# “Birth to Death” Analysis of the Energy Payback Ratio and $CO_2$ Gas Emission Rates from Coal, Fission, Wind, and DT Fusion Electrical Power Plants

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Presented at the 6th IAEA Meeting on Fusion Power Plant Design and Technology, Culham, England, March 23–27, 1998

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# Abstract

The amount of electrical energy produced over the lifetime of coal, LWR fission, DT-fusion, and wind power plants is compared to the total amount of energy required to procure the fuel, build, operate, and decommission the power plants. The energy payback ratio varies from a low of 11 for coal plants to a high of 27 for DT-fusion plants. The magnitude of the energy investment and the source of the various energy inputs determine the $CO_2$ emission factor. This number varies from a low of 9 to a high of 974 tonnes of $CO_2$ per $GW_eh$ for DT-fusion and coal plants respectively.

## 1. Introduction

Future electrical energy plants will have to provide two to three times the present amount of electricity generated on a worldwide basis by the year 2050[1]. When one examines the options for the 21st century, beyond the time when natural gas and oil are viable technologies due to dwindling resources, coal and fission power plants must be given serious consideration. The use of fusion to replace current facilities for base loaded electrical plants and wind driven units for intermittent power is also being investigated.

How is one to judge the positive and negative attributes of these four options in order to guide present research investments? The most successful electrical energy sources must excel in many areas: economics, safety, reliability, and environmental impact. It is the purpose of this paper to address two issues which feed into the economic and environmental impact assessments of these energy sources. First, the energy payback ratio (i.e., the total amount of useful energy derived from a power plant divided by the total amount of energy invested in the power plant) should be as large as possible to generate favorable economics. Second, the amount of pollutants emitted per kWh of electricity generated should be as low as possible. This paper will concentrate on one pollutant that is currently in the public's view, $CO_2$ gas. One may be tempted to invoke the popular, but mistaken view that nuclear and renewable energy sources do not emit greenhouse gases. That is nearly a true statement when considering the electricity generation process itself but it does not recognize that considerable energy (much of it fossil energy) is required to mine, transport, fabricate materials of construction, as well as to build and decommission the plants. When the total “birth to death” energy invested in nuclear and renewable facilities is amortized over the useful lifetime of the plant, there will be a finite, though smaller greenhouse gas emission rate compared to coal fired plants.

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

## 2. Calculation of Energy Payback Ratio

The concept is straightforward. Add up all the useful energy produced by an electrical power plant over its lifetime and divide it by the total amount of energy needed to gather all the fuel and construction materials, as well as the energy needed to construct, operate, and decommission the plant. Simply put, the energy payback ratio (EPR) is:

$$EPR = \frac{E_{n,L}}{\left(E_{mat,L} + E_{con,L} + E_{op,L} + E_{dec,L}\right)} \qquad 1)$$

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

$E_{mat,L}$ = total energy invested in materials used over a plant lifetime L.

$E_{con,L}$ = total energy invested in construction for a plant with lifetime L.

$E_{op,L}$ = total energy invested in operating the plant over the lifetime L.

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

In practice, the determination of the output energy is easy but the determination of the input energy is not. Two approaches to calculate the input energy have been used in the past. First, the Input/Output method[2, 3] relies on the simple concept that to a large degree, the more expensive an item or service is, the larger the energy content of that item or service. Previous authors have established the equivalence between money spent on various activities (e.g., construction, railroad transportation, etc.) or hardware (pumps, wiring, concrete, etc.) and their energy densities in terms of both thermal and electrical energy inputs. This approach allows one to calculate energy input once the cost of each activity is known.

The second approach is the Process Chain Analysis (PCA)[4, 5], which addresses each process contributing to the useful lifetime of the power plant. The PCA method sums up the energy expended for each process. This method is best suited to calculating the energy requirements of material procurement by determining the energy required to mine, transport and refine the raw materials into elemental form. This approach is very specific to the types of fuels used in each process which greatly aids the calculation of $CO_2$ emission rates.

It is expected that the I/O method slightly overestimates the energy intensity because some of the cost is needed for profit, bank interest, and so forth. On the other hand, the PCA approach probably underestimates the energy investment because it does not include indirect energy requirements such as those associated with heating administration buildings, embodied in the steel of trucks or railroad tracks, etc. In this study the I/O and PCA techniques have been combined using the PCA method when possible and using the I/O method to assess non-materials related processes. It is thought that the combination of the two will result in a reasonable, but not perfect, assessment of the energy inputs.

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

## 3. Calculation of the $CO_2$ Emission Per kWh of Electricity Produced

Every time energy (thermal or electrical) is used to make a product, some waste products are released to the environment. In the best case, this waste product is just heat. In most cases, the waste products can include greenhouse gases such as $CO_2$, $SO_X$, $NO_X$, $CH_4$, etc. For example, previous analyses[6-8] have been conducted to determine the pollutants released during the mining of coal, the mining of Fe, railroad transportation of freight, etc. The

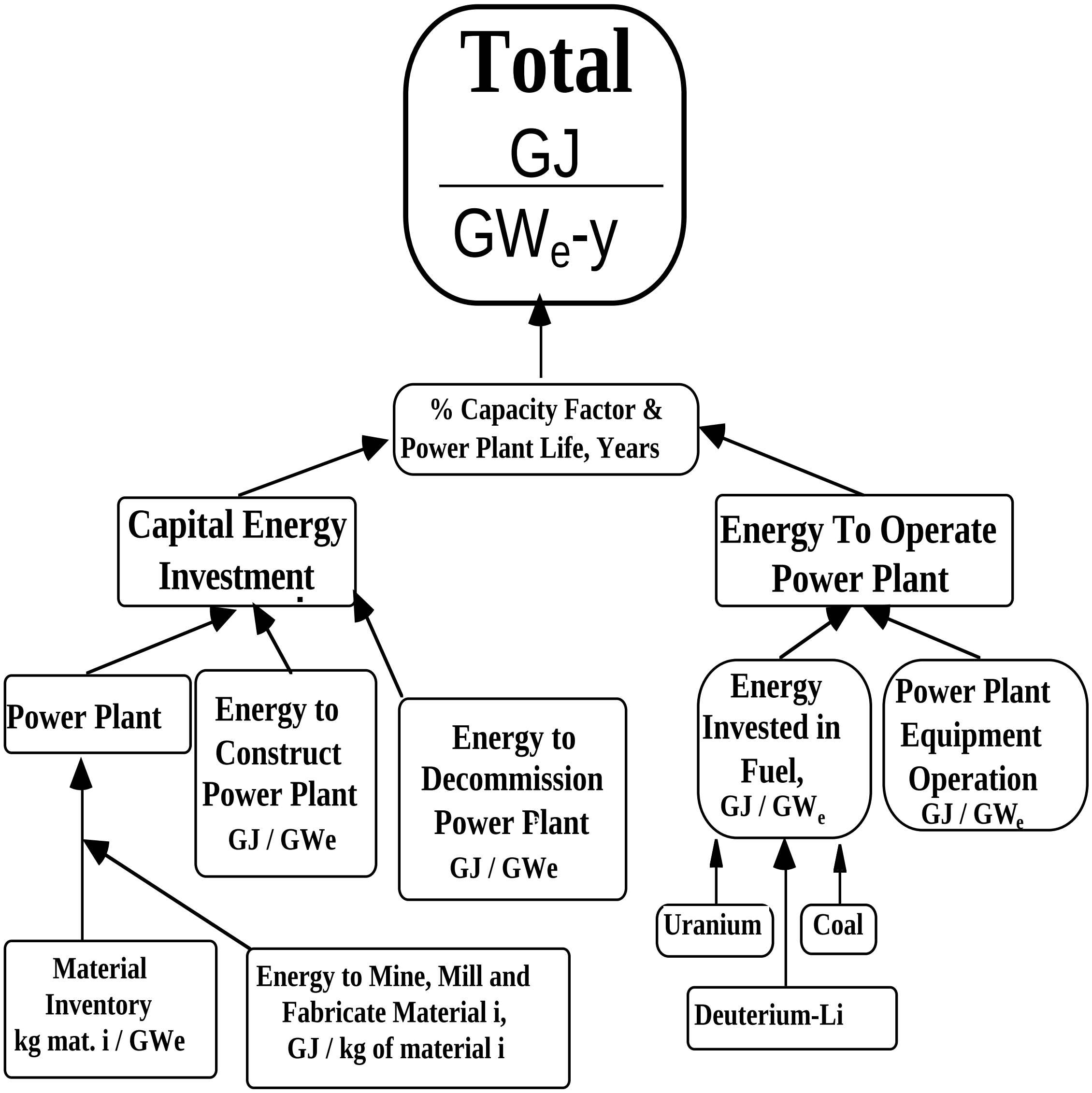

**Figure 1. Schematic of the method used to calculate the energy inputs to various electrical power plants.**

analyses include both thermal and electrical energy. Furthermore, the pollutants emitted during the generation of electricity (the subject of this paper) depend on whether the power plant is fueled by coal, uranium, deuterium and tritium (DT), or wind. Once the EPR is determined, one can use the components of energy input to calculate the emission of a specific pollutant (i.e., $CO_2$ per kg of fuel, metal, or concrete per $GW_e y$ of net electricity sent to consumers). This emission coefficient is stated mathematically in Equation 2:

$$\frac{kg.CO_2}{GW_e y} = \frac{\sum_i \left( \frac{kg.CO_2}{kg.M_i} \right) \bullet kg.M_i}{E_{n,L}} \qquad 2)$$

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

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

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

## 4. Selection of Power Plants For This Study

The major parameters of the four power plants used for this study are summarized in Table 1. For simplicity, the capacity factors were all chosen to be 75% for the base loaded plants. This is close to the current experience for coal and fission plants while it is purely an assumption for fusion since no plants have been built yet. The capacity factor for the wind power plant is calculated from actual production data[9]. The inventory of materials required for construction was taken from the references listed in Table 1 for coal, fission, and DT-fusion. The materials inventory for the wind plant was compiled from data supplied by the manufacturer and more detail is given in reference[10].

## 5. Energy Intensity and $CO_2$ Emission Factors for Materials

In order to complete the process chain analysis, a survey of the specific energy intensities for materials used in the four power plants outlined in Table 1 was compiled in reference[15]. Table 2 is an abbreviated summary of that work given here to illustrate the order of magnitude

**Table 1: Summary of Power Plant Designs Used to Determine Energy Payback Ratio**

| Parameter | Coal[11] | Fission[12] | Fusion[13] | Wind[14] |
|---|---|---|---|---|
| Power Level-MWe | 1,000 | 1,000 | 1,494 | 25 |
| Fuel | US average coal-1990 | 3% enriched U | Deuterium-Tritium | Not Applicable |
| Capacity Factor-% | $75^a$ | $75^a$ | $75^a$ | 24 |
| Life-CY | 40 | 40 | 40 | 25 |
| Other | Conventional Steam | Pressurized Water Reactor | Tokamak | • 3 blade<br>• No energy storage |

a = assumed

**Table 2: Energy Intensities of Power Plant Materials, Ref. [15]**

| Material | GJ/Tonne of Material |
|---|---|
| **Aluminum** | 208 |
| **$B_4C$** | 211 |
| **Calcium (Quicklime)** | 9 |
| **Chromium** | 83 |
| **Concrete** | 1.4 |
| **Copper** | 131 |
| **Helium** | 536 |
| **Insulation Materials** | 95 |
| **Lead** | 35 |
| **Lithium** | 853 |
| **Manganese** | 52 |
| **Mercury** | 87 |
| **Molybdenum** | 378 |
| **Nickel** | 184 |
| **NbTi** | 211 |
| **Silver** | 16,800 |
| **Sodium Metal** | 124 |
| **Steel - Carbon/Low Alloy** | 34 |
| **Steel - Stainless** | 53 |
| **Vanadium** | 3,710 |
| **Yttrium** | 1,470 |
| **Zirconium** | 1,610 |

and variation between material's energy intensities. Note that unless otherwise stated, most of these values refer to the raw ingot form of the metals, not the fabricated product, therefore they may slightly underestimate the total energy input.

Examples of the $CO_2$ emission factors of power plant materials used in this analysis are given in Table 3. These values were calculated by multiplying the $CO_2$ emission factor of specific fuels by the quantity of the fuels used to manufacture the materials. These results are consistent with the energy intensity of the materials listed in Table 2. Note that the $CO_2$ emission factors vary between materials by a factor of a 1,000 or more.

**Table 3: The $CO_2$ Emission Factors for the Procurement of Power Plant Materials, Ref. [15]**

| Material | kg $CO_2$ per Tonne of Material |
|---|---|
| **Aluminum** | 13,300 |
| **$B_4C$** | 13,200 |
| **Calcium** | 619 |
| **Chromium** | 5,390 |
| **Concrete** | 520 |
| **Copper** | 7,450 |
| **Helium** | 33,600 |
| **Insulation Materials** | 5,680 |
| **Lead** | 2,500 |
| **Lithium** | 53,00 |
| **Manganese** | 3,500 |
| **Molybdenum** | 20,300 |
| **Mercury** | 4,940 |
| **Nickel** | 9,830 |
| **NbTi** | 13,200 |
| **Silver** | 1,060,000 |
| **Sodium Metal** | 7,730 |
| **Steel - Carbon/Low Alloy** | 2,470 |
| **Steel - Stainless** | 3,280 |
| **Vanadium** | 228,000 |
| **Yttrium** | 84,000 |
| **Zirconium** | 97,200 |

## 6. Mass Requirements for the Four Electrical Power Plants

A summary of the non-fuel mass required for each power plant (normalized to a $GW_e$-y of electrical energy produced) is given in Table 4. As expected, the smallest mass requirement is for the coal power plant and the largest is for the fusion reactor. The fusion system is large because of its inherently lower power density compared to fission reactors and the need to shield from 14 MeV neutrons (i.e., thick walls of the primary containment structure). The large normalized mass required for wind units results from the fact that the wind unit operates only approximately one third of the time that a coal plant operates and therefore suffers from a reverse economy of scale. The mass requirements as shown in Table 4 were coupled with the energy intensity factors of Table 2 to yield the energy investment for construction materials. This is listed in Table 5.

**Table 4: Summary of Power Plant Materials (Tonnes/$GW_e$-installed)**

| | **Coal**[11] | **Fission**[12] | **Fusion**[13] | **Wind**[14] |
|---|---|---|---|---|
| **Aluminum** | 255 | 18 | 323 | 0 |
| **$B_4C$** | 0 | 0 | 1,374 | 0 |
| **Chromium** | 122 | 0 | 0 | 0 |
| **Concrete** | 74,257 | 179,681 | 505,799 | 305,891 |
| **Copper** | 454 | 729 | 6,951 | 211 |
| **Fiberglass** | 0 | 0 | 0 | 19,863 |
| **Helium** | 0 | 0 | 94 | 0 |
| **Insulation Materials** | 0 | 922 | 0 | 0 |
| **Lead** | 0 | 46 | 13,898 | 0 |
| **Lithium** | 0 | 0 | 1,153 | 0 |
| **Manganese** | 112 | 434 | 0 | 0 |
| **Mercury** | 0 | 0 | 2 | 0 |
| **Molybdenum** | 42 | 0 | 0 | 0 |
| **Nickel** | 10 | 125 | 708 | 0 |
| **NbTi** | 0 | 0 | 144 | 0 |
| **Silver** | 0 | 0.5 | 0 | 0 |
| **Sodium Metal** | 0 | 0 | 12,085 | 0 |
| **Steel – Carbon / Low Alloy** | 39,681 | 33,988 | 50,835 | 75,516 |
| **Steel - Stainless** | 612 | 2,080 | 56,883 | 9,049 |
| **Vanadium** | 4 | 0 | 0 | 0 |
| **Yttrium** | 0 | 0 | 3 | 0 |
| **Zirconium** | 0 | 0 | 68 | 0 |
| Total | **115,550** | **217,590** | **650,319** | **410,529** |

| **Table 5: Energy Investments for Electricity Generating Plants ($TJ_{th}/GW_{e}y$)** | | | | |
|---|---|---|---|---|
| **Process** | **Coal** | **Fission** | **DT-Fusion** | **Wind*** |
| Construction Materials | 55 | 58 | 269 | 676 |
| Plant Construction | 92 | 137 | 335 | 199 |
| Fuel Mining | 1,258 | 88 | 48 | NAppl. |
| Fuel Preparation (cleaning, milling, enrichment, etc.) | incl. in mining | 1,203 | incl. in mining | NAppl. |
| Fuel Transportation | 1,059 | 8 | neg. | NAppl |
| Operation | 440 | 239 | 435 | 489 |
| Waste Disposal & Transportation | 6 | 172 | 16 | NAvail. |
| Decommissioning | 10 | 19 | 55 | 50 |
| Land Reclamation (fuel only) | 4 | 0.1 | neg. | neg. |
| **Total** | 2,925 | 1,923 | 1,158 | 1,414 |
| | | | | |
| **Energy Payback Ratio** | **11** | **16** | **27** | **23** |

*w/o energy storage

## 7. Lifetime Energy Inputs for the Four Electrical Power Plants Considered Here

A summary of the energy investments for the four power plant options considered in this paper is given in Table 5 where the results are normalized to a $GW_{e}y$ of net electrical energy. Note that the wind generation numbers do not include energy storage. If that were included, the EPR would be somewhat lower.

## 8. Carbon Dioxide Emissions From the Four Electrical Power Plants Considered Here

The normalized $CO_2$ gas emission rates for the four electrical power plants considered here are listed in Table 6. The results are given in tonnes of $CO_2$ per $GW_{e}h$. Note that the wind numbers do not include energy storage. If the storage were included, the $CO_2$ gas emission rates would be slightly higher.

**Table 6: Comparison of $CO_2$ Emissions from Energy Systems, by Process (Tonne $CO_2/GW_eh$)**

| Process | Coal | Fission | DT-Fusion | Wind* |
|---|---|---|---|---|
| Materials (non-fuel) | 0.6 | 0.7 | 2.8 | 8.6 |
| Plant Construction | 0.7 | 1.2 | 2.7 | 1.6 |
| Fuel Mining | 8.4 | 0.4 | 0.4 | NAppl. |
| Fuel Preparation (cleaning, milling, enrichment, etc.) | incl. in mining | 8.9 | incl. in mining | NAppl. |
| Fuel Transportation | 9 | 0.2 | incl. in mining | NAppl. |
| Operation | 956 | 2.2 | 3.1 | 4.0 |
| Waste Disposal & Transportation | 0.05 | 1.4 | 0.04 | NAvail. |
| Decommissioning | 0.1 | 0.01 | 0.4 | 0.4 |
| Land Reclamation (fuel only) | 0.03 | 0.001 | neg. | neg. |
| **Total** | **974** | **15** | **9** | **15** |

*w/o energy storage

## 9. Discussion of the Results

### *9.1 Energy Payback Ratios*

The most striking observation from Table 5 is the wide variation in source of energy inputs for the four types of electrical power plants considered here. Figure 2 illustrates this difference by showing the percent of energy input to the generation of electricity over the life of a plant. The data in Table 5 was regrouped into four categories:

- Fuel Mining, Preparation, and Transportation
- Plant Materials and the Construction of the Plant
- Operation of the Plant
- Decommissioning and Waste Disposal.

It is obvious from Figure 2 that the major energy input for the coal power plant is associated with the procurement of the fuel (coal) for the facility. Approximately 79% of the energy input comes from mining and transportation of the coal. On the other hand, only 5% of the lifetime energy inputs for a coal plant are tied up in the materials of construction and the actual construction of the power plant itself.

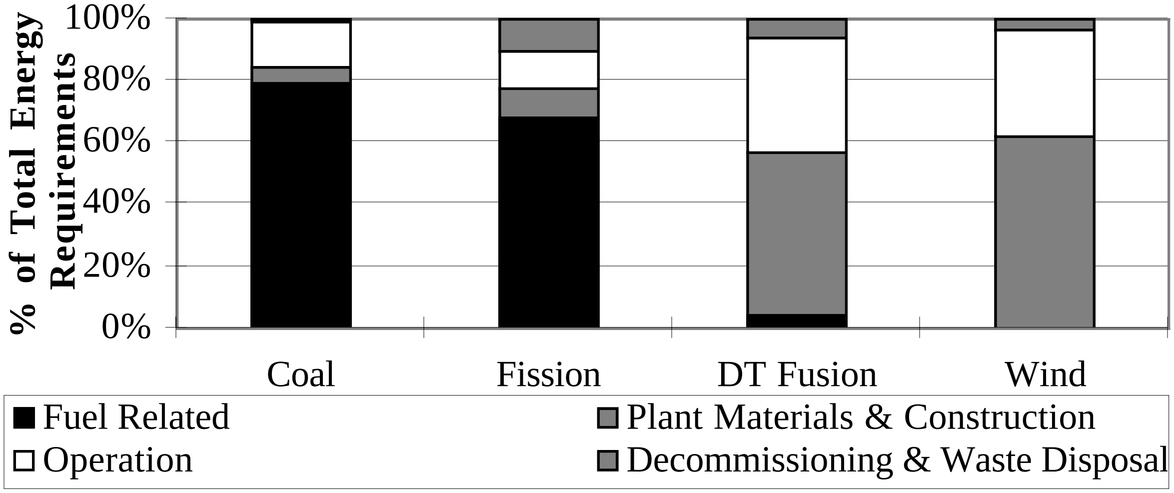

**Figure 2. The energy input to electricity generating varies considerably among the 4 power plants considered in this study.**

While the concentration of energy in the fuel cycle is no surprise for coal units, it is somewhat surprising that it plays such an important role in the LWR fission facilities (accounting for two thirds of the energy input over the plant lifetime). Because of the need to enrich the uranium fuel in $^{235}$U from 0.711% to ≈3%, a great deal of electrical energy is required. For this paper, it was assumed that gas centrifuge technology was used to enrich the uranium. If gaseous diffusion technology were used, the fraction of the energy input to the fuel cycle would be even higher.

In contrast to the coal and fission power plants, there is very little energy invested in the fuel cycle for DT-fusion (≈4%) and nearly 52% of the energy requirements come from the construction materials and the plant construction itself. The reason for this dramatic shift is the fact that DT-fusion has a very low power density in the reactor compared to fission and the reactors are much bigger. In addition, the surrounding buildings need to be bigger. The need to shield people and equipment from 14 MeV neutrons also results in rather thick (1-2 meters) concrete shielding that adds to the materials inventory (see Table 4) and consequently to the energy needed to make the building itself. The high number of neutrons generated in the DT cycle and larger buildings will also place a burden on the decommissioning process which amounts to ≈6% of the energy needs. The energy needed to operate the fusion plant accounts for ≈38%.

Finally, the "fuel" for wind facilities is "free" but the structures and machinery needed to harvest wind energy are not. More than 60% of the energy input into a wind power plant comes from the materials of construction and the construction of the towers along with the infrastructure (roads, power transmission, etc.). Further complicating this analysis is that energy storage has not been included so that it is somewhat unfair to compare base loaded technologies such as coal, fission and fusion to an intermittent source of electricity like wind. Inclusion of energy storage facilities (pumped hydro, superconducting magnet energy storage, etc.) would increase the energy required for a given output. Nevertheless, when the actual materials of construction are accounted for in the Buffalo Ridge (Minnesota)[14] units, one finds that the normalized energy intensity (TJ/GW$_e$y) for the physical plant is close to that of the much larger fusion facilities and certainly greater than that needed for fission and coal facilities. One other point to note is the large fraction of energy (≈35% of the total) used in the operations of the plant. The energy consumed during the O&M is comprised of both routine maintenance (e.g., vehicles, turbines), and periodic replacement of components. The energy requirements were calculated using the actual O&M costs of Buffalo Ridge[10] and an I/O energy intensity multiplier[5].

Another way to consider the energy input information that the energy payback analysis provides is to consider the absolute, not relative, energy intensities. Figure 3 graphically shows that the energy intensities in the fuel cycle alone drop from a high of ≈2,300 TJ/GW$_e$y for coal to ≈1,300 TJ/GW$_e$y for fission and <50 TJ/GW$_e$y for DT fusion. On the other hand, the energy invested in the power plant increases from a low of ≈150 TJ/GW$_e$y for coal to a high of ≈875 TJ/GW$_e$y for wind units. Finally, the energy in plant operations ranges from a low of 240 TJ/GW$_e$y for fission to ≈490 TJ/GW$_e$y for wind plants.

A summary of the overall energy payback ratios (EPRs) is given in Figure 4. The coal units produce 11 times more energy in electricity than is required to make the electricity over the lifetime of the plant described in Table 1. The EPR is slightly higher in LWR fission plants (16) and more so for wind (23) and DT fusion facilities (27). One should remember that the values for wind do not include energy storage and that the values for DT-fusion are projected on the basis of fusion reactor designs, not operating facilities.

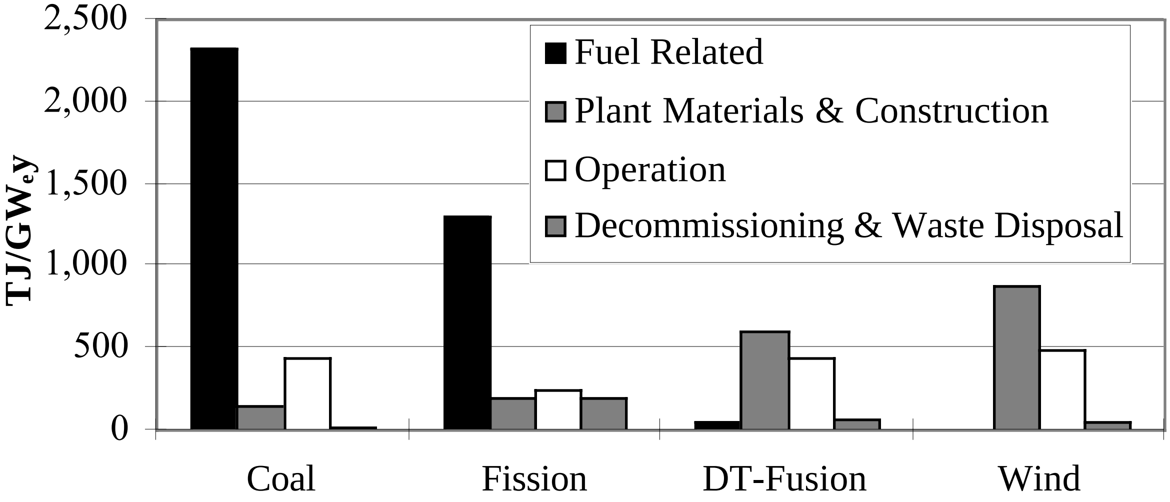

**Figure 3. The contribution to the energy payback ratio is dominated by fuel in coal and fission facilities and by power plant materials and construction in DT-fusion and wind facilities.**

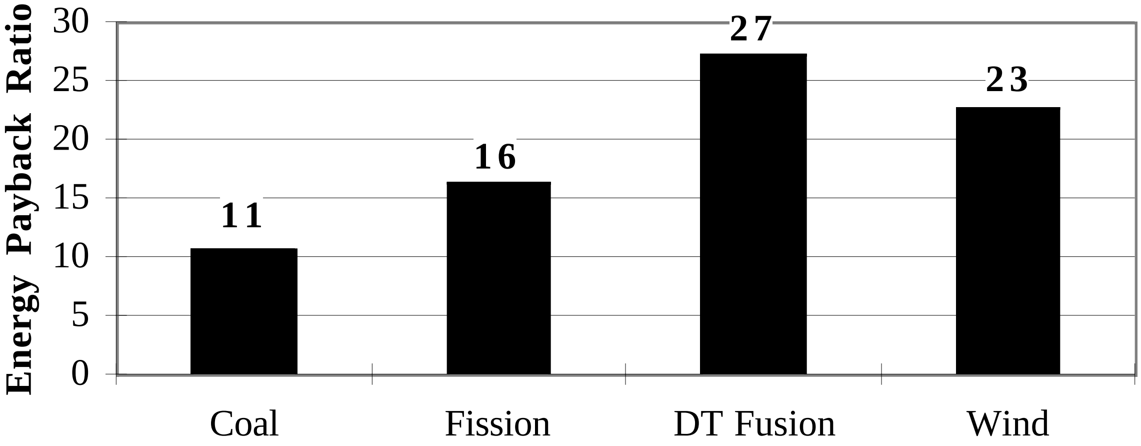

**Figure 4. The energy payback ratio (EPR) for electricity production varies by more than a factor of 2 from coal to DT-fusion power plants.**

The estimated uncertainty was calculated for the energy inputs of each power plant[15]. It is not surprising that of the four technologies analyzed, the standard deviation was greatest for the fusion power plant (=15% of mean) and lower for the three operating technologies: coal, fission and wind (<10%). Despite the variance, the range of estimated uncertainty does not affect the general ranking of energy payback ratios for the power plants by creating any overlaps.

### *9.2 $CO_2$ Emission*

With one major exception, the same general source term trends observed in the EPR analysis apply to the $CO_2$ emission rates. That exception is amply illustrated in Figure 5 where it is shown that 98% of the $CO_2$ emitted during the operation of the coal plant comes from the operation of the plant (i.e., burning of the coal) whereas 79% of the energy invested in coal fired plants stems from the procurement of the fuel (Figure 2). This is not too surprising considering that the energy in coal is released by the conversion of coal to $CO_2$ and other molecules.

Perhaps the most striking feature of the $CO_2$ analysis is the shear magnitude of the gaseous release as shown in Figure 6. Over 970 tonnes of $CO_2$ are released from coal fired plants per $GW_eh$ (the average electrical energy consumed in an hour by a United States city of 1,000,000 people). This is to be compared to 15 tonnes $CO_2/GW_eh$ released from the generation of electricity by fission plants and wind facilities, and ≈9 tonnes $CO_2/GW_eh$ from DT-fusion plants.

The estimated uncertainty was calculated for the $CO_2$ emissions of each power plant[15]. The standard deviation was smallest for the coal plant (<5% of mean) and highest for the fission plant (=13%). The standard deviation of the coal-fired power plant is stabilized by the high certainty of the carbon content of coal. The higher standard deviation of the LWR was due to possible variations of the electrical mix used to enrich uranium. The range of uncertainty does not significantly vary the total $CO_2$ emissions of each power plant.

## 10. Conclusions

The results from this analysis show that there is more than a factor of two in the net energy payback ratios for coal, fission, wind, and DT-fusion electrical power plants. It is found that the energy inputs to various energy facilities are identified with a wide variety of sources. Fuel tends to dominate the coal and fission systems while the construction materials and plant construction dominates in the DT-fusion and wind units.

Perhaps the most important result of this analysis is the tabulation of $CO_2$ emission rates for the non-coal facilities. This leads to the realization that in contrast to popular belief, the nuclear and wind facilities are not zero-emission energy sources and that when a proper accounting method is used, values ranging from 8 to 17 tonnes of $CO_2/GW_eh$ are calculated. Certainly the $CO_2$ emissions from non-fossil fuel sources are much smaller than the ≈974 tonnes $CO_2/GW_eh$ from coal fired power plants (as well as natural gas and oil fired units). It is

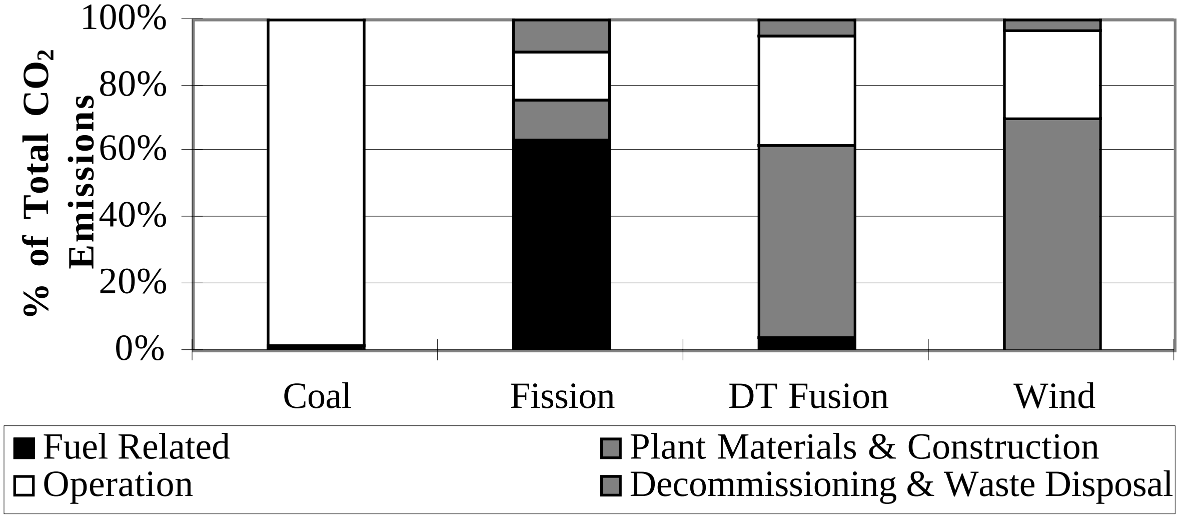

**Figure 5. The contribution to the $CO_2$ emission rates varies widely between the 4 power plants considered here.**

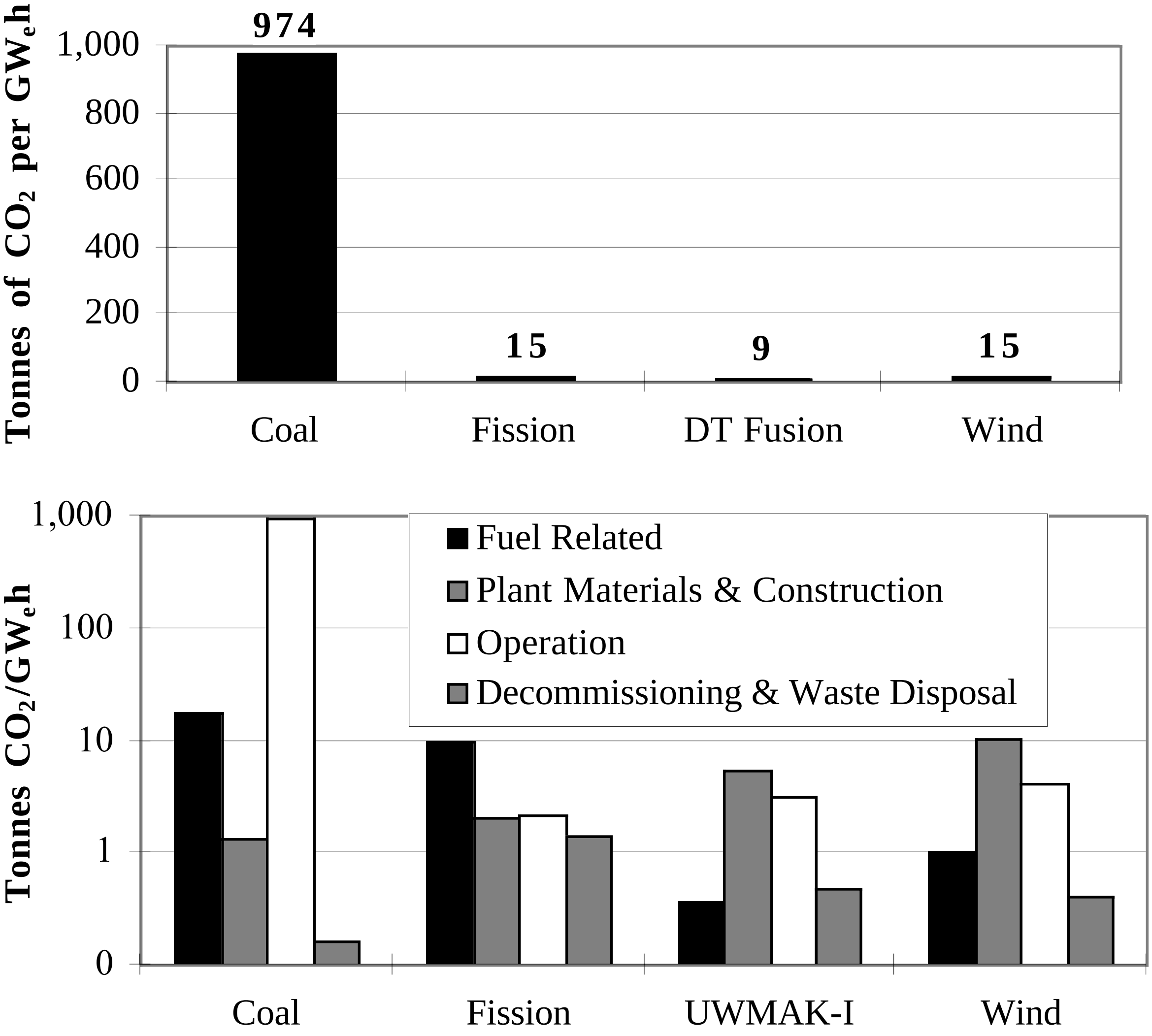

**Figure 6. The $CO_2$ emission per $GW_eh$ is dominated by the combustion of coal (Figure 6a) but other factors such a procurement of fuel, construction materials, and the building, operating and decommissioning of the fission, DT-fusion, and wind power plants contributes ≈ 6-15 tonnes of $CO_2$ per $GW_eh$ (Figure 6b).**

important to recognize that any electrical power producing facility will require some fossil energy inputs, and thus, result in some greenhouse gas emissions.

## Acknowledgment

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