Energy Payback Ratios and Lifetime CO_2 Emission Levels for DT and D^3He Fusion Power Plants

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Abstract

The amount of electrical energy produced over the lifetime of DT- and D^{3}He-fusion 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 is similar for the two quite different fuel cycles, 31 for D^{3}He-fusion and 27 for DT-fusion, even though there is a significant difference in the source of invested energy. The CO_2 emission factor is calculated from the energy investment and the source of the various energy inputs. This number is similar for both fusion fuel cycles, with ≈9 tonnes of CO_2 per GW_eh for DT-fusion and ≈10 tonnes of CO_2 per GW_eh for D^{3}He-fusion.

1. Introduction

A number of uncertainties face the world's future electrical generation industry. As *developing* nations rapidly increase their energy consumption and the energy needs of *developed* nations are increasingly met by electricity, new sources of this energy will be required. It is unlikely that natural gas and oil supplies will remain economically viable fuels for the production of electricity as the midpoint of the 21st century is approached. It is possible that by 2050, the annual amount of electricity generated worldwide will be 2-3 times greater than the present rate[1].

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

It is likely that of the two fusion fuel cycles analyzed here, the deuterium-tritium fuel cycle will be the first to become economically viable due to more favorable physics and availability of the fuel. Deuterium-helium-3 (D^{3}He) fusion power plants will likely be the second generation fusion plants. The main advantage of D^{3}He-fusion plants comes from the reduction by a factor of 50-100 of the number of neutrons emitted per kWh. This advantage will greatly reduce the radiation damage in the D^{3}He system and result in much smaller amounts of radioactive waste generated when compared to fission and DT-fusion. The main drawback to D^{3}He-fusion is that there are no abundant terrestrial sources of ^{3}He. Wittenberg et al.[2] first proposed that the Moon, discovered to have trapped one million tonnes of ^{3}He in its regolith, could supply the necessary ^{3}He for a D^{3}He-fusion economy.

Most successful power plants must excel in the areas of economics, safety, reliability, and environmental impact. This paper will focus on two of the issues that feed into the economic and environmental impact assessments of these energy sources. One focus is the energy payback ratio, which is a ratio of useful energy derived from the plant over its life, divided by the total amount of energy invested in the power plant. The second measurement is the amount of carbon dioxide (CO_2) gas that is emitted by all of the power plant activities over the life of the facility. A common view is that nuclear power does not emit greenhouse gases. However, when all of the energy (most of it from fossil fuels) invested in the fuel procurement, construction materials, and operation of the plant are accounted for, there is a finite amount of greenhouse gases emitted.

It is recognized that there are many other issues that will influence future debates in which future 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 of the energy payback ratio 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:

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

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

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

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

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

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

There are two approaches commonly used in calculating the energy requirement part of the energy payback ratio; the Input/Output method (I/O)[3, 4] and the Process Chain Analysis (PCA)[5, 6]. The I/O is an economic tool assigning an energy intensity to monetary costs of different services and materials. The PCA is an engineering tool which analyzes the actual energy consumed for various materials and services, totaling up the energy requirements of each link in the chain. The analysis in this paper follows the PCA method, though the energy requirements for some of the individual processes were calculated using the I/O method. In the case of fusion, these processes include power plant construction and decommissioning. The details are outlined in refs. [7, 8].

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[9-11] have been conducted to determine the pollutants released during the mining of coal, the mining of Fe, railroad transportation of freight, etc. The analyses include both the thermal and electrical energy input. 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, or fusion fuels. 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 amortized over a GW_ey of net electricity sent to consumers). An example is given 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 power plants used for this study are summarized in Table 1. For simplicity, the capacity factors were all chosen to be 75% for each. While this is merely an assumption for the fusion plants, which haven't been built, it is close to the current performance of coal and fission plants. The inventory of materials required for construction was taken from the references listed in Table 1. The mass of steels, other metals and concrete are normalized at the bottom of the table in tonnes/GW_e-installed.

The DT-fusion plant is based on the UWMAK-I reactor[12], which contained the most detailed and comprehensive fusion reactor material inventories available. The D^3He-fusion reactor design is based on the ARIES-III[13] nuclear island, with the balance of plant scaled from the UWMAK-I design properly adjusted for the different power conversion cycles.

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

Parameter	**Coal**[14]	**Fission**[15]	**DT Fusion**[12]	**D^{3}He Fusion**[13]
Power Level-MWe	1,000	1,000	1,494	1,000
Fuel	US average coal-1990	3% enriched U Gas Centrifuge	Deuterium-Tritium	Deuterium - Helium-3
Capacity Factor-%	75	75	75	75
Life-CY	40	40	40	40
Other	Conventional Steam Plant	Pressurized Water Reactor	• Tokamak • UWMAK-I	• Tokamak • ARIES-III
Mass (tonnes/GWe): Steels	40,416	36,068	107,718	65,430
Other Metals	877	919	36,708	3,655
Concrete	74,257	179,681	505,799	490,050

5. Energy Intensity and CO_2 Emission Factors for Materials

The energy intensities and CO_2 emission factors for power plant materials are listed in ref. [7] along with a complete inventory of materials for each power plant.

6. Energy Intensity and CO_2 Emission Factors for Helium-3 Fuel Cycle

The ^{3}He fuel cycle is the most complex of the four power plants listed in Table 1. Because of the lack of a sufficient terrestrial source of ^{3}He, it has been proposed that the Moon is the nearest and best source for the fuel[2]. Based on a 50-year projection of the electricity needs of the United States beginning in 2025, it was assumed that D^{3}He fusion would begin with a 0% share of the total U.S. electricity market in 2025 and end with 33% in 2075. Once the electrical demand was established, the amount of ^{3}He needed was determined and from this the mass of materials needed on the Moon for a lunar outpost dedicated to the mining of the fuel was calculated. The total imported mass needed to build and sustain a lunar outpost as well as the number of crew that traveled between the Earth and Moon determined the number of rocket trips to the Moon[7].

The space transportation system used in this analysis was based upon the 6,000 tonne NEPTUNE heavy lift launch vehicle (HLLV) as detailed in ref.[16]. The system is comprised of an HLLV with separate stage 3 modules for cargo and passenger trips. These HLLV's carry the payload from Earth to a lunar space station where cargo and passengers are transferred to a Lunar Bus (LUBUS) which transports the payload to the lunar base.

For the energy analysis, the embodied energy of all materials exported to the Moon and the rockets themselves was calculated based on the energy intensity of titanium[7]. The masses for habitat modules and lunar outposts were taken directly from work performed by H. Hermann Koelle[17, 18], while the mass for the miner is from Sviatoslavsky[19]. Masses for the volatile separation facility, miner maintenance facility, ancillary equipment and consumables were estimated based on Koelle's data. Around 50,000 tonnes of materials were estimated to be exported from the Earth to the Moon over 50 years.

The energy consumed in launches was also calculated. The HLLV's use liquid hydrogen (LH2) and liquid oxygen (LOX) for all stages. It has been assumed that the LOX for return trips was produced on the Moon as a byproduct of ^{3}He volatile separation. The energy embodied in production of the LH2 and LOX was calculated also.

The CO_2 emissions were determined in a similar manner as the energy investment. The mass of all materials exported to the Moon (including the rockets) was multiplied by the embodied CO_2 emission factor of titanium[7]. For the rocket launches, the CO_2 embodied in the production of rocket fuels was counted as was the CO_2 emitted in the Earth's atmosphere during launches.

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 2 where the results are normalized to a $GW_e y$ of net electrical energy.

8. CO_2 Gas Emissions from the Four Electrical Power Plants Considered Here

The normalized CO_2 gas emission rates for the power plants considered here are listed in Table 3. The results are given in tonnes of CO_2 per $GW_e h$.

9. Discussion of the Results

9.1 Energy Payback Ratios

The wide variation of energy inputs for individual sources is shown in Table 2 for the four electrical power plants. Figure 1 illustrates this difference by showing the percentage of

Table 2. Energy Investments for Electricity Generating Plants, $TJ_{th}/GW_e y$

Process	Coal	Fission	DT-Fusion	D^3He Fusion
Fuel Mining	1,258	88	48	103
Fuel Preparation (cleaning, milling, enrichment, etc.)	incl. in mining	1,203	incl. in mining	incl. in mining
Fuel Transportation	1,059	8	neg.	incl. in mining
Construction Materials	55	58	269	126
Plant Construction	92	137	335	440
Operation	440	239	435	298
Waste Disposal & Transportation	6	172	16	4
Decommissioning	10	19	55	48
Land Reclamation (fuel only)	4	0.1	neg.	neg.
Total	2,925	1,923	1,158	1,019
Energy Payback Ratio	11	16	27	31

Table 3. Comparison of CO_2 Emissions from Energy Systems, by Process Tonne CO_2/GW_eh

Process	**Coal**	**Fission**	**DT-Fusion**	**D^3He Fusion**
Fuel Mining	8.4	0.4	0.4	1.9
Fuel Preparation (cleaning, milling, enrichment, etc.)	incl. in mining	8.9	incl. in mining	incl. in mining
Fuel Transportation	9	0.2	incl. in mining	incl. in mining
Materials(non-fuel)	0.6	0.7	2.8	1.8
Plant Construction	0.7	1.2	2.7	3.5
Operation	956	2.2	3.1	2.1
Waste Disposal & Transportation	0.05	1.4	0.04	0.01
Decommissioning	0.1	0.01	0.4	0.4
Land Reclamation (fuel only)	0.03	0.001	neg.	neg.
Total	974	15	9	10

energy input to the generation of electricity over the life of a plant. The data in Table 2 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 can be seen in Figure 1 that the energy input for coal and fission power plants is dominated by processes related to the fuel cycle, while the largest energy investment for the fusion power plants is related to construction and plant materials.

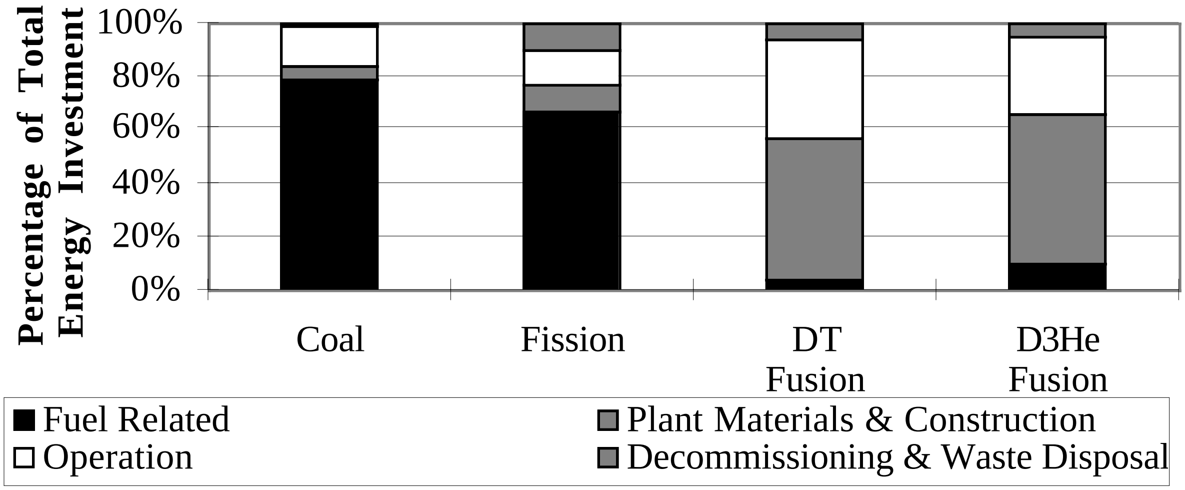

Figure 1. The energy input to electricity generating varies considerably among the 4 power plants considered in this study.

While the energy investments of coal and fission are dominated by their fuel cycles, the majority of the energy investments for the fusion plants are embodied in the power plant materials and construction activities. Nearly 52% of the energy investment in DT-fusion comes from the construction materials and plant construction itself, while ≈56% of the energy invested in D^3He-fusion comes from these same processes.

The relatively small contribution of the ^{3}He fuel cycle to the total energy investment of D^3He-fusion is perhaps the most surprising discovery considering the different source of fuels. The fuel cycle for DT-fusion comprises approximately 4% of the total, while it is 10% for the D^3He fuel cycle. Both plants require a similar amount of deuterium, which means that the energy investment in the fuel cycle of ^{3}He is nearly twice that of procuring lithium for the DT fuel-cycle. One reason the difference in the energy investment for these two fuels is not greater is due to the large difference in mass of each (3 and 1,700 tonnes for ^{3}He and Li respectively)[7]. It should be noted that Li also functions as a heat transfer medium as well, but the energy invested in the organic coolant for the D^3He plant is negligible. The largest part of the ^{3}He fuel cycle energy investment is from the transportation of mining equipment, habitat, and personnel to the Moon. Even though ^{3}He must be transported via rocket from the Moon, the fact that all lunar base and mining materials are amortized over a 50-year period, significantly reduces the energy/tonne investment of ^{3}He.

The large percentage of energy invested in the materials and the construction of the fusion power plants should not be surprising due to the fact that both DT- and D^3He-fusion have very low power densities compared to fission. This results in bigger reactors. In addition, the surrounding buildings need to be bigger. The need to shield people and equipment from 14 MeV neutrons in DT-fusion reactors also results in rather thick (1-2 meters) concrete shielding that adds to the materials inventory (see Table 1) and consequently to the energy needed to make the building itself. The smaller mass of the D^3He-fusion reactor is due to a smaller amount of neutrons produced during operation, which thereby requires less shielding for worker safety and equipment. At the same time, due to the fewer neutrons, the first wall of the D^3He reactor will not have to be replaced during the operating lifetime of the power plant.

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

The energy requirements for decommissioning the fusion plants were normalized from the values for fission based upon a ratio of the mass of materials to be removed. Because of the larger buildings and the high number of neutrons generated in the DT fuel cycle, it seems

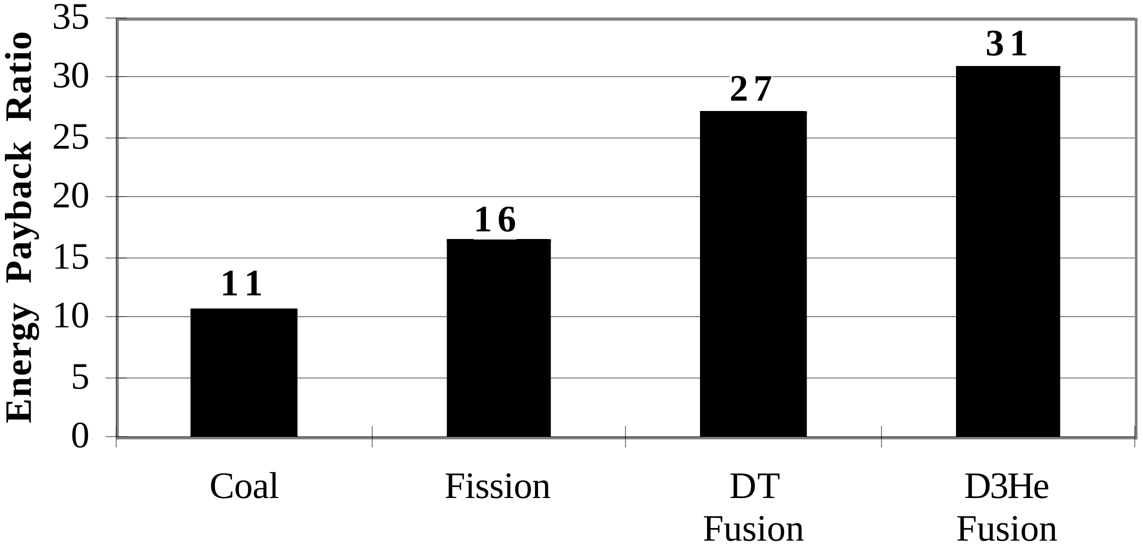

Figure 2. The energy payback ratio (EPR) for electricity production varies by more than a factor of 2 from coal to DT-fusion power plants.

natural that the absolute energy required would be higher for decommissioning the DT fusion plants compared to a fission facility. Decommissioning accounts for ≈6% of DT- and ≈5% of D^3He-fusion's energy needs.

A summary of the overall energy payback ratios (EPRs) is given in Figure 2. The coal units produce 11 times more energy in electricity than is required to make it over the lifetime of the plant. The EPR is somewhat higher in LWR fission plants (16) and projected to be 27±4 for DT-fusion and 31±5 for D^3He-fusion facilities. One should remember that the values for fusion are projected on the basis of fusion reactor designs, not operating facilities.

9.2 CO_2 Emission

For each power plant, except coal, the trend for CO_2 emissions parallels the energy investment, which can be seen in Figure 3. For coal, 98% of CO_2 is emitted during the operational phase, while ≈79% of the energy consumed is related to the fuel cycle. For fission, and both fusion plants, the CO_2 emissions vary slightly from the energy investment percentages. Half of the CO_2 emissions for both fusion plants are related to the plant materials and construction. The contribution of CO_2 from the ^3He fuel cycle procurement is 19% of the total, which is higher than the 4% of energy from similar processes in the DT cycle. Figure 4 shows the magnitude of the CO_2 emissions per GW_eh for the four power plants. The total CO_2 emissions for both fusion power plants are nearly the same. The DT-fusion power plant has a total of 9±1 tonnes of CO_2 per GW_eh, while the D^3He-fusion power plant is responsible for 10±2 tonnes of CO_2 per GW_eh.

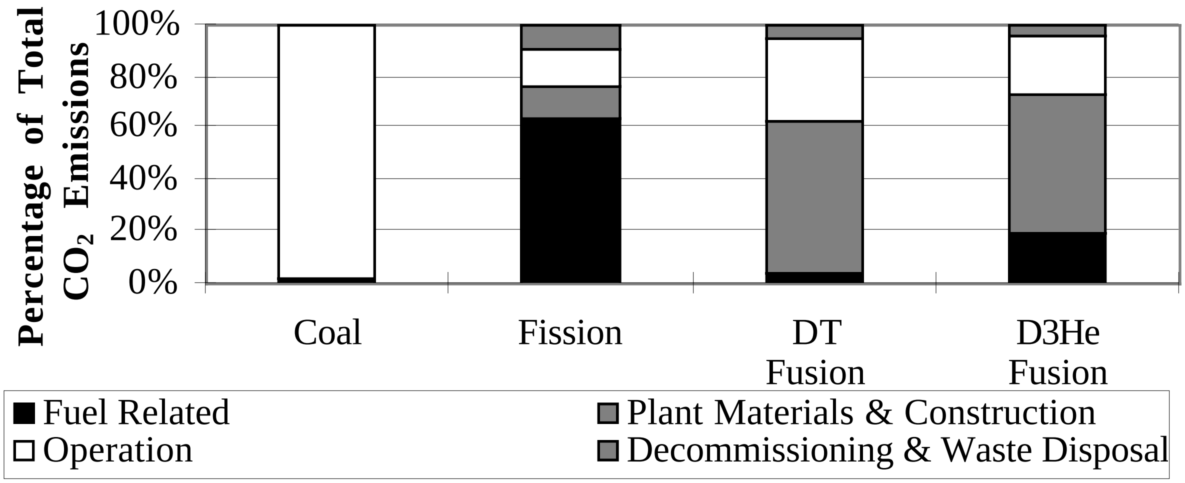

Figure 3. The contribution to the CO_2 emission rates varies widely between the 4 power plants considered here.

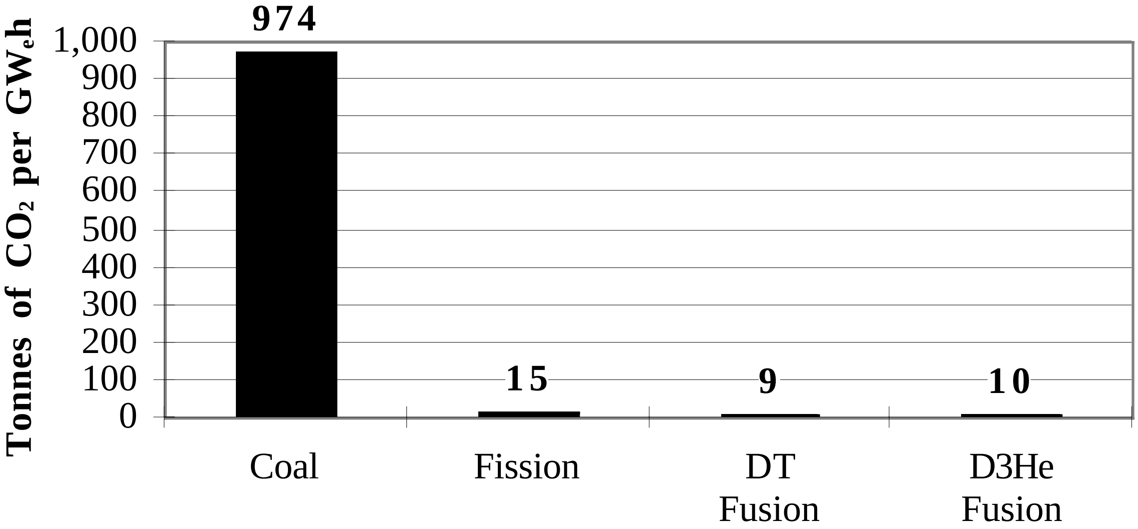

Figure 4. The CO_2 emission per GW_eh is dominated by the combustion of coal.

10. Conclusions

The results from this analysis show that there is more than a factor of two difference in the net energy payback ratios for coal, fission, DT-fusion and D^3He-fusion electrical power plants. It is found that the energy inputs to various energy facilities are identified with a wide variety of sources. While the energy investment in procuring the fuel tends to dominate the coal and fission systems, the construction materials and plant construction dominate the DT- and D^3He-fusion plants.

Perhaps the most important result of this analysis is that the D^3He-fusion fuel cycle requires a similar amount of energy as that of DT-fusion, despite having to leave our biosphere to obtain the helium-3. With nearly identical EPR's and CO_2 emission factors, attention can be focused on the reduced level and amount of radioactive waste that is inherent to D^3He-fusion power plants. The intangible effect of reduced radioactive waste on societal acceptance must be explored in the future.

Another important conclusion is that nuclear facilities are not zero-emission energy sources and that when a proper accounting method is used, values ranging from 9 to 15 tonnes of CO_2/GW_eh are calculated. Such numbers are certainly much smaller than the ≈970 tonnes CO_2/GW_eh from coal fired power plants, but it is important to recognize that any electrical power producing facility will require some fossil energy input, thus resulting in some greenhouse gas emissions. Nuclear technologies cannot be called a "no-emissions" technology, but compared to coal and other fossil fuels, they are a "low-emissions" option.

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