoline, 5 lb/ 10^6 ft^3 natural gas and 159 x (sulfur content) lb/ 10^3 gal residual oil (a sulfur content of 2.25% derived from [8]). Coke was assumed to have the same emission factor as coal, except for the sulfur content of 0.75% by weight [8].

[d] Emission factors were derived from ref. [8] and based on: 469 lbs/10^3 gal diesel, 20 lbs/10^3 gal distillate fuel oil, 102 lbs/10^3 gal gasoline, 10.5 kg/tonne bituminous/subbituminous coal, 55 lb/10^3 gal residual oil, 140 lb/ 10^3 ft^3 natural gas, 13.2 lb/10^3 gal butane, and 12.4 lb/10^3 gal propane. LPG emission factor is based on the propane emission factor. Coke was assumed to have the same emission factor as coal.

[e] Carbon monoxide emission factors were derived from [8] and based on the following: 3.3 lb/ 10^3 gal butane, 2.5 kg/tonne bituminous/subbituminous coal, 132 lb/10^3 gal diesel, 5 lbs/10^3 gal distillate fuel oil, 3,940 lb/10^3 gal gasoline, 35 lb/10^6 ft^3 natural gas, 3.1 lb/10^3 gal propane, and 5 lb/10^3 gal residual oil. Coke was assumed to have the same emission factor as coal.

[f] Ref. [10], p. 21.

[g] Ref. [11], p.155.

[h] Assumed to be the same as diesel.

[j] Liquid Petroleum Gas

[k] Ref. [12], p 15. Metallurgical coke is assumed to be the same as petroleum coke.

[m] Ref. [13], p. 984. Based on fuel at the plant outlet plus burning.

Table A-3: Air Emissions in the Production of Materials Used in Electric Power Generation Technologies (kg pollutant per tonne material)

Material		SOx	NOx	CO	PM
Aluminum	(low)	0.00[14]	23.00[15]	342.00[15]	49.79[14]
	(high)	83.00[15]			147.00[16]
Asbestos[1]		83	5.19	1.34	NA
Brass/Bronze[2]	(low)	3,537	20	2.54	83
	(high)				183.85
Cadmium[3]		26	4.65	1.78	NA
Chromium[4]		9	3	55	6.35
Concrete	(low)	0.72[14]	NA[5]	NA	0.49[12]
	(high)				6.21
Copper	(low)	995.06[14]	20.00[15]	2.54[15]	83.00
	(high)	3,537.00[15]			183.85[14]
$CuZn_{28}Sn$[6]		3,537.00[15]	20.00[15]	2.54[15]	183.85[14]
Fiber Glass[7] **(insulation)**		5.68	2.07	0.22	1.67[16]
Lead[8]		20.07[14]	9.18	2.86	37.97[17]
Lime		NA	1.56[8]	NA	2.55[8]
Lithium[9]		368	135	14.2	38.84[17]
Magnesium[10]		109	49.5	6.63	NA
Manganese[11]		9.00	3.00	55.00	6.35

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[1] Calculated from the fuel emission factors in table A-2 and the fuel requirements as found in ref. [2].
[2] All figures based on copper.
[3] SOx and CO emission factors are based on those of zinc. NOx emission factor calculated from the fuel emission factors found in table A-2 and the fuel requirements as found in ref. [6].
[4] Based on the emission factors for stainless steel.
[5] (Data) Not Available
[6] All figures based on copper.
[7] SOx, NOx and CO data calculated from the fuel emission factors in table A-2 and the fuel requirements as found in ref. [5].
[8] NOx and CO data calculated from fuel mission factors in table A-2 and fuel requirements as found in ref. [6].
[9] SOx, NOx and CO data calculated from the fuel emission factors in table A-2 and the fuel requirements as found in ref. [5].
[10] Calculated from the fuel emission factors in table A-2 and the fuel requirements as found in ref. [2].
[11] Emission factors are estimates based on the emission factors of steel.

Table A-3: Continued

Material	SOx	NOx	CO	PM
Mercury[1]	25.2	49.9	43.5	NA
Molybdenum[2]	70.00	37.00	4.78	NA
Nickel / Inconel[3]	28,296.00	19.9	3.00	184
Niobium-Titanium[4]	70.00[15]	37.00[15]	4.78[15]	NA
Silver[5]	28,300	3,380	1,160	NA
Sodium metal[6]	57.6	21.0	2.23	NA
Steel	9.00[15]	3.00[15]	55.00[15]	6.35[15]
Tin[7]	3,540	93.1	9.83	184
Titanium	70.00[13]	37.00[15]	4.78[15]	NA
Vanadium[8]	70.00	37.00	4.78	NA
Yttrium[9]	70.00	37.00	4.78	NA
Zinc	26.00[15]	14.00[15]	1.78[15]	NA
Zirconium[10]	70.00	37.00	4.78	NA

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[1]Calculated from the fuel emission factors in table A-2 and the fuel requirements as found in ref. [6].
[2]Emission factors are estimates based on the emission factors of titanium.
[3]The SOx emission factor is based on eight times the emission factor of copper [18], NOx and CO were calculated from the fuel emission factors in table A-2 and the fuel requirements as found in ref. [6], and PM is based on copper.
[4]Emission factors are estimates based on the emission factors of titanium.
[5]The NOx and CO emission factors for silver are based on calculations from the fuel emission factors in table A-2 and the fuel requirements as found in ref. [6], while the SOx emission factor is based on that of nickel.
[6]Calculated from the fuel emission factors in table A-2 and the fuel requirements as found in ref. [2].
[7]Emission factors for SOx, CO and PM are based on copper, while the NOx factor is calculate from the fuel emission factors in table A-2 and the fuel requirements as found in ref. [3].
[8]Emission factors are estimates based on the emission factors of titanium.
[9]Emission factors are estimates based on the emission factors of titanium.
[10]Emission factors are estimates based on the emission factors of titanium.

Table A-4: The Pollutant Emission Factors for the Production of Electricity

(MT pollutant per MWh(e) generated)

Pollutant	Standard Mix[1]	Aluminum Mix[2]
Carbon Dioxide[3]	0.6214	0.4503
Sulfur Dioxide[4]	0.0052	0.0038
Nitrogen Dioxide[5]	0.0019	0.0015
Carbon Monoxide[6]	0.000201	0.000145

[1]Based on the 1993 US average of electrical production [7], which consists of the following; coal - 57%; nuclear - 21.2%, natural gas - 9.2%, hydroelectric - 9.1%; and petroleum - 3.5%. Emission factors for each are from ref. [11] and are as follows (

[2]Based on the average of electrical production for aluminum smelters [1], which consists of: coal - 41.25%, hydroelectric - 39.9%, nuclear - 9.66%, natural gas - 6.66%, and petroleum - 2.53%.

[3]Carbon dioxide emission factors for each electrical generation technology are from ref. [11] and as follows (MT CO_2 emitted/GWh(e) generated): coal - 964, petroleum - 726.2, natural gas - 484, hydroelectric - 3.1, and nuclear - 7.8.

[4]Sulfur dioxide emission factors for each technology are from ref. [15] and as follows (MT SOx emitted/GWh(e) generated): coal - 7.5, petroleum - 8, natural gas - 7, hydroelectric - negligible, and nuclear - negligible.

[5]Nitrogen dioxide emission factors for each technology are from ref. [15] and are as follows (MT NOx/GWh(e) generated): coal - 2.7, petroleum - 7, natural gas - 2.5, hydroelectric - negligible, and nuclear - 0.001.

[6]Carbon monoxide emission factors for each technology are from ref. [15] and are as follows (MT CO/GWh(e) generated): coal - 0.25, petroleum - 1.3, natural gas - 0.13, hydroelectric - negligible, and nuclear - negligible.

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