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COMPARISON OF NUCLEAR AND COAL POWER PLANTS USING NET ENERGY ANALYSIS

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Abstract

Net Energy Analysis has been used to compare coal and nuclear power plants. Net Energy Analysis is a method by which a system is studied in terms of the energy needed to construct and operate every unit or item associated with that system, its effects to the environment and the energy produced by the system. The results of the comparison are expressed as the ratio of the total energy output divided by the total energy input.

1. INTRODUCTION

The decision to develop and market new products, processes or energy systems has always been based on economic grounds. In the 1960's, environmental constraints were added to the financial considerations. In the 1970's, in particular after the 1973 "oil crisis", a new question has appeared, "How many units of energy does a system produce per unit of energy consumed for the construction, operation, etc., of that system?" In other words, are there systems which are more "energy efficient" than others and still produce the same final product? The present work tries to answer such a question for a coal-fired and a nuclear power plant, both generating electricity. The method used for the study is Net Energy Analysis (NEA).

Net Energy Analysis is an "energy" bookkeeping method in contrast to an economic analysis which is based on a monetary balance. In 1974, NEA received an official blessing of some sort when, under public law 93-577, also known as the Non-Nuclear Energy Research and Development Act of 1974, it became mandatory to provide a net energy analysis for every new technology. That law states that "the potential for production of net energy by the proposed technology at the stage of commercial application shall be analyzed and considered in evaluating proposals".

2. 'THE NET ENERGY ANALYSIS (NEA) METHOD

2.1. A BRIEF DISCUSSION OF NEA

Consider a power plant generating electricity. The consumer receives electric energy delivered through a distribution grid. However, the final product-electricity-has been subsidized by many energy-consuming items such as materials for construction, capital, labor, fuel, etc. Net energy produced by a system has been defined as the amount of energy that remains for consumer use after the energy costs of finding, producing, upgrading, and delivering the energy have been paid (1).

It becomes obvious from this statement that NEA necessitates the representation of every input and output of a process or power plant in terms of energy units. When one attempts to do this, several questions arise.

(i) Input energy of fuel. For a power plant, should that be the energy generated or the potential energy of the fuel? This is particularly important for a nuclear power plant because there is a huge difference between the potential energy of the Uranium fuel and the heat generated in the reactor. Also, how does one treat the potential energy of the Plutonium produced?

(ii) System Boundary. Is the system the power plant itself (building) or its site included? What about the area used by the mining activities?

(iii) Environmental Effects. Should the energy cost of land reclamation be counted? How should mining accidents or effects of Uranium and coal mining be taken into account? Radiation effects? And how about disabilities, chronic illnesses and deaths due to gaseous and liquid effluents from power plants?

(iv) Environmental Input. How should the environmental input be counted? For example, how does one take into account solar energy, land production or loss of production, use of running water, etc.?

(v) Different types of energy. How does one add up different kinds of energy, e.g. thermal and electrical? Should one consider different types of energy separately and keep different balances for thermal, electrical, hydroenergy, etc.? When "energy out" is compared to "energy in", which energy is it?

There is no unique answer to these questions. This is one reason why NEA is a controversial subject. The other, is the fact that NEA tries to bridge the gap between economics and energetics. By doing so, it brings together economists and engineers, two groups of people who do not necessarily use the same language. An account of the controversy surrounding NEA may be found in references 2-8.

There are two general approaches in using NEA for the study of a system (6). The first is the Input-Output analysis which is based upon the matrix approach developed by Leontieff for economics. The "energy" matrix gives the energy required to move from one sector of the economy to another, after the flow of all goods and services has been expressed in terms of their "energy cost". This energy matrix has been calculated by Herendeen and Bullard for the U.S. economy (9, 10) in terms of 1963 dollars. Table I shows a part of the matrix for a selected sector of the U.S. economy.

The second approach in Process Analysis which looks at an actual production process and determines its energy input and output. Many inputs are themselves products of other processes and one has to go back along the production chain tracing the energy input for every link of the chain.

2.2. APPLICATION OF NEA TO THIS STUDY

In this work, the input-output approach was used along with direct information, when known, about the energy consumed by a particular process. The five questions discussed in 2.1 were treated as follows

TABLE I

Energy-Cost Ratios for Selected Industrial Sectors (1963)

Sector	10^4 BTU (e)/\$	10^4 BTU (th)/\$	Total Primary Energy (10^4 BTU/\$)†
Maintenance & Repair Construction	0.2631	5.8612	6.7117
Hospitals	0.4033	2.5339	3.8374
Mining of Non-ferrous Metals, except Copper	0.9388	4.3215	7.3558
Miscellaneous Chemical Products	0.9902	25.3790	28.5800
Ground or Treated Minerals	0.9969	10.1650	13.3870
Motor Freight Transportation	0.1633	7.8759	8.4037
New Construction, Public Utilities	0.4211	6.1923	7.5534
Miscellaneous Business Services	0.3158	2.1861	3.2067
U.S. Average	0.530	6.96	8.67

†BTU (TOT) = BTU (TH) + 3.23 * BTU (EL) for 1963

(i) Input energy of fuel. Plutonium produced in a reactor was disregarded, in view of the present government policy which does not allow spent fuel reprocessing and Pu recycling. The energy input was taken as the heat generated in the reactor. For a coal plant, this problem is much simpler since essentially all the energy in the coal becomes heat and is used for the generation of electricity.

(ii) System Boundary. As far as input is concerned there is no fixed boundary. For both types of power plants, the energy input was traced through the complete cycle of the fuel used. As far as output is concerned, the boundary was taken as the switchyard, i.e., the distribution system and its associated losses were not considered. The reason for this decision is the fact that the distribution system is identical for all power plants.

(iii) Environmental Input and (iv) Environmental Effects. They were taken into account in terms of the changes caused to the environment and the energy needed to reverse the changes. Thus, the cost of land reclamation due to mining of Uranium or coal as well as the restoration of the land of the site itself was considered. Loss of production of agricultural products from the land used for mining and for the site was disregarded. It is not certain that that land would have been used for agriculture. Even if it had been, land potential is not the same in different parts of the country and to use average quantities would be erroneous. Water used for the plant was also disregarded. The water is taken from a river or lake, is used for cooling and then returned to the environment with a very small loss. The small increase in temperature that results from this water use is a long-term effect well beyond the scope of this discussion. The energy penalty for water use should be considered if it can be shown that as a result of the construction and operation of the plant, some other sector of the economy suffered a loss.

(v) Different types of energy. Energy requirements for construction and operation of a power plant over its lifetime of 30 years are determined by considering thermal and electrical energy used for all the processes and materials involved. But how does one combine these two types of energy and compare them to the energy output which is electrical energy? There is no unique answer to this question. Rotty, Perry and Reister (11) in a report prepared for the Federal Energy Administration defined four different energy ratios. Each ratio has a different aspect and answers a different question. Two of these ratios were considered in this work.

$$EG_1 = \frac{\text{Electrical Energy Out}}{\text{Equivalent thermal Energy In}} = \frac{E_o}{T_i + 3.34 * E_i} \qquad (1)$$

$$EG_2 = \frac{\text{Electrical Energy Out}}{\text{Total Energy In (All inputs Equivalent)}} = \frac{E_o}{T_i + E_i} \qquad (2)$$

Here: E_o = electrical energy output, E_i = input energy in the form of electricity, T_i = input energy in the form of heat. The coefficient 3.34, multiplying the electrical input, takes into account the fact that thermal energy is used for the production of electricity and the net efficiency of this process is $\frac{1}{3.34} \approx 30\%$. This efficiency is by no means a universally accepted number. Different investigators used numbers than range from 3 to 4. The 3.34 value is an average that takes into account distribution losses and the mix of fossil, nuclear and hydro power plants.

Equations (1) and (2) will give an indication as to how energy-efficient a particular type of power plant is. The natural tendency would be to choose the plant that maximizes the ratio chosen as the criterion. In the opposite direction, one might be tempted to say that any system that results in $EG_1 < 1$ or $EG_2 < 1$ should not be built. But, such a decision may or may not be a sound one, depending on the type of energy needed. Thermal energy cannot replace electricity. Therefore, if electricity is needed, electricity will be generated with the available fuels and processes including those that lead to ratios (1) or (2) being less than one. This fact lead us to the definition of a third energy ratio which we define in this way

$$EG_e = \frac{\text{Electrical Energy Out}}{\text{Electrical Energy In}} = \frac{E_o}{E_i} \qquad (3)$$

The ratio EG_e gives the gain of the system in terms of energies of similar quality. Whereas there is controversy about the lowest meaningful values of EG_1 and EG_2, there is no argument about the lowest value of EG_e: No system should be built with $EG_e \leq 1$.

All three ratios defined above have been utilized in this study. For this reason, a separate account of thermal and electrical energies has been kept in all cases.

3. ENERGY REQUIREMENTS FOR A PRESSURIZED WATER REACTOR (PWR)

3.1. OPERATIONAL CHARACTERISTICS OF THE PLANT

Originally, the study dealt with the PWR being built by the Union Electric Company in Callaway County, Missouri. But, as the study was proceeding, it became obvious that the results were general and could apply to any reactor of similar size. Even for a Boiling Water Reactor (BWR), the numbers would not be too different. Energy requirements were calculated for a 1 000 MWe PWR operating for 30 years with a 75% capacity factor. The reactor uses 81 metric tons of 3% enriched Uranium, 1/3 of the core being refueled each year. No reprocessing was considered. However, the cost of radioactive waste disposal was taken into account.

3.2. CALCULATION OF THE ENERGY INPUT

The energy input was divided into ten components

(1) Uranium mining
(2) Uranium milling
(3) Conversion
(4) Enrichment
(5) Fuel Fabrication
(6) Fuel Transportation
(7) Radioactive Waste Disposal
(8) Construction and Operation of the Power Plant (including maintenance)
(9) Land Reclamation
(10) Human Costs (radiation effects, mining accidents, etc.)

It was assumed that Uranium was obtained from ore containing .208% U_3O_8, it was converted to UF_6 and enriched to 3% in a gaseous diffusion plant using .2% tails. Energy requirements per metric ton of uranium are given in (11) for the first 8 components. For land reclamation it was assumed that $3 000 per acre are needed. Uranium mining amounts to 1 000 tons of ore per acre of land. The site occupies 6 600 acres, 1% of which will need reclamation. Human costs due to effects of Uranium mining, milling, radiation effects, etc., are given in (12). For both land reclamation and human costs, the money was transformed into energy by using the information given in Table I.

The results are summarized in Tables II and III. Enrichment consumes 91% of the electric energy. The biggest fraction of thermal energy, 50%, goes to construction and operation of the power plant.

To calculate the energy ratios, the total electric output of the plant needs to be calculated. This is

$1\ 000 \text{ Mwe} * 8760 \text{ h/y} * (.75) \text{ cap. factor} * 30\text{y} * 3.6 * 10^9 \frac{\text{J}}{\text{Mwh}} = 709\ 560 \text{ TJ}$. The energy ratios are

$$EG_1 = \frac{709560}{176569} = 4.02 \qquad (4)$$

$$EG_2 = \frac{709560}{41566 + 37739} = 8.95 \qquad (5)$$

$$EG = \frac{709560}{41566} = 17.07 \qquad (6)$$

The plant produces 23 562 TJ of electric energy per year. The years of operation it takes to produce (pay off) the energies used in the denominators of Eqts. 4-6 are, 7.46, 3.35 and 1.76 years respectively.

3.3. EFFECT OF CHANGES IN ENRICHMENT TAILS

The results of section 3.2 were based on 3% enriched fuel and .2% enrichment tails at the gaseous diffusion plant. The value of the tails affects the amount of Uranium feed needed for the enrichment plant as well as the number of SWU's. A series of calculations was performed using tails from .2% up to .65%. The results are shown in Table IV. There is an "optimum" value of tails, which is about .5% for EG_1, .4% for EG_2 and .6% for EG_e.

4. ENERGY REQUIREMENTS FOR A COAL-FIRED PLANT

4.1. OPERATIONAL CHARACTERISTICS OF THE PLANT

The operational characteristics of the fossil plant are those of the Monroe power plant owned by the Detroit Edison company. It is a 750 Mwe plant that will use deep mined coal. Its total cost was reported to us to be $\$141 * 10^6$ (1974). It will use $1.55 * 10^6$ tons of coal per year. The lifetime and the capacity factor were taken to be the same as those of the PWR (30y, .75%).

TABLE II

Energy Requirements For A 1000 MWe PWR

		Electric (TJ)	Thermal (TJ)	Total (3.34 * EL + TH)
1.	U-Mining	330	2 641	3 743
2.	U-Milling	376	2 623	3 879
3.	Conversion	249	6 722	7 554
4.	Enrichment	37 944	3 132	129 865
5.	Fuel Fabrication	936	2 338	5 464
6.	Transportation	9	351	381
7.	Rad. Waste Disposal	19	206	269
8.	Power Plant Construction and Operation	1 660	19 100	26 644
9.	Land Reclamation	22	495	569
10.	Human Costs (Rad. Effects, Mining Accidents, etc.)	21	131	201
	TOTAL	41 566	37 739	176 569

TABLE III

Energy Requirements For A 1000 MWe PWR (In % Of Total)

		Electric	Thermal	Total
1.	U-Mining	.8	7	2
2.	U-Milling	.9	7	2
3.	Conversion	.6	18	4
4.	Enrichment	91	8	74
5.	Fuel Fabrication	2	6	3
6.	Transportation	.02	.9	.2
7.	Rad. Waste Disposal	.04	.5	.1
8.	Power Plant Construction and Operation	4	51	14
9.	Land Reclamation	.05	1.3	.3
10.	Human Costs	.05	.3	.1

TABLE IV

Change of Energy Ratios As A Function of Enrichment Tails

Tails	EG_1	EG_2	EG_e
.2	4.02	8.95	17.07
.25	4.35	9.37	19.04
.3	4.63	9.65	20.86
.35	4.86	9.81	22.61
.4	5.04	9.83	24.28
.45	5.15	9.66	25.79
.5	5.16	9.29	27.19
.55	5.02	8.63	28.14
.6	4.57	7.35	28.32
.65	3.59	5.25	26.56

4.2. CALCULATION OF THE ENERGY INPUT

The energy input was divided into six components

(1) Mining of coal
(2) Transportation of coal
(3) Construction of the plant
(4) Operation of the plant (includes maintenance)
(5) Land reclamation
(6) Human costs (mining effects, air pollution, etc.)

The energy needed to mine and transport one ton of coal is given in (13). The energy used for the construction and operation of the plant was calculated from the reported monetary costs and the energy factors of Table I. Land reclamation was treated in the same way as for the nuclear plant.

Human costs are the most difficult to calculate. There is plenty of data for the effects from nuclear power plants, but relatively little for fossil plants. The effects of radiation have been studied extensively. The health effects of air pollution such as SO_2, NO_x, etc., are not so well documented. Our sources for the numbers given below are Ref. 12 and 14.

The human cost as a result of the operation of a coal-fired plant is due to three categories of ill-effects.

(i) Accidents leading to disability. Ref. 14 gives the number of disabilities of coal mining as 10 times that of Uranium mining, for the same number of MWh produced. The numbers are for 1969, but there is no evidence that the ratio may be different now. Ref. 12 gives the cost for Uranium injuries. Using that number and the energy factor for hospital care from Table I we obtained as energy cost due to accidents 30 TJ_e and 189 TJ_t.

(ii) Radiation from coal-fired plants, due to radioactive thorium and radium contained in the coal, is 410 times the radiation from a PWR, but BWRs emit 180 times that of coal-fired plants (14). The effect of radiation (12) is given as \$12934 per 750 MWe in 1969 dollars. At the present time the reactor mix in the U.S. is such that 63% of nuclear electricity comes from PWR's and 37% from BWR's. Therefore, the radiation from coal plants is worth $\$12934 * (410 * 63 + 180 * .37) = \$4.20 * 10^6$. This number was deflated to 1963 dollars and was again transformed into energy giving as a result 419 TJ_e and 2618 TJ_{th}.

(iii) Air pollution. The air pollutants from a coal-fired plant cause disease and death to many people. Well documented numbers for mortality risk due to air pollutants do not exist. Ref. 14 gives the mortality risk due to 3.5% sulfur coal with 15% ash to be $3.34 * 10^{-4}$ per year per person. If 1.5% sulfur coal is used the corresponding number is $1.54 * 10^{-4}$. If 75% of the sulfur is removed, the risk is $5.34 * 10^{-5}$. Assuming 30 years of operation and 220 million people in the U.S. one can obtain the number of persons who will become victims of air pollution.

These individuals will be hospitalized, before they die. It is impossible to arrive at a certain number for the period of hospitalization. We used one month's hospitalization for the base case. Tables VI and VII summarize the energy input for the coal-fired plant. Tables VI and VII correspond to 75% of sulfur removed and one month hospitalization for human costs.

The total energy produced by the coal plant is $750 \text{ MWe} * 8760 \frac{h}{y} * .75 * 30y * 3.6 * 10^9 \frac{J}{Mwh} = 532\,170 \; TJe$. The energy ratios are

$$EG_1 = \frac{532\,170}{72\,925} = 7.3$$

TABLE V
Human Costs Of Coal-Fired Plants

	Accidents		Radiation		Hospitalization (1 month)		Total	
	TJ_e	TJ_t	TJ_e	TJ_t	TJ_e	TJ_t	TJ_e	TJ_t
3.5%S	30	189	419	2807	101	633	550	3440
1.5%S	30	189	419	2807	47	294	496	3101
75% removed	30	189	419	2807	21	10	451	2817

TABLE VI
Energy Requirements For A 750 MWe Coal-Fired Plant
(75% Sulfur Removed, 1 Month Hospitalization)

	Electr (TJ)	Thermal (TJ)	Total (El * 3.34 + Th)
1. Mining-Milling of Coal	3208	15298	26013
2. Transportation	307	15159	16184
3. Construction	386	5671	6960
4. Operation and Maintenance	509	6686	8386
5. Land Use-Restoration	371	9820	11059
6. Human Costs	451	2817	4323
TOTAL	5232	55451	72925

TABLE VII
Energy Requirements For A 750 MWe Coal-Fired Plant
(in % of Total; 75% Sulfur Removed, 1 Month Hospitalization)

	Electr.	Thermal	Total
1. Mining & Milling of Coal	61	28	36
2. Transportation	6	27	22
3. Construction	7	10	10
4. Operation and Maintenance	10	12	11
5. Land Use and Restoration	7	18	15
6. Human Costs	9	5	6

$$EG_2 = \frac{532\ 170}{5\ 232 + 55\ 451} = 8.77$$

$$EG_e = \frac{532\ 170}{5\ 232} = 101.7$$

4.3. EFFECT OF CHANGES IN HUMAN COSTS

The biggest uncertainty for the energy requirements comes from the human costs. We performed a limited sensitivity analysis by assuming different hospitalization rates, i.e., by changing only a fraction of the human cost. The results are shown in Table VIII.

If the sulfur is removed from coal, the energy ratios do not change because the removal of sulfur amounts to elimination of the biggest cause of ill effects.

5. CONCLUSIONS

This work is an attempt to compare the energy requirements for a nuclear and a coal-fired plant using the method of Net Energy Analysis. The results of this study indicate that both types of power plants are net producers of energy.

For the nuclear plant, the biggest sink of electric energy is the enrichment process. At the present time, gaseous diffusion is the method used for enrichment. The U.S. government announced recently the decision to build an enrichment plant based on the centrifuge method in Portsmouth, Ohio. The energy requirements of the centrifuge are about 1/10 of those for gaseous diffusion. Therefore, if the centrifuge is used for enrichment, the nuclear power plant will become much more attractive in terms of net energy production.

For the coal plant, the biggest sink of energy is coal mining. There is not much that can be done about it. In fact, it is quite probable that the fraction energy required for coal production and land reclamation will increase. Much needs to be done in the area of human costs. In particular, quantitative studies of the effects of air pollutants are needed.

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7. BIOGRAPHY

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