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Energy Economics of Nuclear and Coal Fired Power Plant

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원자력과 화력 발전소간의 에너지 비교 분석

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Abstract

The upturn of Korean nuclear power program can be considered to have started in early 70's while future plants for the construction of new nuclear power plants virtually came to a halt in United States. It is projected that power plant systems from combination of nuclear and coal fired types might shift to all coal fired type, considering the current trend of construction on the new plants in the United States. However, with the depletion of natural resources, it is desirable to understand the utilization of two competitive utility technologies in terms of invested energy. Presented in this paper is a comparison between two systems, nuclear power plant and coal fired steam power plant in terms of energy investment. The method of comparison is Net Energy Analysis (NEA). In doing so, Input-Output Analysis (IOA) among industries and commodities is done. Using these information, net energy ratios are calculated and compared. NEA is conducted for power plants in U. S. because the availability of necessary data are limited in Korea. Although NEA does not offer conclusive solution, this method can work as a screening process in decision making. When considering energy systems, results from such analysis can be used as a general guideline.

요 약

1970년대 초반에 한국의 원자력 발전소 계획이 시작된 반면, 미국에서는 1970년대 후반 이래로 신규 원자력 발전소 건설은 실질적으로 중단되었다. 신규 발전소 건설 현황을 고려해 보면, 발전소가 원자력과 화력의 적절한 조합에서, 모두 화력 발전소로 옮겨가는 것으로 보인다. 그렇지만, 천연자원의 고갈이라는 관점에서, 경쟁관계인 두 발전소를 투입된 에너지의 측면에서 고찰하는 것이 필요하다. 본 논문에서는 원자력과 화력의 두 발전소를 에너지 투자의 측면에서 비교 분석하였다. 비교 방법은 순에너지분석(NEA)이다. 그러한 분석을 통하여 산업체와 상품들에 대한 입력－출력 분석(IOA)을 수행하였다. 이

러한 정보를 이용하여 순에너지비율(net energy ratio)을 계산하고 비교하였다. 한국의 자료가 불충분하기 때문에 미국의 발전소를 대상으로 NEA를 수행하였다. 순에너지분석이 결론적인 해답을 주지는 못하지만, 이 방법은 의사 결정 과정중의 제거절차(screening process)로 쓰일 수 있다. 에너지 계통을 고려할 때, 이러한 분석 결과는 일반적인 지침으로 사용될 수 있다. 이러한 분석은 다른 계통의 에너지 사용에 대한 고찰을 하는 데도 적용될 수 있을 것이다.

1. Introduction

Safety issues have been one of the main contributing factors for the drastic reductions in orders for new nuclear power plants. Since late 70's future plans for the construction of new nuclear power plants virtually came to a halt in the United States. For instance, the accidents at Three Mile Island and at Chernobyl plants generated much doubts in the public about the reliability of nuclear power plants. Another related reason is that due to federal regulations, the cost of the new nuclear power plants has increased as a consequence of more strict regulation, resulting in longer lead time for licensing and construction. For this reason, however, efforts are being made to reduce the necessary lead time for licensing and construction through modular design and one-step licensing approach. Between 1967 and 1977, the capital cost of a nuclear power plant was more than tripled on the average. During this period, the price of coal decreased to the point where it can be competitive as the main fuel in utility plants. At present, in the United States, other alternatives like solar energy, wind energy, tidal energy, fusion power, and others have been outweighed, technologically and/or economically by nuclear and coal fired steam power systems. For these reasons, two systems are selected for comparison.

As a basis of comparison 500 MWe plants have been selected. According to the estimation made by the U.S. Department of Energy, there were about 130 coal fired steam power plants to come on line between 1981 and 1990[1]. The capacities range from 500 to 750 MWe for the majority (53%) of them. The average capacity for the units is 524 MWe. The trend of demand for lower capacity units can be explained, partly, by the fact that some sectors of the industry in U.S. are transforming into highly service oriented and information oriented industries which are less energy intensive. Bituminous coal with sulfur content of 0.5% is chosen to fuel the model coal fired steam power plant[1]. Bituminous coal with sulfur content of 0.5% is scheduled to fuel more than 50% of the units that were to come on line between years 1981 and 1990. Bituminous coal is read ily available and is used for plants in the regions of northeast, southeast, central and northwest parts of the United States.

For nuclear power plant, a Pressurized Water Reactor (PWR) is selected. Selection of type of nuclear power plant is, purely, historical. A large percentage of nuclear power plants in the United States are PWR type. Since the average size of the installed and planned units range between 500−750 MWe, the 500 MWe has been selected as a basis of comparison. Normally, the utility industry takes conservative approach and therefore, although newer reactor concepts may be more efficient and economical are not readily adopted. Nuclear fuel that will be used for this type of nuclear plants may be about 3% enriched uranium[2].

NEA method was applied for the analysis in this study[3]. This method was selected because the U.S. public law 93−577 requires that "the potential for production of net energy by the proposed technology at the stage of commercial development shall be analyzed and considered in evaluating proposal". This method can be applied to obtain some form of performance index as well. Although both systems are and have been commercialized for many years, it

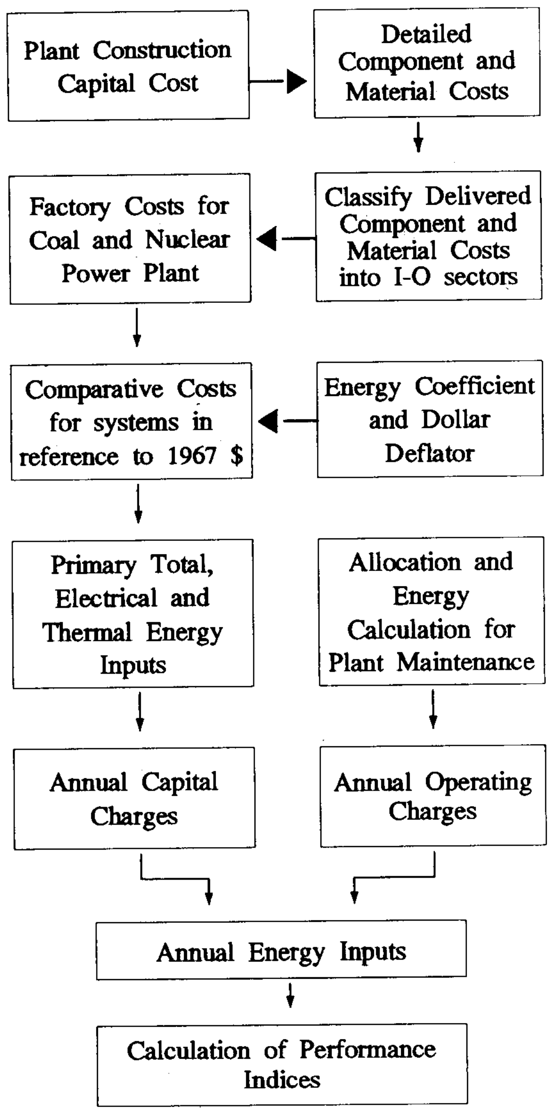

Fig. 1. Flow Diagram of the Analysis

may be useful to understand the implication of the result of NEA.

The scope of the analysis has been limited to the investment in energy. Many factors such as political influences, social influence, and changes in environmental safety standard have been left out of the analysis. However, this limitation must be kept in mind when forecasting and doing analysis.

2. Methodology

Perry et. al. defines Net Energy as "the energy remaining for use outside an energy system after deducting from the gross output of the system all of the energy required for construction and operating the system except for the energy content of the primary energy resource being processed".

For any energy system, NEA can offer the following informations [3]:

1. amount of total energy required to build and operate the energy system.
2. forms of the expended energy.
3. amount of net energy that can be saved.

As a first step, all of the energy costs of the energy system must be identified. The energy costs include the energy costs of individual components which are involved in construction and operation of the system. Energy cost of the components must be included since components have embodied energy, energy consumed to manufacture a certain product.

Energy consumption or expenditures may be categorized into two categories, direct and indirect expenditures. Direct energy expenditure is the energy used for construction and operation of the system which includes the production, and delivery of primary energy resources, and the generation of electricity, but excluding the energy content of the energy resources. Indirect energy expenditure or embodied energy consumed during the production of the components can be obtained by using data from Census of Manufactures and Census of Transportation along with energy intensity coefficients.

Net energy analysis consist, basically, of two steps[3]:

1. Quantitative determination of all relevant energy flows
2. Aggregation of these flows into appropriate indices of system performance.

The process of NEA is shown in Figure 1. They can be described in more detail as follows.

The plant construction capital cost must be found as a starting point. Then, they must be disaggregated to find detailed component and material costs. Afterward, these detailed component and material cost must be classified into appropriate categories in I-O sectors that are available in Input-Output tables. Since these costs include both wholesale and retail margins, and these margins do not reflect embodiment of energy, they must be discounted to find the factory costs. Unfortunately, the Input-Output tables are not available for every year. Rather, they are available for 1967 and 1977 while the costs are in 1980 and 1983 dollars. Therefore, they must be brought back to either 1977 or 1967. Then using energy coefficients the energy embodied in the components and materials can be found in terms of primary, electrical and thermal inputs. Assuming the amortization period of 35 years, annual capital charges in terms of energy is calculated.

There is another part of the energy cost that should be accounted for. The energy requirement for plant maintenance and annual operating expenditure must be included.

Combining both annual capital charge and operating charge, the annual energy input is found. From these, performance indices can be calculated.

The result of the NEA, shown in Table 12, can be represented in absolute values (numbers) but performance indices have been used for easier comparison. The comparison of these performance indices must be done with caution since different energy systems for certain boundaries may differ. However, close similarities, such as purposes, exist in systems being analyzed, therefore use of performance indices, in this case, can be justified.

As a part of NEA, IOA reveals the relationship between energy producing industries, like utility industries and energy consuming industries, for example, steel manufacturing industries. As a consequence of the analysis, primary energy resource requirement and net energy yield can be obtained.

3. Analysis

The procedure of carrying out NEA for the estimation of embodied energy in the components can be described as follows. Initially, the description of the process with detailed breakdown of the cost is required. IOA can be used to analyze the system by utilizing a set of energy intensity coefficients for U.S. economic sectors. Although most of the items can be assigned to one of the sectors, some cannot be categorized specifically to any sector, in which case, cost estimates for these may lose the accuracy relative to that of other components that have been assigned to some specific sectors. By using energy coefficients, laborious work of collecting all the consumed energy and dividing by the cost for each sectors can be reduced since these coefficients represent the total embodied energy independent of the energy consumption path and find the actual energy consumed for the construction and operation of the plants.

For energy data, Bullard's energy analysis handbook, tables from Oak Ridge Associated Universities, Hannon et. al. and Reister provide energy coefficients for various sectors and construction.

The energy intensity data from 1967 are used due to unavailability of consistent newer data, moreover, most of the Census for Manufactures, Producers, and Consumers are referred back to 1967. One drawback of using data acquired in 1967 is that it does not account for change in efficiency of manufacturing processes due to technological improvement. This study, therefore, does not account for the energy consumption change in manufacturing processes over the years.

The energy expenditures in total primary energy, by the convention of the U.S. bureau of Mines, was defined as the sum of fossil energies, such as coal, gas and crude oil. Availability of solar energy, wind energy and other form of energies are omitted from the primary energy. Total energy can be divided into two uses: generation of electricity and heat. Relationship can be expressed by following equation[3].

$$\text{Total primary} = \text{heat} + 4.06^{*}\ \text{electrical energy}$$

Above relation represents conversion factor for producing primary energy into electrical energy. The factor 4.06 is the ratio of total primary energy required for production and delivery of 1 btu of electricity. This factor includes transmission loss and embodied energy of the generating unit and lastly, but most importantly, direct use for generation of electricity. This equation can be modified slightly on the coefficient depending on the efficiency of the plant and sophistication of the transmission method to obtain the more accurate result, since this is the general expression for the utility industry at time of analysis pursued. One assumption of equal usefulness of primary energy resources is made for representation of a performance index.

It has been established that embodied energy is necessary part of the NEA. Since the Bullard energy intensity coefficients are available for 1967, it is necessary to have cost estimates in the bill of materials and price deflator to convert the value of current dollars to 1967. It is imperative to use detailed price deflator since inflation rate for each sector would be different. Note that even after two decades price inflator guide in producer price index is referred back to 1967.

Since the price paid does not accurately reflect the embodied energy in the product, it is necessary to calculate the producer prices by subtracting wholesale and retail margin and transportation costs. The energy costs for transportation have been added in later stage of the analysis. Among the transportation methods, only transportation by rail and trucks has been considered. It was found that air and sea freight costs were negligible relative to the dominant costs of land transportation.

In order to calculate the total embodied energy, the value of the shipment from the Census of Manufactures and the weight of total shipment from the Census of Transportation were obtained. Average price has been, then, calculated as ratio of value to weight of shipments. Next, this average price ($/ton) has been multiplied by energy intensity to obtain the energy content in the product. However, certain precaution has to be taken in making such an assumption of using average values not to create erroneous result. A good example is the case of steel industry. Prices vary vastly from semi-finished carbon steel to stainless steel tubing even though energy consump-

Table 1. Plant Construction Capital Cost Items (from CONCEPT-5 : DOE)

Categories	Cost (in million Dollars)			
	Component	Materials	Labor	Total
Coal Fired Unit (1983 $)	**177.540**	**49.749**	**143.963**	**371.252**
Boiler Plant Equipment	89.903	9.316	38.152	137.371
Structure & Improvement	1.933	26.826	27.358	56.117
Turbine Plant Equipment	57.138	3.194	17.166	77.498
Electric Plant equipment	11.910	7.395	16.210	35.522
Main Condenser Heat Rej. Sys.	7.801	1.606	7.127	26.534
Misc. Plant Equipment	8.848	1.412	10.600	20.860
Nuclear Power Unit (1980 $)	**203.500**	**79.232**	**237.247**	**519.979**
Reactor Plant Equipment	95.965	9.306	44.589	149.860
Structure & Improvement	5.718	49.100	100.072	154.890
Turbine Plant Equipment	65.808	4.773	28.635	99.216
Electric Plant equipment	16.383	10.468	33.394	60.245
Main Condenser Heat Rej. Sys.	8.967	1.612	8.699	19.278
Misc. Plant Equipment	10.659	3.973	21.858	36.490

Table 2. Detailed Component and Material Costs for Coal Fired and Nuclear Power Plant

Items	Cost (in million Dollars)		I-O
	Coal (1983 $)	Nuclear (1980 $)	Sector
Structure & Improvement	**28.759**	**54.818**	
Substructures	1.974	5.954	3612
Superstructures	19.806	37.828	4004
HVAC	1.144	3.459	4006
Plumbing and Drains	0.953	1.388	3612
Paving	0.574	0.412	3102
General Cut and Fill	0.550	3.842	900
Fencing and Gates	0.196	0.060	4005
Alarm	0.013	–	5308
Railroads	1.425	0.780	4004
Lighting	0.404	0.913	5503
Conveyor Galleries	0.954	–	4806
Stacker/Reclaimer	0.117	–	4806
Coal Pile Membrane Barrier	0.229	–	3612
Maintenance and repair Shop	0.303	–	4806
Elevator	–	0.182	4806
Boiler or Reactor Plant Equipment	**99.219**	105.271	
Fossil Steam Supply System	47.219	–	4006
Instrumentation and Control	0.808	2.635	5305
Tank and Pressure Vessel	0.011	0.456	4006
Heat Transfer Equipment	0.296	–	4006
Draft Equipment	0.006	–	4903
Soot Blowing Equipment	0.775	–	4903
Steam Generator Equipment	0.455	–	4208
Purification and Filtration	9.469	–	5305
Piping	0.548	3.568	4208
Ductwork	1.285	–	4006
Valves	0.095	1.715	5305
Ash Handling System	4.225	–	4502
Coal Handling System	15.095	–	4502
Fuel Gas Desulfurization	1.868	–	4806
Lime handling	12.799	–	4502
Computer System	3.025	–	5101
Insulation	0.853	1.139	3617
Painting	0.210	0.262	2701
Foundation	0.117	0.565	3612
Nuclear Steam Supply System	–	66.917	4006
Reactor Equipment	–	2.085	4806
Main Heat Transfer Trans.Equip.	–	2.074	4208
Rotating Machinery	–	0.145	5304
Heat Exchanger	–	0.118	4006
Alarm	–	0.108	5308
Plant and Control System	–	1.122	5305
Auxiliary Cooling System	–	6.160	4901
Process Computer	–	5.925	4806
Coolant Treatment and Recycle	–	4.619	2701
Fuel Handling and Storage	–	2.132	4806
Other Equipment	–	0.629	4806

Table 2. (Continued)

Items	Cost (in million Dollars)		I-O
	Coal (1983 $)	Nuclear (1980 $)	Sector
Turbine Plant Equipment	**60.300**	**70.581**	
Turbine Generator and Accessory	38.734	43.793	4301
Foundation	0.817	0.765	3612
Condenser	3.240	4.420	4006
Tank and Pressure Vessel	0.282	0.471	4006
Piping	4.135	6.977	4208
Valves	1.546	2.340	5305
Instrumentation and Control	0.489	0.814	5305
Rotating Machinery	1.459	1.848	5304
Main Vapor Piping System	4.091	3.590	4208
Gas Removal System	0.270	0.326	2701
Feedwater Heater	1.694	1.418	4006
Insulation	1.193	1.262	3617
Painting	0.173	0.209	2701
Demineralizing Water	0.919	1.231	2701
Turbine Auxiliary	0.082	0.005	4301
Gas Storage System	0.170	0.137	4006
Condensate Polishing	1.038	0.975	2701
Electrical Plant Equipment	**19.312**	**26.851**	
Switchgear and Control	8.666	7.338	5303
Transformer	2.284	1.661	5302
Cable and Wires	4.191	7.042	3810
Cable Trays and Conduits	2.072	3.027	5503
Other Electrical Equipment	1.639	1.880	5308
Diesel Generator	0.460	5.903	5304
Main Condenser Heat Rejection Sys.	**9.407**	**10.579**	
Substructure	0.184	0.188	3612
Mechanical Equipment	4.127	4.512	4806
Cooling Tower	4.055	4.813	4006
Superstructure	1.041	1.066	4004
Misc.Plant Equipment	**10.260**	**14.632**	
Transportation and Lift Equipment	0.634	2.168	4603
Diesel Locomotive	0.621	–	4603
Bulldozers	0.587	–	5401
Air, Water and Steam System	0.245	1.277	4208
Fire Protection System	2.852	5.631	5308
Auxiliary Steam System	1.477	1.590	4208
Communication System	0.190	0.176	5308
Signal System	0.208	1.414	5308
Furnishing and Fixtures	0.010	0.009	5000
Chemical Lab.and Instrument Shop	0.302	0.625	5000
Office Equipment and Furnishing	0.093	0.074	5000
Change Room Equipment	0.057	0.088	5000
Environment Monitoring Equipment	0.276	0.419	5308
Cafeteria Equipment	0.075	0.109	5000
Wastewater Equipment	2.596	0.992	4806
Rotating Machinery	0.002	–	5304
Tank and Pressure Vessel	0.026	0.049	4006
Piping	0.003	–	4208
Valves	0.003	–	5305
Foundation	0.007	0.011	3612

Table 3. Delivered Component and Material Costs and Estimated Factory Cost (10^6 1983 Dollars) for Coal Fired Power Plant

Input-Output Sector No.	Input-Output Sector Name	Cost at Site	Transport Rail	Transport Truck	Trade Retail	Trade Wholesale	Cost at Factory
900	Stone, clay and minerals	0.550	0.048	0.117	–	0.008	0.377
2701	Industry chemicals	2.610	0.035	0.035	–	0.141	2.399
3102	Paving	0.574	–	0.009	0.016	0.019	0.530
3612	Ready mixed concrete	4.458	–	–	–	0.081	4.377
3617	Asbestos products	2.046	0.195	0.081	0.406	0.227	1.137
3810	Non-ferrous wires	4.191	0.027	0.056	0.050	0.132	3.926
4004	Fabricated structural steel	22.272	0.575	0.465	–	0.953	20.279
4005	Metal doors and sashes	0.196	0.001	0.002	0.021	0.016	0.156
4006	Fabricated plate steel	59.422	0.844	0.535	0.036	2.252	55.755
4208	Pipe fitting	10.954	0.044	0.139	0.483	1.155	9.133
4301	Steam engines	38.816	0.113	0.054	–	0.450	38.199
4502	Mining machinery	32.119	0.446	–	–	4.015	27.658
4603	Hoists and cranes	1.255	–	0.001	–	0.005	1.249
4806	Special industrial machinery	9.965	–	–	–	0.312	9.653
4901	Pump and compressor	–	–	–	–	–	–
4903	Blowers	0.781	–	0.010	–	0.063	0.708
5000	Machine shop products	0.537	–	–	–	0.036	0.501
5101	Electronic computing mach	2.934	–	–	–	0.091	2.934
5302	Transformers	2.284	0.010	0.010	–	0.019	2.145
5303	Switchgears	8.666	0.018	0.042	–	0.525	8.081
5304	Motors/generators	1.921	–	0.192	0.192	0.384	1.153
5305	Industrial controls	12.410	–	–	0.621	1.180	10.609
5308	Electronic industrial equipment	5.178	–	–	–	0.155	5.023
5401	Construction machinery	0.587	0.008	–	–	0.073	0.506
5503	Wiring device	2.476	0.012	0.036	0.291	0.199	1.938
	Subtotal	**227.289**	**2.376**	**1.784**	**2.116**	**12.491**	**208.522**
6501	Rail						2.376
6503	Motor freight						1.784
6901	Wholesale trade						12.491
6902	Retail trade						2.116
	Total						**227.289**

tion does not vary as much as the variation in prices. For a better approximation, one can assume that basic steel product has similar energy content. The assumption of having same energy content may contain some error but the magnitude of the error accumulated will tend to be much lower than the error caused by extensive use of price index. However, there is a better method, although it is not followed upon in this analysis, which is to disaggregate every steel industry into matter of types of steel products and obtain embodied energy using Bullard's energy coefficients. In 1967 U.S. the economic sectors were categorized into 357 sectors. The calculation can become very lengthy and cumbersome for this size of matrix. In 1977 the U.S. economic sectors have been disaggregated into more than 500 sectors. Some discretion must be used and degree of accuracy must be kept in mind when using these data. The accu-

Table 4. Delivered Component and Material Costs and Estimated Factory Cost (10^6 1980 Dollars) for Coal Fired Power Plant

Input-Output Sector		Cost at	Transport		Trade		Cost at
No.	Name	Site	Rail	Truck	Retail	Wholesale	Factory
900	Stone, clay and minerals	3.842	0.335	0.817	–	0.056	2.634
2701	Industry chemicals	7.622	0.102	0.102	–	0.412	7.066
3102	Paving	0.412	–	0.006	0.011	0.014	0.381
3612	Ready mixed concrete	8.871	–	–	–	0.161	8.710
3617	Asbestos products	2.611	0.249	0.103	0.518	0.290	1.451
3810	Non-ferrous wires	7.042	0.045	0.094	0.084	0.222	6.597
4004	Fabricated structural steel	39.674	1.024	0.828	–	1.698	36.124
4005	Metal doors and sashes	0.060	–	0.001	0.007	0.005	0.047
4006	Fabricated plate steel	82.158	1.160	0.740	0.050	3.114	77.087
4208	Pipe fitting	19.076	0.070	0.242	0.841	2.011	15.905
4301	Steam engines	43.798	0.128	0.061	–	0.508	43.110
4502	Mining machinery	–	–	–	–	–	–
4603	Hoists and cranes	2.168	–	0.002	–	0.009	2.157
4806	Special industrial machinery	16.450	–	–	–	0.515	15.942
4901	Pump and compressor	6.160	–	–	–	0.193	5.967
4903	Blowers	–	–	–	–	–	–
5000	Machine shop products	0.905	–	–	–	0.061	0.844
5101	Electronic computing mach	2.687	–	–	–	0.081	2.606
5302	Transformers	1.661	0.007	0.007	–	0.015	1.632
5303	Switchgears	7.338	0.015	0.036	–	0.445	6.842
5304	Motors/generators	7.896	–	0.789	0.789	1.578	4.740
5305	Industrial controls	8.726	–	–	0.437	0.830	7.459
5308	Electronic industrial equipment	9.628	–	–	–	0.288	9.340
5401	Construction machinery	–	–	–	–	–	–
5503	Wiring device	3.940	0.019	0.050	0.463	0.317	3.084
	Subtotal	**282.732**	**3.167**	**3.885**	**3.200**	**12.823**	**259.657**
6501	Rail						3.167
6503	Motor freight						3.885
6901	Wholesale trade						12.823
6902	Retail trade						3.200
	Total						**282.732**

racy of the result highly depends upon the compilation of the original data.

The table from the Oak Ridge Associated Universities (Energy Information Agency report 77－12) has a breakdown of energy usage into coal, gas, oil, and electricity. However, only two items have interests for us. They are primary form of energy and electricity. Again, these data represent embodied energy in each ton of average product. For electricity, a conversion factor of 3413 btu/kw-hr is used[3].

Energy systems and their costs are analyzed for both competitive systems. The estimates shown in Table 1 are for components, materials, and labor excluding contingency and engineering fee. Table 2 shows the comparison of detailed costs with their related economic sectors. Transportation and trade margins for 1967 are used to estimate the factory costs assuming that these margins are still valid for

Table 5. Energy Coefficients and Dollar Deflator by Input-Output Sectors

Input-Output Sector		Inflation Ratio		Energy Coefficient [3] (1000 Btu / 1967 $)	
No.	Name	1983/1967	1987/1967	Paimary	Electrical
900	Stone, clay and minerals	2.862	2.167	120.219	9.260
2701	Industry chemicals	3.401	2.125	303.231	26.146
3102	Paving	7.860	5.384	578.968	7.453
3612	Ready mixed concrete	3.091	2.584	194.712	9.554
3617	Asbestos products	3.401	2.631	119.140	9.075
3810	Non-ferrous wires	2.054	1.971	136.902	11.650
4004	Fabricated structural steel	3.122	2.577	136.902	8.384
4005	Metal doors and sashes	2.958	2.413	111.517	12.815
4006	Fabricated plate steel	2.939	2.587	115.544	7.466
4208	Pipe fitting	4.328	2.065	81.634	5.922
4301	Steam engines	3.360	3.042	78.994	5.745
4502	Mining machinery	3.522	2.682	78.606	5.944
4603	Hoists and cranes	2.821	2.591	73.996	5.804
4806	Special industrial machinery	3.158	2.562	65.641	5.634
4901	Pump and compressor	3.493	2.591	61.145	5.095
4903	Blowers	3.370	2.562	68.990	5.837
5000	Machine shop products	2.866	2.591	61.673	5.726
5101	Electronic computing mach	0.865	0.019	423.502	62.345
5302	Transformers	2.234	1.685	82.671	7.258
5303	Switchgears	2.509	1.946	52.207	5.096
5304	Motors/generators	3.242	2.449	70.507	6.260
5305	Industrial controls	3.259	2.570	43.378	4.288
5308	Electronic industrial equipment	2.377	1.865	66.313	6.031
5401	Construction machinery	0.522	2.682	62.359	5.352
5503	Wiring device	3.336	2.570	81.331	6.923
6501	Rail	3.480	2.890	98.685	3.097
6503	Motor freight	3.175	2.356	58.149	1.993
6901	Wholesale trade	2.789	2.245	39.636	2.221
6902	Retail trade	2.905	2.339	39.636	4.009

1980 and 1983. Tables 3 and 4 represent the summary of costs at site, trade costs, transportation costs and factory costs.

Next step in the analysis is the calculation of the capital energy expenditures. The tables 5 and 6 summarize the energy consumption associated with the materials. The summary of energy usage according to types excluding the energy used during construction are summarized in the table 7. Both systems are compared based on same net output of 500 MWe with the amortization period of 35 years. This amortization period represents the period of average power plant life. Then, the data represented in the table 8 are the summary of annual capital charges of the energy for the construction.

The operating energy expenditures must be taken into account next. The annual energy consumption by power plants includes the energy required to extract and to transport the fuel to the location of power plant. It also includes operating consumables and

Table 6. Comparative Costs for Systems in Reference to 1967 Dollars

Input-Output Sector		Coal (million $)		Nuclear (million $)	
No.	Name	1983	1967	1980	1967
900	Stone, clay and minerals	0.377	0.132	2.634	1.216
2701	Industry chemicals	2.399	0.705	7.066	3.297
3102	Paving	0.530	0.067	0.381	0.071
3612	Ready mixed concrete	4.377	1.416	8.710	3.371
3617	Asbestos products	1.137	0.334	1.451	0.552
3810	Non-ferrous wires	3.926	1.911	6.597	3.347
4004	Fabricated structural steel	20.279	6.496	36.124	14.019
4005	Metal doors and sashes	0.156	0.053	0.047	0.020
4006	Fabricated plate steel	55.755	18.971	77.087	29.798
4208	Pipe fitting	9.133	2.110	15.905	7.702
4301	Steam engines	38.199	11.369	43.110	14.169
4502	Mining machinery	27.658	7.853	–	–
4603	Hoists and cranes	1.249	0.443	2.157	0.832
4806	Special industrial machinery	9.653	3.057	15.942	6.222
4901	Pump and compressor	–	–	5.967	2.303
4903	Blowers	0.708	0.210	–	–
5000	Machine shop products	0.501	0.175	0.844	0.375
5101	Electronic computing mach	2.934	3.392	2.606	2.836
5302	Transformers	2.145	0.960	1.632	0.969
5303	Switchgears	8.081	3.221	6.842	3.516
5304	Motors/generators	1.153	0.356	4.740	1.935
5305	Industrial controls	10.609	3.255	7.459	2.902
5308	Electronic industrial equipment	5.023	2.113	9.340	5.008
5401	Construction machinery	0.506	0.144	–	–
5503	Wiring device	1.938	0.581	3.084	1.200
6501	Rail	2.376	0.683	3.167	1.096
6503	Motor freight	1.784	0.562	3.885	1.649
6901	Wholesale trade	12.491	4.479	12.823	5.482
6902	Retail trade	2.116	0.728	3.200	1.425
	Total	**227.289**	**75.776**	**282.732**	**115.312**

provision for general repairs. However, the energy required to extract and transport the uranium has been omitted. This was assumed to be very small. Also, energy consumed during enrichment process has been excluded due to insufficient data. The energy required to extract the coal is 0.92% of its energy content[3]. Average hauling distance is taken to be 300 miles with 970 btu/ton-mile[3] as energy consumption rate for its transportation. The operating consumables are assumed to be mostly chemicals. The energy requirements for the plant maintenance are calculated with the weighted energy intensity coefficients based on their fractional part of total output. This is shown in Table 9. The annual operating and maintenance costs and energies are listed in Table 10. Finally all the energy inputs are combined and summarized in two categories. These two categories are electrical and thermal. The values for the capital

Table 7. Primary Total, Electrical and Thermal Energy Inputs

Input-Output Sector		Coal (in 10^9 Btu)			Nuclear (in 10^9 Btu)		
No.	Name	Total	Elec.	Thermal	Total	Elec.	Thermal
900	Stone, clay and minerals	15.87	4.96	10.91	146.19	45.72	100.47
2701	Industry chemicals	213.78	74.84	138.94	999.75	349.99	649.77
3102	Paving	38.79	2.03	36.76	41.11	2.15	38.96
3612	Ready mixed concrete	275.72	54.93	220.79	656.37	130.70	525.61
3617	Asbestos products	39.79	12.31	27.48	65.77	20.34	45.43
3810	Non-ferrous wires	193.74	90.39	103.35	339.32	158.31	181.01
4004	Fabricated structural steel	889.32	221.12	668.20	1919.23	477.19	1442.04
4005	Metal doors and sashes	5.91	2.78	3.13	2.23	1.05	1.18
4006	Fabricated plate steel	2121.99	575.05	1546.94	3442.98	903.23	2539.75
4208	Pipe fitting	172.25	50.73	121.52	628.75	185.19	443.56
4301	Steam engines	898.08	265.18	632.90	1119.27	330.49	788.78
4502	Mining machinery	617.29	189.51	427.78	–	–	–
4603	Hoists and cranes	32.78	10.44	22.34	61.55	19.61	41.94
4806	Special industrial machinery	200.67	69.93	130.74	408.42	142.32	266.10
4901	Pump and compressor	–	–	–	140.82	47.64	93.18
4903	Blowers	14.49	4.98	9.51	–	–	–
5000	Machine shop products	10.79	4.07	6.72	23.13	8.72	14.41
5101	Electronic computing mach.	1436.52	858.58	577.94	1201.05	717.85	483.20
5302	Transformers	79.36	28.29	51.07	80.11	28.55	51.56
5303	Switchgears	168.16	66.64	101.52	183.56	72.75	110.81
5304	Motors/generators	25.10	9.05	16.05	136.43	49.18	87.15
5305	Industrial controls	141.20	56.67	84.53	125.88	50.52	75.36
5308	Electronic industrial equipment	140.12	51.74	88.38	332.10	122.63	209.47
5401	Construction machinery	8.98	3.13	5.85	–	–	–
5503	Wiring device	47.25	16.33	30.92	97.60	33.73	63.87
6501	Rail	66.72	8.59	58.13	107.06	13.78	93.28
6503	Motor freight	32.68	4.55	28.13	95.89	13.34	82.55
6901	Wholesale trade	177.53	40.39	137.14	217.29	49.43	167.86
6902	Retail trade	28.66	11.85	16.81	56.11	23.19	32.92
	Total	**8094.33**	**3239.02**	**4855.31**	**12627.93**	**3397.65**	**8630.28**

Table 8. Summary of Annual Capital Charges (assumes 35 year amortization period)

Coal (in billion Btu)			Nuclear (in billion Btu)		
Total	Electrical	Thermal	Total	Electrical	Thermal
231.267	92.544	138.723	360.798	114.218	246.580

energies and operation and maintenance energy requirements for both systems are shown in Table 11.

4. Findings and Conclusions

Net energy analysis proves that nuclear power plant is more efficient electric power generation system of the two analyzed. Table 12 represents the summary of energy inputs, outputs, and energy ratios for com-

Table 9. Allocation and Energy Calculations for Plant Maintenance [3]

Input-Output Sector		F_n	Energy Coefficient		Fraction Weight	
No.	Name		Primary	Electric	F_n/primary	F_n/Electric
1202	Maintenance consumables	0.696	63.904	2.993	10.89	232.54
2701	Chemicals	0.143	303.231	26.146	0.47	5.47
3203	Rubber products	0.018	110.504	8.893	0.16	2.02
3701	Steel products	0.054	282.390	14.004	0.19	3.86
3805	Primary non-ferrous	0.018	173.590	23.369	0.10	0.77
4907	General industrial appl.	0.018	71.245	5.818	0.25	3.09
5308	Electric industrial appl.	0.035	66.313	6.031	0.53	5.80
5503	Wiring device	0.018	81.331	6.923	0.22	2.60

Table 10. Annual Operating Costs (in millions of 1967 dollars) and Energies (in billion Btu excluding fuel) for Coal and Nuclear Power Plant

Items	Cost	Mining		Transport		Trade			
		Total	Primary	Elec.	Primary	Elec.	Primary	Elec.	Primary
				Coal power plant					
Coal for boiler	7.07	251.77	6.22	369.09	–	–	–	620.85	**6.22**
Coal for calciner	0.13	4.70	0.12	6.89	–	251.77	–	263.36	**0.12**
Limestone	0.77	55.00	4.21	30.67	–	–	–	85.67	**4.21**
Operating consum.	0.44	121.30	10.50	1.00	–	0.80	0.20	123.10	**10.70**
Maintenance	3.95	308.40	15.40	–	–	–	–	308.40	**15.40**
Total								**1401.36**	**36.65**
				Nuclear power plant					
Operating consum.	3.054	854.43	72.88	6.941	–	5.55	1.39	866.92	74.27
Maintenance	1.958	152.87	7.63	–	–	–	–	152.87	7.63
Total								**1019.79**	**81.90**

Table 11. Summary of Annual Energy Inputs

	Coal (billion Btu)			Nuclear (billion Btu)		
	Total	Electrical	Thermal	Total	Electrical	Thermal
Capital energy	231.27	92.54	138.73	360.80	114.22	246.58
O&M	1401.36	148.80	1252.56	1019.79	332.52	687.27
Total	**1632.63**	**241.34**	**1391.29**	**1379.59**	**446.74**	**933.85**
Fuel value		27365			27492	

parison. Shown in Figure 2 are the important parameters from the study.

From the study, it is evident that, although the nuclear power plant has higher conventional heat rate than the coal fired steam power plant, the nuclear power plant is more efficient in terms of the total energy invested. The ratio of delivered energy and total primary energy subsidy was compared between two

Table 12. Comparison for Energy Inputs, Outputs and Ratios

Indices of Performance	Coal	Nuclear
System Characteristics		
Reference system capacity, MWe	500	500
Net system capacity, MWe	455.5	455.5
Plant utilization factor (availability), %	65	65
H_0: Conventional heat rate, Btu/kWh	10400	10600
I: Primary energy resources (fuel), 10^{12} Btu/yr	26.974	27.492
I = Conventional heat rate * Net output		
Average Annual Output		
E_0: Net output of production system, 10^9 kWh/yr	2.594	2.594
E_1: Delivered output, 10^9 kWh/yr	2.363	2.363
or 10^9 Btu/yr	8.065	8.065
(assumes 9% loss due to transmission and distribution)		
Average Annual Input		
E_s: Electrical energy subsidy, 10^6 kWh/yr	17.417	32.240
or 10^9 Btu/yr	59.444	110.034
T_1: Primary energy subsidy for generation and delivery of electricity ($T_1 = E_s$ * 4.06), 10^9 Btu/yr	241.343	446.740
T_2: Primary energy subsidy not associated with electricity, 10^9 Btu/yr	1391.290	933.851
T_P: Total primary energy subsidy ($T_P = T_1 + T_2$), 10^{12} Btu/yr	1.633	1.380
Energy Ratios		
R_1: Delivered output(E_1) Total primary energy subsidy(T_P)	4.939	5.844
$1000 \div R_1$: Total primary energy subsidy expressed as Btu input per 1000 Btu output	202.480	171.116
R_2: Delivered output Equivalent electrical energy subsidy($T_P \div 4.06$)	20.052	23.727
R_4: [Delivered electricity(E_1)-Electricity Subsidy(E_s)] $\div$ Thermal energy subsidy(T_2)	5.059	8.518
$1000 \div R_4$: Thermal energy subsidy expressed as Btu input per 1000 Btu of net system electricity output	197.670	117.398
Subsidy Heat Rates		
H_1: Subsidy heat rate ($T_P \div E_1$), Btu/kWh	691.971	594.003
H_4: Subsidy heat rate for net system output(T_2 (E_1-E_s)), Btu/kWh	597.408	400.664
Overall Heat Rates		
G_1: Overall heat rate (($I + T_P$) $\div$ E_1), Btu/kWh	12274	12218
G_4: Overall heat rate for net system output (($I + T_2$) (E_1-E_s))	12264	12156

proposed systems. The coal fired steam power plant had 4.94 while the nuclear power plant had 5.844 for these ratios. In all aspect of energy investment except conventional heat rate, nuclear power plant was found to be more efficient. The energy required for operating consumables and maintenance require-

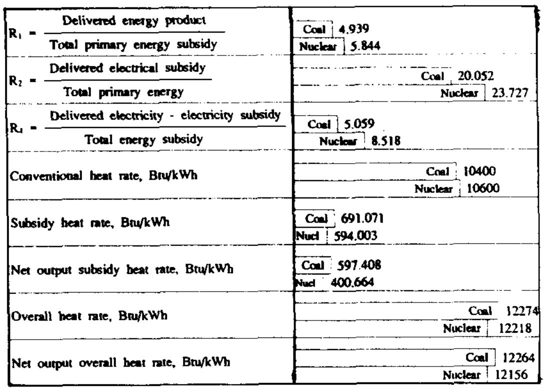

Fig. 2. Important Parameters From the Study

ment takes sizable portion of the total energy requirement. Hence, the energy ratio was found to be sensitive to the amount of energy input due to operating and maintenance requirements. Although the nuclear power plant had better energy ratio, it consumed more energy due to the higher energy requirement for the construction of the plant itself.

We have utilized energy accounting to identify and compute the energy flows in society that are necessary to deliver energy in a particular form, such as delivering electrical energy converted from primary energies. The analytical procedure itself can provide a deeper and more explicit understanding of the energy dependence of energy-producing technologies on energy-intensive sectors of the economy. This understanding can aid in identifying system components that might be especially sensitive to energy price and availability and in assessing to see if conditions exist where the energy yield from a particular technology would fail to be substantially greater than the energy subsidy. However, such a failure should contribute to an unfavorable engineering economic analysis as well.

There are many factors governing the feasibility and acceptability of energy supply and conversion systems. Energy analysis can provide information about two of these factors: net energy yield and energy resource requirements.

The large volume of data is necessary to perform the Net Energy Analysis. Currently, it is of a great task to perform the Net Energy Analysis in Korea due to unavailability of proper data for the analysis. The compilation of such database may only be tackled by a dedicated effort by a government agency. Therefore, Korea government should make an effort to prepare the data. Based on these data, one can perform the Net Energy Analysis for the energy systems, identify the merits and demerits of the energy systems in terms of energy investment, and insure substantiality in the long-term plan for the development of power sources.

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