Development of a Method to Fully Assess the Environmental Costs of Electrical Energy by Nuclear Power Plants

Abstract

A major problem affecting the assessment of the environmental and social costs of energy in addition to the monetary cost is a lack of standardization of assessment techniques which makes comparisons difficult or invalid. The University of Florida has adopted the EMERGY analysis process developed by Howard T. Odum[1,2,3] to perform a self-consistent study of energy production to assess the full range of environmental, social and economic costs. The EMERGY analysis makes the ordering of energy values and the assignment of energy units (emjoules) to environmental and economic costs possible. The need for such a study arises from Federal directives for utilities to more fully assess the environmental and social costs of electricity production. The University of Florida has completed an implementable EMERGY analysis of a nuclear power plant that meets the spirit of the Federal directive. The development of the EMERGY analysis can serve as an example for utilities to follow in the future in their assessment of environmental and social costs. The reported study analyzes the integrated economic, energy, and environmental costs involved in the construction, maintainance, operation, and decommissioning of a steam nuclear power electric generating facility. Data were collected or calculated on the energy, economic, and environmental costs (emergy inputs) associated with the construction, operation, and decommissioning of a 1000 MW_e nuclear power plant. These total energy cost data were analyzed and compared to the electrical output of the same size plant utilizing different fuel sources. The study shows that relatively low amounts of energy, economic, and environmental costs (in emergy units) are required to produce a given amount of electricity from the nuclear power plant compared to other electricity production options. The energy analysis employed in this study was an EMERGY analysis. The EMERGY concept is an accounting system or language that allows comparisons to be made between different energy systems or subsystems. An EMERGY analysis accounts for environmental and economic effects as well as direct energy and material use in a defined system. Each material, monetary quantity, or energy source is assigned an emergy value (in emjoules or sej's) based on how much solar energy it took to create it.

The EMERGY inputs into the system under study are summed and divided into the energy output. The result is a ratio (EMERGY yield ratio), which indicates the efficiency and environmental impact within the system. This study yielded a ratio of 8.45 for a 1000 MW_e nuclear power plant. Previous studies showed a ratio of 2.5 for coal, 0.48 for solar and 0.25 for wind

Introduction

Federal and state governments are seeking to have energy production systems, (i.e. wind, coal, gas, hydro, nuclear, etc.), evaluated on a consistent basis, taking into account the social and economic effects in addition to the cost (dollar) effects. A major problem affecting the evaluation of the environmental and social costs of energy production in conjunction with the monetary cost is a lack of standardization, without which comparisons are difficult or invalid. A conflict has arisen between those intent on protecting their view of the environment and those intent on providing continuing economic development. Previous studies of the environmental consequences have been done by the Pace Law School Energy Project, which is part of the Pace University School of Law's Center for Environmental Legal Studies, located in White Plains, New York. As one of the few national energy policy and environmental advocacy institutions that work at the center of environmental, energy and economic issues, they pioneered their view of the quantification of the environmental costs of energy production. Their publication, *Environmental Costs of Electricity by Richard Ottinger*[4], remains the only research and policy study internationally addressing the environmental and social costs of electricity production. This study has cast Nuclear Power in an unfavorable light, citing environmental consequences and remains the only widely available study on the economic and social cost of the various forms of energy production. The University of Florida has adapted the EMERGY analysis developed by Howard T. Odum[1,2,3] to develop an objective, self-consistent study of the costs of energy production including the social and economic consequences. The EMERGY analysis makes the ordering of energy values and the assignment of energy units (emjoules) to environmental and economic costs possible. The need for the study arises from both the Federal directives for utilities to more fully assess the environmental and social costs of electricity production and the environmental bias of studies available to date. To date utilities feel that there is no method of analysis that allows meaningful comparisons to be made. It is intended that the developed EMERGY analysis will serve as an example for utilities to follow in the future. The proposed study has analyzed the integrated economic, energy, and environmental costs involved in constructing, maintaining, operating, and decommissioning a steam nuclear power electric generating facility. The study has integrated the disparate types of nuclear electric generation costs, energy, economic, and environmental into a common energy basis (in this case an EMERGY basis).

Project Objectives and Significance

Evaluation of environmental issues always seems to be characterized by adversarial decision-making, rancor, and confusion. Dr. Odum has set out the basis of a science-based evaluation system that represents both the environmental values and the economic values with a common measure. His unit, EMERGY, measures both the work of nature and that of humans in generating products and services. The EMERGY units are defined in solar equivalent units or solar emjoules (sej). The unit name EMERGY arises from the concept that putting more energy into something generates more value. The concept EMERGY is scientifically defined to give a quantitative measure to this ancient principal. Thus, when we use steel, or concrete, in building our structure, we carry along the EMERGY associated with it. Similarly, where we have waste streams, or the potential for accidents, we similarly carry along the EMERGY associated with building and operating the waste facilities and the environmental consequences of any accidents. By drawing a system window frame around each part of an energy system and diagramming its contents we can evaluate as a part of the environmental realm what went into that energy system in terms of EMERGY, a measure of its true cost. When looking at an energy system, we are then interested in the net EMERGY yield, which is the ratio of the EMERGY output divided by the EMERGY input.

The objective of our research project was to develop an EMERGY study of a Nuclear Power Plant and compare it to an alternate power source to demonstrate the true environmental costs of nuclear power versus other power sources. A key to the EMERGY system of measurement is the transformities used to quantify the energy hierarchy. Dr. Odum's system of accounting for all environmental effects is based on recognizing that the universe is organized in a hierarchy of energy transformations quantitatively described by transformities. Development of an accepted nuclear power plant study will serve to deflect the rhetoric of anti-nuclear forces that nuclear power is environmental unsound.

Project Description

The development of inputs to the system was the first task. The specific subject of this analysis is the construction, maintenance, and decommissioning of a 1,000 MWe nuclear power plant. The boundary of the system encompasses the plant and the property it sits on. The output of the system is net electricity generation. This study draws upon an earlier study completed by Dr. Christopher Lapp (Department of Environmental Engineering - University of Florida) in 1991. It was undertaken to address the new technologies and efficiencies that have occurred in the nuclear power industry and its supporting industries. These new technologies and efficiencies combine to show a large increase in the overall benefit of nuclear power within the method of this analysis. The amount of energy required to provide goods and services expressed as an emjoules per dollar ratio has decreased substantially in the past 30 years due to increases in energy efficiency.

The focus in this study is on current and future costs. The 30 years of experience in the research, construction, and operation of nuclear reactors is not viewed as relevant because no new reactor has been built in over a decade and the country is currently facing a decision to continue the nuclear option. Past development costs can be viewed as representing sunk costs not contributing to the total cost of a new nuclear reactor. It is important that the decision to invest in nuclear power plants be based on representative cost estimates and not on the cost of prior generation plants. The highly publicized reports on the high costs associated with nuclear power (e.g. 15 - 17 cents/KWhre for the San Onofre plant) with the implication that these costs represent what current generation nuclear power plants will provide is extremely misleading. It is important to note that the high costs cited by those opposed to nuclear energy apply to the earliest plants built during the infancy of the nuclear power generation industry. In the past forty years the nuclear power industry has gone through approximately three generations and is currently building (in foreign countries) the fourth generation where costs and environmental effects are substantially lower. In fact, the cost of nuclear power has remained between two and three cents per KWhre for the past 15 years and has been steadily decreasing since 1987. One of the largest inputs of energy and cost into the nuclear power generation process is uranium enrichment. Gaseous diffusion enrichment was originally developed as part of the Manhattan project. In the early years massive enrichment plants were built at great expense as part of the weapons program. In order to enrich uranium to 4% approximately 1700 separation stages are used. This many stages represents a plant size of well over 50 acres. Because of the billions of dollars already sunk in the existing gaseous diffusion plants and equipment, the U.S.A has maintained a singular commitment to diffusion technology. Recently developed enrichment technologies such as centrifuge and laser enrichment requires between two and ten percent of the energy used for diffusion enrichment depending on the specific method or plant. Russia, Netherlands, U.K., and Germany all have operating centrifuge enrichment plants. The U.S. is looking to implement an energy efficient enrichment program. But despite the huge energy cost, the gaseous diffusion enrichment industry with its sunk cost (under operational control of the U.S. Enrichment Corp.), is sufficiently large to delay replacement at present. The cost of diffusion (largely due to the cost of electricity) is not significantly greater than centrifuge enrichment (capital plus energy) when the capital costs of gaseous diffusion are ignored. Currently the world has a large oversupply of enrichment capacity, which delays the upgrading of current capacity. This study has employed centrifuge enrichment, which represents the current state of the art and is used in most of the world. All of the technologies and efficiencies employed in this study associated with the reactor and its support industry are presently available. No technologies were integrated into the analysis, which do not exist on an industrial scale.

The power plant is a single 1000 MWe unit. It contains one reactor capable of generating 3000 MWth, with a 33% efficiency. The reactor uses UO2 enriched to 4% and a planned fuel burn up of 43,000 MWD/MTU. The plant is situated near a fresh water body such that 50,000 m3/hour of makeup water are available. The plant has a single 400-foot tall hyperbolic wet natural draft-cooling tower situated in close proximity to the plant. The plant (reactor, service buildings, cooling tower) consumes 200 acres of land for the duration of its operation and is surrounded by an additional 1200 acres of undisturbed land. The power plant is situated 20 miles from the nearest urban center and 50 miles from the nearest downwind (prevailing wind) urban center. The site contains a mix of woods, field, and rural agricultural areas. The inputs into the system are as follows:

1) Research and Regulation

2) Construction

3) Materials

4) Fuel for Materials

5) Fuel for Construction Goods & Services

6) Fuel Cycle: Mine, Mill, Conversion, Enrich, Fabricate, Waste Disposal

7) Operation & Maintenance

8) Decommissioning

9) Emergy Charge for Accident Risk

Detailed descriptions follow below of these inputs and how emergy values for each were determined.

OUTPUT: The net electricity which is produced by the model plant in 40 years at an average capacity of 75% is 262.8 Terawatt-hr_e .The plant is expected to operate at full power 75% of the time for the 40 years that it will be operational. A factor of 75% is reasonable if not conservative since Capacity factors are presently trending above 80%, especially for newer reactors. The last three years have shown a rolling average for the capacity factor of 91%.

REGULATION & RESEARCH: The regulation of the nuclear industry is paid for by the industry itself. One hundred percent of the NRC's funding is provided by the different parts of the nuclear industry in amounts commensurate with the regulation they require. Electricity producing nuclear power facilities account for this cost in their operation & maintenance budgets. Therefore the emergy of regulation is included in the O & M section below.
The majority of the research performed to date, which has benefited the nuclear industry, is considered *sunk cost* in this study. Some research will no doubt continue to be performed in the future, which will help the nuclear industry. This research should be considered. The main government sponsored programs in nuclear research amounts to approximately $5 billion for the past 10 years. It is reasonable to assume that the next 10 years will be the same in constant dollars). The amount of benefit for one 1000MW, plant is 1% (the fraction of the plants power generation share of the whole industry) of $5 billion or $50 million.

CONSTRUCTION: There are four major sources of emergy input associated with construction: materials, fuel for materials processing, fuel for construction, and goods & services. To determine the amount of materials emergy, the quantity of the materials used to construct the plant is determined. Using sources on plant decommissioning and construction, estimates were made for the amount of concrete, steel, aluminum, and copper needed for the model plant. These materials represent the major sources of emergy from materials in the plant. A certain amount of fossil fuels is used to process the materials. These amounts were found per kilogram of each material. Multiplying by the amount of materials yields the total fuel for materials. The fuel used in the construction of a nuclear power plant was determined and converted into emergy units. The value of goods & services provided to the plant was determined by estimating the total cost of the plant. This analysis was done using data for costs of nuclear power plants recently completed and adding adjustments for inflation. An additional amount was added to this to take into account the additional costs of certain aspects of the plant, which lead to lower environmental and social costs (such as a cooling tower or a better but not cheaper plant site).

FUEL CYCLE: The nuclear fuel cycle in the U.S. is presently the largest emergy input associated with the nuclear power plant. This is largely due to the massive electricity demands of gaseous diffusion enrichment. As discussed earlier, this study employs centrifugal enrichment. This one change has a profound impact on the fuel cycle and on the total emergy cost of nuclear power.. Not only does this change increase the attractiveness of nuclear power but also it provides a powerful argument for replacing gaseous diffusion enrichment without delay. The fuel cycle was subdivided into the following six sections: mining, milling, processing, enrichment, fabrication, and waste disposal.

Uranium is obtained from ore, which typically contains 0.2 w/o Uranium. There are primarily two uranium isotopes in nature: 99.3 w/o U^{238} and 0.7 w/o U^{235}. The U.S. has a large uranium supply with most mines located in the western states. Unlike coal mines, a majority of uranium mines are deep hard rock mines with commensurate negligible land disruption. A 1000 MWe coal power plant consumes 6.2 billion pounds of coal per year, (assume pure deposit at mine) while a similar nuclear plant requires 200 million pounds of ore. Even if all uranium and coal mines were above ground, (actually a majority of coal mines are) the coal plant's fuel requirement would consume thirty times as much land. Uranium mines also tend to be safer (fewer cave-ins, less gas) than coal mines. The only significant health or environmental effects associated with the mining process are silicosis and radon gas, both of which affect miners. These effects are discussed in the *Environmental Effects* section. Once the ore is mined it is sent directly to a milling plant. Milling involves the purification of the ore to a level around 96% Uranium. The ore arrives at the mill and is crushed and ground. After a physical separation process, the remaining ore is subjected to chemical leaching and ion exchange or other extraction methods. Most of the radioactive uranium daughters are deposited in the tailings. The waste from the process contains suspended solids (tailings), which settle out, and liquid wastes, which are treated. Most of the radiation from the milling process occurs at and around the tailings pile as a result of radium and radon. Other wastes are treated or buried as necessary. The environmental effects of milling are negligible. Approximately 42 million lbs. of yellowcake (10.5 million tons of ore) are needed annually to support the U.S. nuclear power industry (currently operating with a burnup of 40,000+ MWD/MTU). Seven thousand MT of U_3O_8 are consumed by the model 1000 MWhre plant (43,000 MWD/MTU) in forty years· Processing or conversion involves the conversion of U_30_8 to UF_6. There are two chemical methods to accomplish this. The details are not relevant to the analysis except that both processes release fluorides, which must be dealt with. Radiation releases are minimal. The UF_6 is then sent to an enrichment plant where the percent of molecules containing a U-235 atom is increased from 0.7% to 4%. The energy cost of enrichment is primarily electrical. Diffusion plants typically use 2.5 MWhre per SWU· This can account for as much as 98% of the electricity consumed in the fuel cycle. The centrifuge enrichment processes uses 10% as much energy as diffusion· The U.S.

Enrichment Corp. does not presently employ centrifuge enrichment. The United Kingdom, Germany, and Netherlands, on the other hand, have several centrifuge enrichment plants operating at an energy cost of between 0.10 and 0.25 MWhre per SWU. The new plants planned for this country are expected to consume as little as 0.05 MWhre per SWU. This study assumes centrifuge enrichment at an energy cost of 0.10 MWhre per SWU. In centrifuge enrichment the UF6 enters small spinning canisters, which use centrifugal forces to separate the lighter U-235. The process does not require the large number of stages that gaseous diffusion does. When the desired 4% enrichment is achieved the gas is sent to a fuel fabrication plant. The first step in manufacturing the fuel is to convert the UF_6 to UO_2. Then the UO_2, which is a powder, is pressed, sintered, incorporated into fuel rods and assemblies and prepared for shipment to the power plant. Every 18 months one third of the fuel in the reactor is replaced. This study assumes a once-through fuel cycle so there is no recycling (the spent fuel contains 1 w/o U-235 and 0.64 w/o Pu-239). The spent fuel is stored on site until it cools and is then shipped to a geologic depository. The regulated government cost in the U.S. for the cost of waste disposal is 1 mill per KWhre delivered. This charge represents the amount that nuclear power plants must pay for the disposal of high-level waste (spent fuel) to the U.S.D.O.E., which will operate the long-term disposal-storage site.

The electric and fossil fuel energy required for the mining, milling, processing, enrichment, and fabrication were found in terms of MWhr. /MTU or J/MTU of material. These energy values are assumed to be constant in time. This is a conservative estimate since the various processes (except for mining) would tend to become more energy efficient in time. The energy efficiency of mining will vary with the quality and availability of ore. The amount of material and energy consumed by the nuclear fuel supply industry per year was found and then normalized to the 1000 MW plant and multiplied by 40 years. Application of the proper transforms then yielded the emergy input.

OPERATION & MAINTENANCE: Data on plant operation & maintenance (industry averages) were carefully examined. In recent years the cost of plant operation & maintenance has decreased from a high of 1.85 cents/KWhre in 1987 to 1.62 cents. O & M costs can vary considerably over the plants life but it is not likely that the cost will exceed 1.85 cents/KWhre for any significant length of time. The O & M expense is approximately $122 million per year per 1000MW plant.

DECOMMISSIONING: At the end of 40 years, the power plant is shut down for the last time. The reactor is given time to cool and for activity to decrease. The decommissioning process involves many complex economic and environmental interactions. There are essentially three stages of decommissioning and an ultimate condition in which the site will be left. Unless land shortages become severe in the future there is little need to turn a former power plant into a park or housing development. Decommissioning will therefore mean returning the site to a state which will require no surveillance, (i.e. neither exposure to individuals on the site nor radiation levels at the site will need to be monitored) and which will not be developed for other uses. Some other decommissioning options include long-term safe storage and conversion. The safe storage option involves removing the fuel and other easily removed components and sealing the reactor building as in first stage decommissioning (described below). The reactor is monitored to assure its continued safety with minimum personnel. In 100 years the activity can fall to one one thousandth of its shut down level. The risk and radiation exposure to workers and thus the cost of decommissioning and decontamination after 100 years would be substantially reduced. The cost would be further reduced in that a fraction of the net cost would be safely invested for the 100 years such that the investment would grow to cover the total cost of final D & D. The net cost for decommissioning the nuclear facility would be rendered relatively insignificant (perhaps as low as $20 million invested at the time of final shut down) . There are two reasons for not choosing this D & D scenario. *Green field* decommissioning at the time of shut down is the most probable and expensive (and thus conservative) option. Also, it is not clear that deriving the benefits from nuclear power and then leaving the clean up to future generations is appropriate or responsible.

The other major D & D option is conversion. The plant is decontaminated and the site of the reactor building is converted for a new nuclear or fossil plant. This option would reduce costs and is probably the most probable. However, the conservative option is green field decommissioning at the time of shut down. The first stage of decommissioning involves isolating the reactor containment building. Valves, plugs, etc are sealed. Systems and buildings external to the containment building are removed and decontaminated, buried, or disposed of as necessary. Walls ceilings and floors are scrubbed or treated to remove radioactive build up. In the second stage, all easily removed components inside containment are removed and decontamination of other components and structures commences. The turbine building and other remaining structures external to containment are removed. Shields are installed inside containment to prevent radiation or radioactive effluents from escaping through gaps or holes made by the removal of structures or components. In the third stage decontamination is finished. Non-radioactive rubble and scrap is removed and disposed of. Radioactive rubble and scrap (activated concrete shielding, steel from structures, etc.) are disposed of according to their activity. It is important to note that the hazard to workers can be great. Doses can exceed thousands of rads per hour in some areas. Robots and tight regulations can reduce detrimental health effects but accidents can occur. The costs of all these D & D activities have been analyzed in great detail elsewhere. The emergy of decommissioning a nuclear facility is determined by finding the estimated cost and applying the sej / $ ratio (environmental effects are included).

EMERGY CHARGE FOR ACCIDENT RISK: The probability of a core incident accident is given in reactor years and is assessed by a risk analysis of the plant. The NRC sets a minimum value of 10,000 reactor years without a core incident or 0.0001 incidents per year. Most reactors exceed this value and newer reactors have an even smaller probability. The more conservative NRC value will be used in this study. The probability of an accident occurring in the plants 40-year operation is 40 years divided by 10,000 or 0.004. This probability value is multiplied by the two largest losses associated with an accident: the cost of cleanup and the cost of replacement power. The accident considered in this study would be severe. In assessing the types of realistic accidents to consider here, two major accidents (Chernobyl and Three Mile Island) were examined.

Chernobyl was the most severe accident to date. The fuel melted, explosions occurred, the reactor caught fire, and a biologically harmful amount of radiological compounds was released into the environment. A Chernobyl type accident, however, is not a credible scenario. The graphite-moderated reactor had positive void and temperature coefficients of reactivity. This meant that an increase in temperature led to an increase in voids (boiling), which led to an increase in thermalized neutrons and thus a still higher temperature and eventual steam rupture, fuel melting and fires. A Chernobyl style reactor could not even be licensed in the United States. In the Three Mile Island accident, a stuck valve led to a loss of coolant flow and a temperature rise. Because of the negative temperature coefficient inherent to all U.S. reactors, the reactor quickly went sub-critical. However, residual neutron fluxes and thermal energy combined with a lack of coolant led to a fuel temperature increase. The increase was quickly compensated for by the ECCS but the reactor operators later wrongly shut off the ECCS for several hours. By the time the mistake was corrected as much as one half of the core had melted. The melted fuel dropped into the bottom of the vessel and was quenched. All of the fuel was contained in the pressure vessel. The TMI accident caused the release of some radiological compounds (from the melted or damaged fuel) into the reactor containment building. Some radioactive gases such as xenon and iodine were released to the environment intentionally, but the resulting radiation was well below background levels. The consequences of TMI were far reaching. The accident led to an increase in regulation, retro-fitting of safety features (triple redundancy, better monitoring) in existing reactors, and the inclusion of new safety features in the design of new reactors. The nuclear power industry spent billions of dollars in the aftermath of TMI. Considering only accidents with probabilities within three orders of magnitude of 0.004 (i.e. probability > 0.000004) leads to the following postulated incident: 1.) LOCA initiated. 2.) Make up water insufficient such that some of the core melts and is then primarily contained in the pressure vessel. 3.) Radioactivity released to the containment structure but little to the environment. The major expenses resulting from this postulated accident are the cost of cleaning and decontaminating the plant and of providing replacement power. The cost of clean up and replacement power for TMI has been estimated at around two billion dollars (1991 dollars). It is assumed that the same site and NSSS will be used for replacement power. It is further assumed that as a result of power plants becoming more complex and inflation the cost of replacement power will increase. The upper boundary cost used in the study was five billion dollars for clean up and replacement power. This cost was transformed into emergy units using the sej / $ transform.

EMERGY CHARGE FOR ENVIRONMENTAL DEGRADATION: The largest environmental impacts associated with nuclear power are fossil fuel use (including coal produced electricity) in support of the reactor, thermal stress, and uranium mining. In the construction of a nuclear power plant and in the fuel cycle process energy is expended in the form of electricity and direct fossil fuel use, which can affect the environment detrimentally. These environmental effects have been thoroughly studied elsewhere but have not been expressed in comparable units. Some studies calculate dollar amounts for the cost of undoing or not doing environmental damage ("no damage" method)· Other studies calculate dollar amounts representing the cost associated with the damage done.

There are two key difficulties with the latter method: Estimating dollar values for likely harm caused by pollutants (or other byproducts of electricity production) in the form of adverse health effects, or potential death in the human population, or in the form of a lowering of the quality of life is difficult to do consistently or accurately. Second, a more rational approach would be to assess the cost of not doing damage as opposed to assessing the cost of undoing or simply writing off the damage already done, since the former highlights the cost and the solution. For these reasons the method employed in this study is the "no damage" method. The production of electricity from coal has many complex environmental and social costs and a detailed analysis is beyond the scope of this study. Since these costs are only a small part of this analysis approximate values from other studies will be used. When coal is burned at a power plant large amounts of NOx, SOx, and COx, are released. These emissions can be reduced by the use of more expensive low sulfur coal and by employing expensive scrubbers and other pollution control devices. Large amounts of ash and liquid waste are also produced. Some of the ash can be used elsewhere (i.e. road underlayment) and the liquid waste treated at some expense. Thermal effects are also a factor but they are no different from nuclear thermal effects (see discussion on nuclear thermal effects below). Coal power production also involves massive land disruption and health problems affecting miners, but underground mining and extensive health and safety regimes while cost intensive, could reduce these effects to negligible levels. The cost of reducing NOx, SOx, and COx emissions in dollars is available in the literature (costs in $ / KWhre). It is important to realize that these cost estimates represent the cost of reducing emissions to levels consistent with current regulations. In order to reduce emissions (and other effects) to levels where the environmental and social costs are negligible relative to other energy inputs, the costs to a utility would as much as double. This is as a result of better coal, emissions control devices and safer mining procedures. For economic reasons, this is not done but it does give a useful value for the environmental cost of coal electricity production. It is this doubled cost which was used in this study. Most of the non-coal fossil fuel used is in the form of oil burned in an industrial plant setting where pollution controls similar to those already mentioned can be employed at similar costs. Therefore, for fossil fuel use, the total number of BTU's is converted into KWhre (of coal burned at a steam power plant) and then into a total cost. The other major source of environmental damage is thermal stress. The model plant analyzed generates 1000 MW of electricity at an efficiency of 33%. Therefore, approximately 2000 MW of thermal energy must be given up to the environment. As discussed above any power plant must do this. For almost a century waste heat from power plants has been dissipated by pumping water from a lake, river, or ocean directly through the condenser and back to the water body (once through cooling with the water temperature increased by 10 to 20 degrees). In the last thirty years, power plants have become larger and more concentrated. It has become apparent that thermal pollution can have serious detrimental effects on the biota in the water bodies. Several things have been done to ameliorate the heat pollution problem. Diffusers added to the return system spread out the temperature effects over a wider area. Cooling ponds are used in the same manner as are other water bodies except that they are artificial. They require huge amounts of land (1000-2000 acres for the model plant at up to $4000/acre)". Some cooling ponds employ spray systems which can reduce the pond size by a factor of twenty. This type of cooling pond results in 1-2% of the spray volume being lost to evaporation. Some disadvantages of cooling ponds are that radioisotopes and other contaminates can build up, local fogging can occur, and the pond water may enter the water table. Closed cycle cooling systems such as cooling towers are the optimum choice when land is scarce or water quality issues prevail. Cooling towers can be wet or dry and can circulate air by natural draft or mechanical draft. Only wet cooling towers are suitable for large power plants. Wet towers cool the intake water by direct contact with the tower's airflow and evaporation accomplishes most of the cooling. The condenser output water in dry cooling towers passes through a piping network and the tower air cools the water by conduction through the piping, Mechanical draft towers rely on fans to circulate air and natural draft towers rely on air buoyancy and chimney effects. Mechanical draft towers can have noise levels approaching 65 dB at 2,500 ft whereas natural draft towers are a quieter 50 dB. A wet natural draft-cooling tower is the best overall choice from an environmental standpoint. It is more costly to construct but its 0 & M costs are very low. A typical tower is 400 feet tall and 500 feet wide at its base and can cost $50,000,000. As much as 3% of the condenser flow can be lost due to evaporation and drift (approximately lm^3 per second for the model plant). The environmental effects of cooling towers include noise and sight pollution, possible local fogging and icing, and possible mineral and chemical additive deposition. The noise level outside the plant site is negligible. A 400-foot tall cooling tower is no doubt considered unsightly to many. However, it is difficult to access an emergy value for this and the value would arguably be negligible. Although local precipitation appears not to have been effected at one carefully studied site, some local fogging occurred when conditions were right. Fogging and icing were significantly reduced in towers above 300 feet. Some chemicals are added to the coolant flow to prevent corrosion and fouling and these chemicals can find their way into the environment as a result of drift and evaporation from the tower but these effects can be reduced by choosing low toxicity chemicals when possible. A literature search produced no study that showed unacceptable levels of toxins or damage to the biota caused by these toxins. The amount of liquid and gaseous wastes emitted during the normal operation of nuclear power plants is negligible. Liquid wastes contained in the plant's water supply are continuously cleaned and treated by a variety of systems. Air in the plant is similarly cleaned. A small amount of radioactive effluent does leave the plant in the form of radioiodine, tritium, noble gases, cesium and activated transition metals, but the activity associated with these effluents is orders of magnitude below background. The only major emergy cost due to the plant's normal operation is thermal pollution. This cost is embodied in the concrete and steel used in the construction of the cooling tower and due to the goods and services associated with its construction. Therefore the emergy input for thermal effects is found by adding the emergy value of the concrete and steel to the emergy value associated with the cost of the tower (using the sej / S transform).

The only other non-negligible environmental impacts caused by nuclear power are direct impacts from the fuel cycle. As discussed in the Fuel Cycle section above, the only significant health or environmental effects associated with the mining process are silicosis and radon gas, both of which effect miners. Silicosis is a lung disorder, which is caused by the prolonged breathing of dust. It can be, and in many mines has been, minimized at some expense by spaying water, proper ventilation, and monitoring worker health.   Inhalation of radon (and daughters) has been linked to increased incidences of lung cancer among smoking miners in some studies, but there is still some debate. The remedy to the problem is increased ventilation and frequent surveying (radon can build up in certain areas). Many of these safety measures are already in place in some mines but as in the environmental effects of coal section above additional costs would be incurred to minimize the health effects. In the case of mining, the added cost is low, but not negligible. Since the cost of nuclear fuel was already conservatively estimated, no additional environmental charge was added. The milling, processing, enriching, and fabricating processes (excluding electricity and fossil effects, which have already been accounted for) have minor environmental effects (as descriped in the Fuel Cycle section above). Small additional costs could reduce fluoride and ammonia emissions and this cost can also be absorbed into the conservative fuel cost estimate.

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RESULTS

The results are presented below. The yield ratio is found by summing all the inputs into the power plant (in emjoules) and dividing the result into the output.

TOTAL OUTPUT 18.9
TOTAL INPUT 2.23
YIELD RATIO 8.45

. This study yielded a ratio of 8.45 for a 1000 MW_e nuclear power plant. This value compares to a ratio of 2.5 for coal, 0.28 for wind and 0.48 for solar and 6.0 for an earlier generation nuclear power plant analyzed by C.W. Lapp and 2.7 for a first generation plant as studied by C. Kylstra and K. Hart in the mid 1970's. These values show the major progress that nuclear power has made in reducing the social and environmental effects and and reducing the cost of nuclear energy production.

COAL:	**2.5**	**NUCLEAR:**	**8.45**	**(This Study)**
WIND:	**0.28**	**NUCLEAR:**	**6.0**	**(C.W. Lapp 1991)**
SOLAR:	**0.48**	**NUCLEAR:**	**2.7**	**(Kylstra, Han 1975)**

In conclusion, Nuclear Power is our most efficient power source from an environmental standpoint.

Bibliography

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