Energy Payback Ratios and CO_2 Emissions Associated with the UWMAK-I and ARIES-RS DT-Fusion Power Plants

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ABSTRACT

The amount of electrical energy produced over the lifetime of the ARIES-RS and UWMAK-I DT-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 varies slightly for the two power plants; 23 for ARIES-RS and 26 for UWMAK-I. By knowing the magnitude of the energy investment and the source of the various energy inputs, a CO_2 emission factor is calculated. This number is similar for both fusion power plants with ≈8 tonnes of CO_2 per GW_eh for UWMAK-I and ≈9 tonnes of CO_2 per GW_eh for ARIES-RS. These fusion plants are compared to other existing electrical producing power plants.

I. INTRODUCTION

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

This paper focuses on two issues that feed into the economic and environmental impact assessments of energy sources. One is the energy payback ratio (EPR), 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 CO_2 gas that is emitted during procurement of all the materials, services, and fuels over the life of the power plant, including operation.

In previous work,[3,4] coal, fission, DT-fusion (UWMAK-I),[5] and wind power were analyzed and compared in terms of these two issues. This paper focuses on comparing an advanced DT-fusion tokamak design (ARIES-RS)[6] to an older design (UWMAK-I). Other electricity generation technologies are included for comparison. The ARIES-RS, as well as many newer DT-fusion designs, feature advanced, low-activation materials, such as vanadium in the nuclear island.

II. CALCULATION OF ENERGY PAYBACK RATIO AND CO_2 EMISSIONS

Details to the approach used in this study can be found in previous publications.[3,4] Both the lifetime energy requirements and CO_2 emissions were mainly determined by following the process chain analysis[7,8] method, while the energy requirements for some of the individual processes, such as power plant construction and operation, were calculated using the Input/ Output[9,10] method of energy accounting.

III. POWER PLANT SELECTION

The major parameters of the four types of power plants used for this study are summarized in Table 1. For simplicity, the capacity factors for the base loaded plants were chosen to be 75%. The actual capacity factor for the wind facility analyzed was 24%.[11] While this is an assumption for the fusion plants that have not been built, it is close to the current performance of coal and fission plants. The capacity factor for the wind unit is calculated from actual production data.[11] The inventory of materials required for construction was taken from the references listed in Table 1. The mass of steel, other metals and

[a] Annual growth rates of 1.4% and 3.1% for low- and high-growth forecasts, respectively.
[b] Electricity demands were forecast to increase by an average of 1.8% to 3.4% per year until year 2020.[1]

Table 1. Summary of Power Plant Designs Used to Determine Energy Payback Ratio					
Parameter	Coal[12]	Fission[13]	Fusion[5]	Fusion[6]	Wind[14]
Power Level-MWe	1,000	1,000	1,494	1,000	25
Fuel	US average-1990	3% enriched U	Deuterium--Tritium	Deuterium-Tritium	Not Applicable
Capacity Factor-%	75[c]	75[c]	75[c]	75[c]	24[d]
Life-calendar year	40	40	40	40	25
Other	Conventional Steam	Pressurized Water Reactor	Tokamak UWMAK-I	Tokamak ARIES-RS	• 3 blade • No energy storage
Mass (tonnes/GWe): Steel	40,416	36,068	107,718	73,250[e]	84,565
Other Metals	877	919	36,708	7,425 [e]	211
Concrete	74,257	179,681	505,799	444,682 [e]	305,891

c = assumed, d = calculated from ref. 11, e = the mass of BOP was scaled from UWMAK-I (see ref. 15 for details)

concrete are normalized at the bottom of the table in tonnes/GW_e-installed.

One of the DT-fusion plants is based on the UWMAK-I reactor which contained the most detailed and comprehensive fusion reactor material inventories available even though the plant is conservatively designed by today's standards. ARIES-RS reflects a contemporary approach to fusion where the TF magnets have twice the field strength and neutron/heat flux wall loadings are 3-5 times higher than those used in UWMAK-I.

IV. ENERGY INTENSITY AND CO_2 EMISSION FACTORS FOR MATERIALS

The energy intensities and CO_2 emission factors for power plant materials and construction services are listed in a previous work.[15] A complete inventory of materials for each power plant, as used in this study, is also compiled in ref. 15.

V. ENERGY INTENSITY AND CO_2 EMISSION FACTORS FOR ARIES-RS

A key difference between the ARIES-RS and UWMAK-I power plants is that ARIES-RS uses vanadium as a higher-temperature structural material instead of stainless steel. This makes a large differencein the energy requirements for the plant due to the high embodied energy content in a unit mass of vanadium. Stainless steel requires around 50 GJ/tonne[16] to manufacture, whereas vanadium requires over 3,700 GJ/tonne.[17] Lithium is a coolant and breeder for both.

There is also a difference in the detail of the two designs. The design for UWMAK-I is very detailed and includes the types and mass of materials for the entire balance of plant (BOP). The ARIES-RS design was limited to the fusion power core only. The BOP for ARIES-RS was based on that of UWMAK-I, with adjustments made due to a lack of thermal flywheels and energy storage in ARIES-RS and a difference in heat exchangers. The BOP mass of the ARIES-RS was scaled from UWMAK-I data by the ratio $(MW(th)_{ARIES\text{-}RS}/MW(th)_{UWMAK\text{-}I})^{0.8}$.

VI. LIFETIME ENERGY INPUTS

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. Note that the wind generation numbers do not include energy storage. If that were included, the EPR would be lower.

VII. CO_2 GAS EMISSIONS

The normalized CO_2 gas emission rates for the four electrical power plants considered here are listed in Table 3. 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 for the wind units would be slightly higher.

VIII. DISCUSSION OF THE RESULTS

A. Energy Payback Ratios

The most striking observation from Table 2 is the wide variation in source of energy inputs for the four types of electrical power plants considered. Figure 1 illustrates this difference by showing the origin of energy input to the generation of electricity over the life of a plant. The data in Table 2 was regrouped into four categories:

- Fuel Related (Mining, Preparation, and Transportation)
- Plant Materials and Construction of the Plant
- Operation of the Plant

Table 2. Energy Investments for Electricity Generating Plants $TJ_{th}/GW_{e}y$					
Process	**Coal**	**Fission**	**UWMAK-I**	**ARIES-RS**	**Wind***
Fuel Mining	1,258	88	48	30	NAppl.
Fuel Preparation	incl. in mining	1,200	incl. in mining	incl. in mining	NAppl.
Fuel Transportation	1,059	8	incl. in mining	incl. in mining	NAppl.
Materials(non-fuel)	55	58	302	581	578
Plant Construction	61	99	335	376	242
Operation	283	384	435	318	517
Waste Disposal & Transportation	TBD	172	16	6	NAppl.
Decommissioning	10	19	55	45	72
Land Reclamation	3	0.1	negl.	negl.	negl.
Total	2,737	2,028	1,191	1,352	1,387
Energy Payback Ratio	12	16	26	23	23

*w/o energy storage

• Decommissioning and Waste Disposal

It is obvious from Figure 1 that the major energy input for the coal power plant is associated with the procurement of the fuel (coal) for the facility. Approximately 85% of the energy input comes from mining and transportation of the coal. On the other hand, only 4% of the lifetime energy input for a coal plant is tied up in the materials of construction and the actual construction of the power plant itself. The energy requirements for fission plants are also dominated by the fuel (64%).

In contrast to the coal and fission power plants, there is very little energy invested in the fuel cycle for UWMAK-I (≈4%) and ARIES-RS (≈2%), while nearly 53% of the energy investment in UWMAK-I and 70% of that for ARIES-RS comes 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 larger. In addition, the mass of the surrounding buildings is larger. 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 1) 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. This amounts to ≈6% of the energy needs of UWMAK-I and ≈4% of ARIES-RS. The energy needed for operation accounts for ≈36% and ≈24% for the UWMAK-I and ARIES-RS DT-fusion plants respectively. A large contribution to the operational energy is the cryoplant for the superconducting magnets that need to be cooled down during the 3-month average downtime per year.

The biggest difference between the energy requirements for the UWMAK-I and ARIES-RS DT-fusion reactors is in the construction materials. Around 70% of

Table 3. Comparison of CO_2 Emissions from Energy Systems, by Process Tonne $CO_2/GW_{e}h$					
Process	**Coal**	**Fission**	**UWMAK-I**	**ARIES-RS**	**Wind***
Fuel Mining	8.4	0.4	0.3	0.2	NAppl.
Fuel Preparation	incl. in mining	10.2	incl. in mining	incl. in mining	NAppl.
Fuel Transportation	9	0.2	incl. in mining	incl. in mining	NAppl.
Materials(non-fuel)	0.6	0.7	3.0	4.9	11
Plant Construction	0.5	0.8	1.2	1.3	2
Operation	956	3.1	3.1	2.3	4.1
Waste Disposal & Transportation	TBD	1.4	0.04	0.01	NAvail.
Decommissioning	0.1	0.01	0.4	0.4	0.6
Land Reclamation	0.03	0.001	negl.	negl.	negl.
Total	974	17	8	9	18

*w/o energy storage

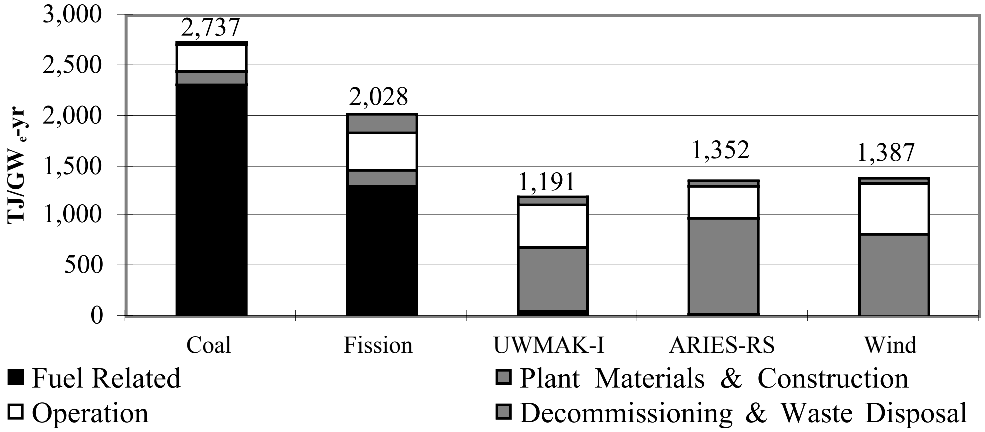

Figure 1. The energy input to electricity generation varies considerably among the 5 power plants considered in this study.

the energy needs for the ARIES-RS are associated with the plant materials and construction, which is in turn greater than the 53% of the energy needs for these same processes in UWMAK-I. The differencenoted is not due to the mass of materials, but in the type of materials themselves. More than 580 $TJ_{th}/GW_{e}y$ are required for the ARIES-RS materials, nearly twice that of UWMAK-I, which requires 302 $TJ_{th}/GW_{e}y$. This is primarily due to the first wall and blanket materials of each reactor.

As previously mentioned, ARIES-RS uses vanadium in the first wall and blanket. Over the lifetime of the reactor, around 3,400 tonnes of vanadium will be required for the first wall and an additional 80 tonnes will line the heat exchangers. By comparison, UWMAK-I requires 4,656 tonnes/GW_e of 316 stainless steel. Though the mass of steel is larger, the reason for the large contrast in energy requirements is due to the variance in the embodied energy requirements for vanadium and steel. Vanadium requires 3,700 GJ/tonne to manufacture,[f] which is nearly 70 times greater than the 50 GJ/tonne embodied in steel. This differencein embodied energy drives the disparity between the materials' energy requirements of each power plant design.

A summary of the overall energy payback ratios (EPR) is given in Table 2. The coal units produce 12 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 for LWR fission plants (16) and considerably higher for UWMAK-I (26) and both ARIES-RS and wind (23). 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.

[f] Based on the production of one tonne of FeV.

B. CO_2 Emissions

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 2 where it is shown that 98% of the CO_2 emitted over the life of the coal plant comes from the operation of the plant (i.e., burning of the coal) whereas 85% of the energy invested in coal-fired plants stems from the procurement of the fuel (Figure 1). 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 sheer magnitude of the gaseous release as evident in Table 3. 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 17 tonnes CO_2/GW_eh released from the generation of electricity by fission plants, 18 tonnes CO_2/GW_eh from wind facilities and ≈8 and ≈9 tonnes CO_2/GW_eh for the UWMAK-I and ARIES-RS DT- fusion plants, respectively.

IX. CONCLUSIONS

The results from this analysis show that there is more than a factor of two differencein the net energy payback ratios for coal, fission, wind, and DT-fusion electrical power plants. It has been 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 the fusion and wind units.

The largest difference in the energy requirements between the two fusion power plants is due to the first wall and blanket materials and the disparity of embodied energy for each. Vanadium, which is used in ARIES-RS, requires

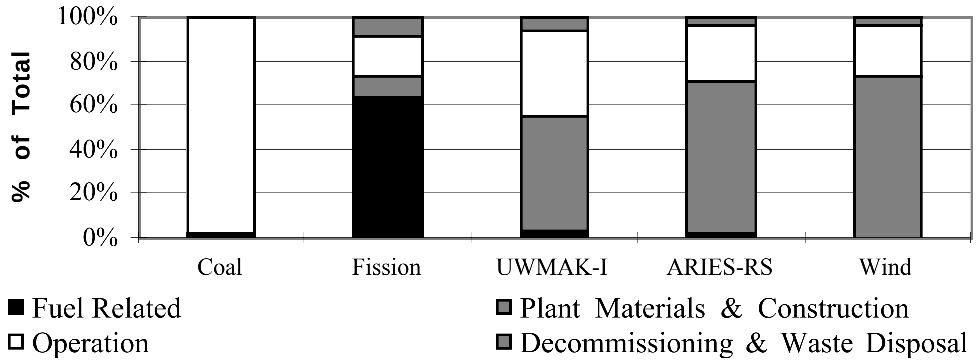

Figure 2. The contribution to the CO_2 emission rates varies widely between the 4 power plants considered here.

nearly 70 times more energy per tonne to produce than stainless steel, the first wall material of UWMAK-I.

Perhaps the most important result of this analysis is the tabulation of CO_2 emission rates for the non-coal facilities. In contrast to popular rhetoric, nuclear and wind facilities are not zero-emission energy sources. When a proper accounting method is used, values ranging from 8 to 18 tonnes of CO_2/GW_eh are calculated. Certainly such numbers are smaller by a factor of 50-100 than the ≈974 tonnes CO_2/GW_eh from coal-fired power plants (as well as similar values for natural gas and oil-fired units), but it is important to recognize that any electrical power producing facility will require some fossil energy input and, therefore, result in some greenhouse gas emission.

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