

Use of Integrated Environmental Decision-Making to Combine Greenhouse Gas and Radiological Hazards on Energy Alternatives Using Life Cycle Analyses - 11208

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ABSTRACT

Base-load energy (electrical) supply units in the United States are coal, natural gas, nuclear power, and oil. Of these four sources, only nuclear offers the ability to avert the generation of CO₂, and thus reduce greenhouse gas (GHG). However, nuclear power plants have radiological emissions and impacts, as to a lesser extent do the fossil fuel supply options. Ideally wind, solar, and geothermal offer the promise of non-polluting green energy supply sources. However, these sources also release GHG (and perhaps radioactivity) during their construction and decommissioning. The purpose of this study was to develop a life cycle analysis of select energy supply units that combines radiological and GHG hazards into a single integrated decision-making process. The focus of this study was on development of an approach for integrating two different metrics into a single life cycle analysis. The two metrics included are those of minimizing GHG emissions, and minimizing radiological emissions in the generation of energy. A life cycle analysis of the environmental impacts of energy supply sources includes the cradle to grave environmental impacts of the fuel cycle. The intent of this study was not to perform the definitive analysis of GHG or radiological releases from different energy technologies. Rather, it was to develop an analysis methodology that can be used by EPA and others to evaluate energy technology GHG releases with various input data and assumptions. Nonetheless, a base case has been analyzed using the developed methodology and representative data, and the results presented.

INTRODUCTION

Currently in the United States, baseload electricity generation units are fueled primarily by coal, uranium, natural gas, hydroelectric, and oil, in order of net generation. Of these technologies, only nuclear and hydroelectric power avoid the direct generation of CO₂ and other greenhouse gases (GHGs), as well as other pollutants associated with the combustion of fossil fuels. The potential to significantly increase the output from hydroelectric power is limited, however, and the major alternative energy sources (wind, solar, and geothermal), while also not direct generators of GHGs, are subject to availability limitations that currently make them unsuitable as baseload supply units.

A comprehensive life cycle analysis (LCA) of the environmental impacts of an electric generating technology must cover all emissions from cradle to grave of the technology. Four energy technologies were evaluated: coal, natural gas, nuclear, and wind. Life cycles / fuel cycles were developed for each. Life cycles can be considered for convenience in three phases arranged sequentially in time: construction, operation, and decommissioning. The processes within each phase can vary within a generation technology and more detail can be added, but the steps illustrated are considered typical. Both primary and secondary emission sources were considered, however, only the primary emission sources have been evaluated in this study. As an example to clarify the distinction between primary and secondary, diesel emissions from trucks and trains used to transport fuel to the electric generating unit are examples of primary emissions, while emissions from crude oil tankers and oil refineries used to process diesel fuel are examples of secondary emissions.

LCA methodologies were developed to estimate and compare the GHG emissions and radiological impacts from each of the four energy technologies. Since no single reference was found that provided the necessary calculation methodology for all of the emission sources analyzed in this study, most of the equations were derived explicitly for this study, based on information and data that was obtained from numerous references. This was necessary in order to ensure that consistent methodologies and data were used across all emission sources. Finally, the calculation methodologies have been incorporated into an Excel spreadsheet, called Energy Technology-Life Cycle Analysis Tool (ET-LCAT).

The focus of this study was not to perform the definitive analysis of GHG or radiological releases from different energy technologies. Rather, it is to develop an analysis methodology that can be used by EPA and others to evaluate energy technology GHG releases with various input data and assumptions. Nonetheless, a base case has been analyzed using ET-LCAT and representative data, and the results presented.

Finally, since the base case input parameters were selected from peer reviewed studies, Agency policy, or experienced engineering judgment, some important insights into some key issues from examination of the base case results. For example, the fossil fuel technologies GHG emissions are one to two orders of magnitude greater than the GHG emissions from either the nuclear or wind technologies. Also, the radiological impacts from the nuclear and coal technologies are approximately the same, and are about three orders of magnitude greater than the radiological impacts from either the natural gas or wind technologies.

LITERATURE REVIEW

This effort began with a search of the literature to determine the extent of information already available on this topic. Literature in five broad areas (Greenhouse Gas Emissions, Radiological Emissions and Hazards, Assessment Methodologies, Social Cost of Carbon, and Monetary Valuation of Radiation Exposure) were sought out and reviewed. The results of the literature review are summarized in this section. Note, because so many documents were reviewed, complete references are not provided in this paper, rather the document is identified by its primary author only. Please contact the authors of this paper to obtain a complete reference for any of the documents discussed below.

Greenhouse Gas Emissions

Thirty documents were reviewed that provide information on the amount of greenhouse gases potentially released from each of the four energy technologies being considered.

EPA's AP-42 emission factors were reviewed. It is anticipated that these factors would be used to estimate the greenhouse gas emissions from coal and natural gas power plants. Obviously, the amount of CO₂ emission from a coal plant would be dependent on the carbon content of the coal. The USGS' "Natural Coal Resources Data System, US Coal Quality Database" (USGS 2009) was used to estimate a range of coal's carbon content.

EPA's eGRID provides information on current electricity usage within the United States, in order that an energy technology mix for current production can be determined. The eGRID information was used to estimate CO₂ emission rates from current coal, natural gas, nuclear, and wind plants. Other documents reviewed provided their own estimates of CO₂ emissions for various energy technologies, including the nuclear fuel cycle, and renewables.

The documents reviewed indicate that for fossil fueled power plants the majority of greenhouse gas emissions are due to the operation phase of the life cycle. Therefore, it was determined to address only the operation phase of the coal and natural gas life cycles. Similarly, for the wind technology there are almost no greenhouse gas emissions during its operational phase, so it was determined to address only the construction and decommissioning phases of the wind technology life cycle.

Radiological Emissions and Hazards

The literature search examined radioactive emissions (both atmospheric or waterborne) from the life cycles for electricity production from coal-fired power plants and light-water cooled nuclear power reactors. Under this task, the search is limited to the process of quantifying only the two electricity generation methods.

According to the World Energy Council (2004), the life cycle of electricity generation plants can be divided into the following main life cycle phases:

- **Fuel preparation:** Exploration/prospecting of fuel resources, fuel resource extraction and processing;
- **Infrastructure:** Construction of power plant, including exploration/prospecting of ores and minerals, material manufacture, production of components, construction and deconstruction of vehicles and roads, and transport;
- **Operation:** Power plant operation, including normal malfunctions;
- **End-of-life processes:** Disposal of waste processes;
- **Background infrastructure:** Construction, deconstruction and reinvestment in suppliers facilities;
- **Transmission/distribution infrastructure:** Construction/deconstruction and maintenance of transmission/distribution networks; and
- **Transmission/distribution to the customer:** Losses on high, medium and low-voltage power networks.

For the purpose of this study, the life cycle considered in terms of radioactive releases are more narrowly defined as: fuel preparation (fuel resource and processing only), infrastructure (transportation only), operation, and end-of life processes (waste disposal).

Pigford (1975), UNSCEAR (1982), Corbett (1993), and NCRP No. 95 were determined to be useful in identifying the relevant cycle phases and quantifying the radioactive emissions from the life cycle of electricity production from coal-fired plants. McBride (1978), DeSantis and Longo (1984), Cohen (1984), and Gabbard (1993) were useful in identifying special topics and controversial issues within the same cycle, while Fabricont (1983), Cohen (1984), and Gabbard (1993) make some interesting but qualitative comparisons between coal and nuclear power generation. The life cycle selected for further study for the coal fuel cycle includes the mining of coal, transportation, and coal-fired plant operation.

Pigford (1975), UNSCEAR (1982), NCRP No. 92, Table S-3, WASH-1248, Table S-4, WASH-1238, NUREG-1437 were determined to be useful in identifying the relevant cycle phases and quantifying the radioactive emissions from the life cycle of electricity production from nuclear light-water-cooled power plants. NUREG-0706 is useful in providing special insight into the radioactive emissions from uranium mining and milling. The life cycle selected for further study for the nuclear fuel cycle includes: uranium mining, milling, conversion of uranium oxide to uranium hexafluoride, uranium enrichment, fuel conversion and fabrication, plant operation including accidental releases, shipment of irradiated fuel and solid radioactive waste, and management of low- and high-level radioactive waste.

AIF/NESP-032, and NUREG-0002 provide useful information on the methodology used to calculate the collective doses reported in Table S-3 and WASH-1248. An updated version of this methodology was used to estimate the radiological hazard for this study.

Finally, Gogolak (1980), Marlay (1979), and Cooper, et al (2003) provide information that demonstrates that ^{222}Rn in natural gas is not a radiological concern. As such, the collective dose due to ^{222}Rn released from natural gas fired powered plants will not be addressed.

Assessment Methodologies

A review was performed of several documents related to various methodologies that could be used to compare the impacts from GHG emissions to radiological emissions and hazards. The World Energy Council (2004), SAIC (2006), Linkov, et al (2004), Marvin Shaffer & Associates (2004), and the CAFE FEIS are documents that generically describe the various assessment methodologies, including benefit-cost analysis, life cycle analysis, and multi-criteria decision analysis. TRACI, Eco-indicator 99, Umberto (2009), and Bauer, et al (2007) describe specific software that implement the various methodologies.

Based upon the review of these documents, it remains the intent of this study to develop and utilize a life cycle benefit-cost methodology to compare the impacts from GHG emissions to radiological emissions and hazards for the four electricity generation energy technologies: coal, natural gas, nuclear, and wind.

Social Cost of Carbon

The “social cost of carbon” is defined as the net present value of the climate change impacts over the atmospheric life of the GHG and the resulting climate inertia associated with one additional net global metric ton of carbon emitted to the atmosphere at a particular point in time. It is obvious from the documents reviewed that much uncertainty exists regarding the dollar value to assign to the social cost of carbon. The recently published CAFE FEIS used \$2 and \$33 per ton CO₂. In a 2008 Federal Register Clean Air Act publication, the EPA recommended utilizing a range of values for the social cost of carbon.

Monetary Valuation of Radiological Exposure

The NRC in NUREG-1530 is currently recommending that a monetary value of \$2,000 per person-rem be assigned to radiological exposures. In DOE-STD-ALARA the DOE recommends applying a nominal monetary value of \$2,000 per person-rem, with a range from \$1,000 to \$6,000. With few exceptions, the other documents reviewed from other countries are consistent with the NRC’s and DOE’s radiological exposure monetary value.

DETAILS OF THE ANALYSIS

Selection of GHG LCA for Base Case

Based on the information developed from the literature search, a methodology (i.e., LCA) for evaluating the GHG releases from energy generation was developed. The methodology that was developed includes GHG emission models for each of the four chosen energy technologies: coal-fired, natural gas, LWR nuclear, and wind, and for each phase of the life cycle: construction, operation, and decommissioning. During the construction phase, the primary method for estimating GHG emissions was the embodied energy approach, which essentially divides the emissions due to the energy required to construct the facility by the expected total energy produced during the lifetime of the facility.

During plant operations, GHG emissions were estimated from the power plant, the fuel cycle, transportation, and waste management. For power plant operations, only GHG emissions from coal and natural gas facilities were estimated. Emission factors taken from EPA's AP-42 emission factor compilation were used. The user must supply the coal carbon content, as well as the heat content of natural gas. GHG emissions were also estimated for fuel cycle facility operations and transportation for all technologies except wind. For coal and natural gas the primary fuel cycle GHG emissions are mining and production, respectively. The nuclear fuel cycle GHG emissions were obtained from WASH-1248, updated as necessary. One of the primary updates to the WASH-1248 data was the inclusion of the option to specify centrifuge enrichment, rather than the more energy intensive diffusion enrichment, which was the only technology available when WASH-1248 was published.

GHG emissions due to decommissioning, including waste management, were also estimated for each technology. The decommissioning GHG releases used a methodology similar to that used for plant construction. Because the material from the plant can be recycled and reused, and because the energy requirements for recycling material are less than the energy requirements for obtaining the virgin material, there can be a GHG "savings" from the decommissioning of a plant. The user of the model can specify the amount of recycle to include in the analysis from zero (i.e., no recycle) to 100% of the plant's material.

A base case for an integrated comparison between generation technologies was developed. The base case includes the four chosen energy technologies. The impacts are presented in terms of the energy-normalized GHG emissions (i.e., grams of CO₂ released per kilowatt-hour (kWh) of electricity produced).

Development of Radiological Life Cycle Analysis

Based on the information developed from the literature search, a methodology (i.e., LCA) for evaluating the radiological releases into the environment was developed, as was a base case for an integrated comparison between generation technologies. The focus of the analysis is to assess energy technology life cycles for radiological releases into air, water, and land (solid waste placed in high-level waste (HLW), low-level waste (LLW), or mixed waste landfills). The four energy technologies evaluated are: coal-fired, natural gas, LWR nuclear, and wind. The impacts are mostly presented in terms of the energy-normalized radiological emissions (i.e., curies released per kWh of electricity produced).

Radiological releases during the construction phase are calculated in a similar fashion as construction GHG emissions, except that U.S. energy mix radiological emission factors are used here. Electrical energy is required in order to extract, process, transport and refine materials into all the finished products

that are needed to construct an electricity generation plant. That energy is often referred to as the material's embodied energy. Because the mix of energy technologies used to generate the electricity necessary to process the construction materials would include technologies that release radioactivity into the atmosphere, there would be a radiological impact from the construction of each of the four energy technologies being evaluated.

Radiological impacts during the operational phase for coal, natural gas, and nuclear electricity generation plant types will be discussed in turn. There is no release of radionuclides during the operation of a wind turbine. From coal plants the radiological impacts are due to the amount of uranium, thorium, and K-40 impurities in the coal, while for natural gas plants the impacts are due to radon contained within the gas. Because of its relatively short half-life (i.e., 3.8 days) much of the radon activity in natural gas will have decayed away before it arrives at the power plant. For nuclear plants the radionuclide releases were estimated for a pressurized water reactor (PWR) (NUREG-0017) and a boiling water reactor (BWR) (NUREG-0016) that would be 'typical' from the existing fleet of nuclear power plants, as well as for an AP1000 reactor, which is 'typical' of the current generation of reactors.

For coal and natural gas fuel cycle facilities, the radon release during coal mining and gas well operation was estimated. For the nuclear fuel cycle, WASH-1248 was used as the basis for non-power plant radiological releases. This approach is consistent with that taken by the NRC in the "Generic Environmental Impact Statement for License Renewal of Nuclear Plants" (NUREG-1437).

There is no transportation associated with the wind technology, while for the coal technology the primary mode of transportation is rail (with some truck and barge), and for the nuclear technology, trucks are the primary mode of transportation. Thus, there are no radiological emissions associated with transport for the coal, nuclear, and wind technologies; only natural gas, which utilizes natural gas fired pumps for transport, has the potential for radiological emissions. The radon release from the burning of natural gas to power the gas transport pumps was estimated.

No radiological waste is generated during operations of natural gas or wind power plants. For coal plants, radium present in the ash will decay into radon, which because it is a gas, can emanate from the ash pile. The radon emanation from ash was reduced to account for the fact that during coal combustion the ash is vitrified. For nuclear plants both LLW and spent fuel were considered. For LLW it was assumed that only direct exposures would occur during the transport of the waste from the power plant to the disposal facility. Consistent with current practice, it was assumed that spent fuel would be stored in an onsite independent spent fuel storage installation (ISFSI), and there would only be direct exposure to the surrounding population.

For this study, it was assumed that the ratio of the decommissioning to construction radionuclide release would be the same as the ratio of the decommissioning to construction CO₂ release.

Radiological impacts from decommissioning waste were estimated for the coal plant's ash pile and the nuclear plant. The ash piles impacts were integrated over a user specified time period (e.g., 100 years). The volume nuclear plant waste would depend on the type of decommissioning performed, and the radiological exposure would be those received during transport of that waste to a disposal facility.

Integration of Radiological and GHG LCAs

So far, this study has discussed and quantified GHG emissions and radiological emissions for the life cycles of the four chosen electric generation technologies. Interestingly, the fossil plant fuel cycles emit some radiation and the nuclear plant fuel cycle emits some GHGs. However, in order to be useful for

decision-making, the two different types of emissions must be compared in a meaningful fashion. How does one compare apples and oranges, or, in our case, CO₂-equivalent emissions to curies (or person-rem)? One needs a common metric that provides useful information relevant to one's concerns.

A risk-based approach that captures the deleterious health effects to a population from chronic low-level exposures to radioactive effluents can be successfully adopted. However, this sort of approach is not well suited to assessing the health effects of GHG emissions for a number of reasons. One primary impediment is that, unlike exposures to radioactivity whose effects are assumed linear with respect to dose over the range of interest, the impacts due to climate changes from GHG emissions are probably not linear and are less understood and not easily quantified. Also, while a large degree of uncertainty exists in the radiological exposure models, an even greater degree exists in the GHG impact models. Finally, while exposures to radioactivity are usually assumed to be uniformly detrimental (at least, certainly not good for you), GHG emissions may affect the climate in positive ways in certain instances or regions (e.g., Greenland), while causing negative effects in other instances or regions (e.g., the Arctic). In addition, raising temperatures may be beneficial to some species and detrimental to other species, including humans. Sea levels may rise and threaten habitation, but crop production may also increase.

Hence, this study chose to monetize (i.e., using a benefit-cost methodology) both the radiological and GHG emissions' effects to facilitate comparison of effects from the four different electric generation technologies. The population risks associated with GHG exposures have been estimated as a so-called Social Cost of Carbon (SCC), and radiological exposures have been quantified by several sources in terms of dollars per person-rem.

The Social Cost of Carbon (SCC) is an economic construct that tries to capture in discounted current dollars the future costs and benefits that may result from the release of CO₂ to the environment. The range of estimates is wide due to the uncertainties described above relating to socio-economic futures, climate responsiveness, and impacts modeling, as well as the choice of discount rate. For instance, for 2007 emission reductions and a 2% discount rate the global meta analysis estimates range from \$-3 to \$159/tCO₂, while the US estimates range from \$0 to \$16/tCO₂. Because of this range of potential values, ET-LCAT was designed so that the analyst has the option to specify any value for the SCC that is deemed appropriate.

This was necessary in order to ensure that consistent methodologies and data were used across all emission sources. Finally, the calculation methodologies have been incorporated into an Excel spreadsheet, called Energy Technology-Life Cycle Analysis Tool (ET-LCAT).

To monetize the radiological impact it was decided to calculate population doses using standard radiological release-to-dose modeling, and then convert the population dose using \$2,000 per person-rem. To calculate the population dose the methodology from NUREG-0002 was expanded to other radionuclides and employed.

SCOPE OF THE ANALYSIS

A comprehensive life cycle analysis (LCA) of the environmental impacts of an electric generating technology must cover all emissions from cradle to grave of the technology. A comprehensive LCA of a generating technology should also include "secondary" impacts, such as emissions from trucks or trains transporting material and emissions associated with the production and supply of components and consumables necessary for the generating technology. This study takes an incremental step in integrating the radiological hazards associated with nuclear power and select fossil fuel alternatives with hazards posed by GHG emissions into a single LCA. Coal and natural gas are selected as surrogates for fossil

fuels, and wind as a surrogate for renewable energy sources; current light-water-cooled reactor (LWR) technology is selected for nuclear energy.

Energy technologies other than the four considered for this study (i.e., coal, natural gas, LWR nuclear, and wind) were considered for inclusion, such as solar-photovoltaics, solar-heat, oil, and heavy water nuclear energy production, but were rejected for various reasons. For example, the petroleum (i.e., oil-fired) energy technology was not included because, compared to the other fossil fuel technologies (i.e., coal and natural gas), oil's contribution to the total electricity generation is small and getting smaller. Both solar-photovoltaics and solar-heat were rejected because the amount of electricity generated by each of these technologies is a very small contributor to the total United States' electricity generation. Heavy water nuclear was not included because it is not used in the United States to generate electricity.

The focus of this study was not to perform the definitive analysis of GHG or radiological releases from different energy technologies. Rather, it is to develop an analysis methodology that can be used by EPA and others to evaluate energy technology releases with various input data, assumptions, and environmental endpoints. That methodology has been incorporated into an Excel spreadsheet, called Energy Technology Life Cycle Analysis Tool (ET-LCAT).

Coal Power Plant Life Cycle / Fuel Cycle

Coal-fired plants account for about half the electric generation in the United States. A simplified, typical coal plant life cycle is illustrated in Figure 1. The boxes shown in black were specifically included in the analysis, while the gray boxes were not.

The LCA for coal followed the coal from either a surface or underground mine to a coal processing facility, and then to a steam electric generating plant. In order to allow the user to tailor the analysis to his/her particular case, the ET-LCAT tool allows the following aspects of the coal power plant life cycle / fuel cycle to be specified:

- Surface or underground mine
- Distance from the coal mine to the power plant
- Coal carbon, uranium, thorium, and K-40 content (ppm)
- Particulate fraction in coal ash
- General plant parameters: Capacity, Life, Thermal Efficiency
- Construction cost (\$/kW)
- Materials of construction (tones/GW)
- Fraction contribution to US electric energy mix

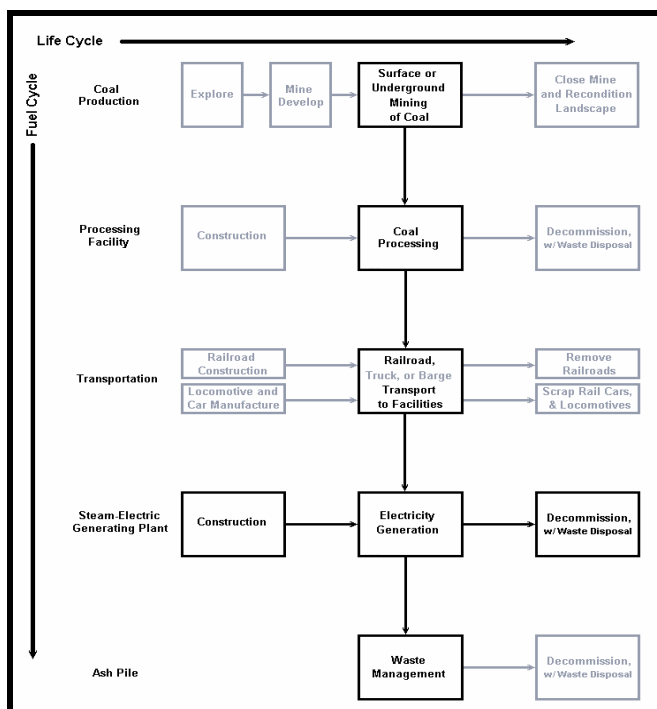


Figure 1: Coal Plant Life Cycle / Fuel Cycle

Wind Turbine Life Cycle

The wind turbine life cycle is considerably simpler than either the two fossil fuel or nuclear life cycles previously discussed. In addition, there is no fuel cycle for wind turbines since the “fuel” supply is local and renewable and wind turbines produce no direct emissions of any kind.

In order to allow the user to tailor the analysis to his/her particular case, the ET-LCAT tool allows the following aspects of the nuclear power plant life cycle / fuel cycle to be specified:

- General plant parameters: Capacity, Life, Thermal Efficiency
- Construction cost (\$/kW)
- Materials of construction (tones/GW)
- Fraction contribution to US electric energy mix

Nuclear Power Plant Life Cycle / Fuel Cycle

Of all the energy technologies, as illustrated in Figure 3, the nuclear fuel cycle is the most complex, although the life cycle still follows the division into construction, operation, and decommissioning. Unlike either coal or natural gas, the natural uranium ore requires expensive and complicated processing after it is extracted from the earth until it finally appears as part of a fuel assembly in a nuclear power plant. All of this front-end processing has been included in the ET-LCAT model, with most data having been taken from 10CFR 51, Table S-3, supplemented where necessary with data from more recent sources (see below) and engineering judgment.

In order to allow the user to tailor the analysis to his/her particular case, the ET-LCAT tool allows the following aspects of the nuclear power plant life cycle / fuel cycle to be specified:

- Reactor type: PWR, BWR, or AP1000
- Fuel enrichment method: Diffusion or Centrifuge
- Enrichment energy requirements (kWh/SWU)
- Low level waste generation rate ($m^3/kW\text{-hr}$)
- Distance to/from LLW disposal site
- NUREG/CR-5884 or NUREG/Decommissioning type: DECON, SAFSTOR1, SAFSTOR2, ENTOMB1, ENTOMB2, or ENTOMB3
- General plant parameters: Capacity, Life, Thermal Efficiency
- Construction cost (\$/kW)
- Materials of construction (tones/GW)
- Fraction contribution to US electric energy mix

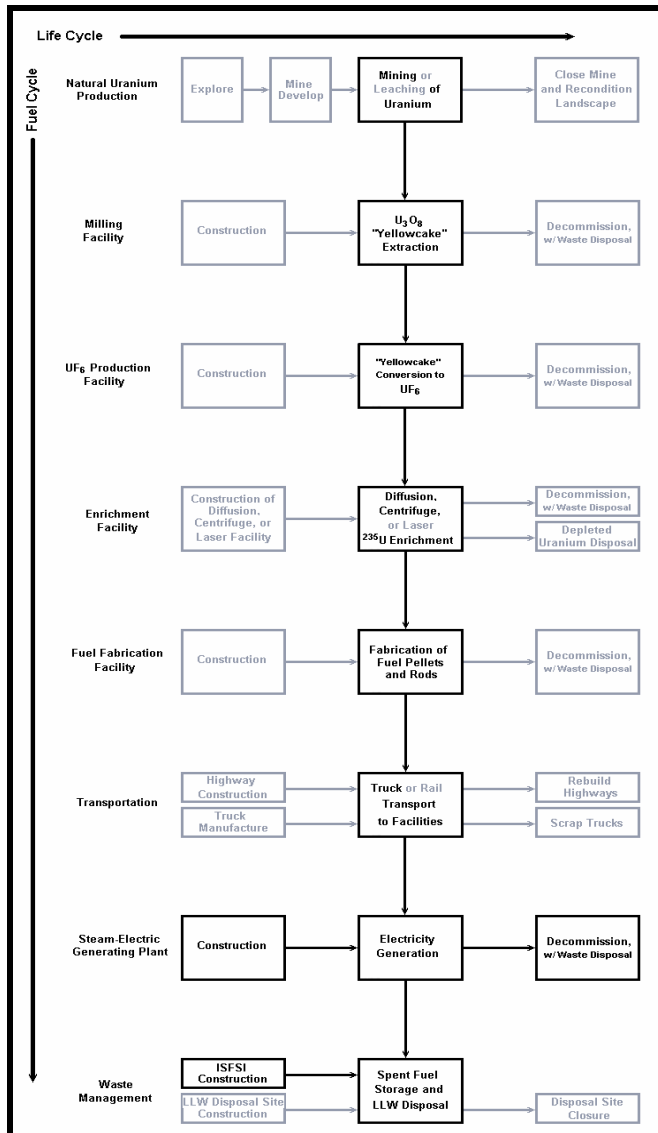


Figure 3: Nuclear Power Plant Life Cycle / Fuel Cycle

Natural Gas Power Plant Life Cycle / Fuel Cycle

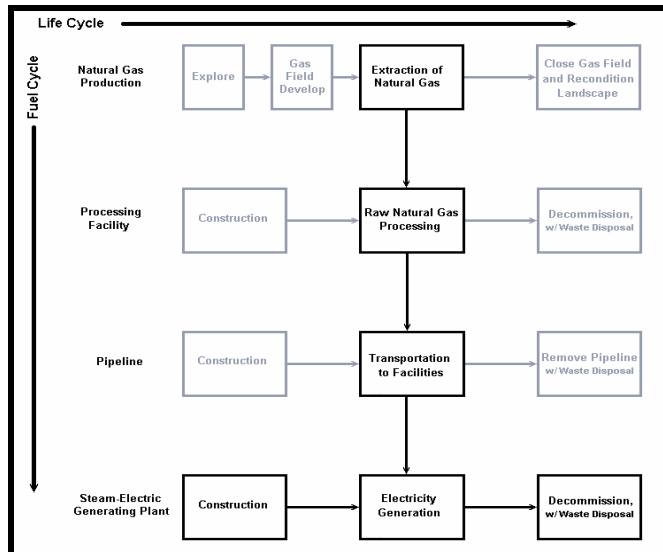


Figure 2: Natural Gas Plant Life Cycle / Fuel Cycle

- Natural gas ^{222}Rn concentration (pCi/liter)
- Natural gas transmission distance
- General plant parameters: Capacity, Life, Thermal Efficiency
- Construction cost (\$/kW)
- Materials of construction (tones/GW)
- Fraction contribution to US electric energy mix

Natural gas-fired power plants produce a bit less than 20% of the electricity in the United States. Figure 2 illustrates the simplified life cycle of a natural gas power plant. As can be seen by comparison to Figure 1, the gas and coal life cycle diagrams are similar on a high level, but differ in details.

The ET-LCAT tool allows the following aspects of the natural gas power plant life cycle / fuel cycle to be specified so that the analysis may be tailored to a particular case:

- Natural gas CO_2 emission factor (lbs $\text{CO}_2/10^6$ scf)
- Natural gas heat content (Btu/ft³)

BASE CASE RESULTS

Although the focus of this study was to develop an analysis methodology that can be used by EPA and others to evaluate energy technology GHG releases with various input data and assumptions, a base case was analyzed using the ET-LCAT and representative data.

While considerable thought was given to the selection of the data used to calculate the impacts and it is believed that the results are representative of energy technology GHG and radiological impacts, it is recognized that different results would have been obtained had different sets of data been selected for the analysis. In order to accommodate different sets of data, much of the data that are used by the ET-LCAT can be modified by the user to tailor the LCA to his/her specific needs. Figure 4 presents the ET-LCAT CO_2 emissions and radiological impacts results using the base case data. The right four column of the top half of Figure 4 show the population doses that result from the radionuclide emissions from the four energy technologies for the base case, while the top half left four columns show the CO_2 emissions. The bottom portion of Figure 4 simply converts the top half doses and CO_2 emissions into their monetary equivalence, so that they can be directly compared.

Since the base case input parameters were selected from peer reviewed studies, Agency policy, or experienced engineering judgment, some important insights into some key issues from examination of the base case results. For example, the fossil fuel technologies GHG emissions are one to two orders of magnitude greater than the GHG emissions from either the nuclear or wind technologies. Also, the radiological impacts from the nuclear and coal technologies are approximately the same, and are about

three orders of magnitude greater than the radiological impacts from either the natural gas or wind technologies. Finally, notice that some of the decommissioning and decommissioning waste GHG emission and radiological impact values shown on Figure 4 are negative. The reason for this is some fraction of the material removed during the decommissioning process was assumed to be recycled, and since the embodied energy required to make new material is less for recycled material than for virgin material, there is a savings in the GHG emissions and radiological impacts by using the recycled materials.

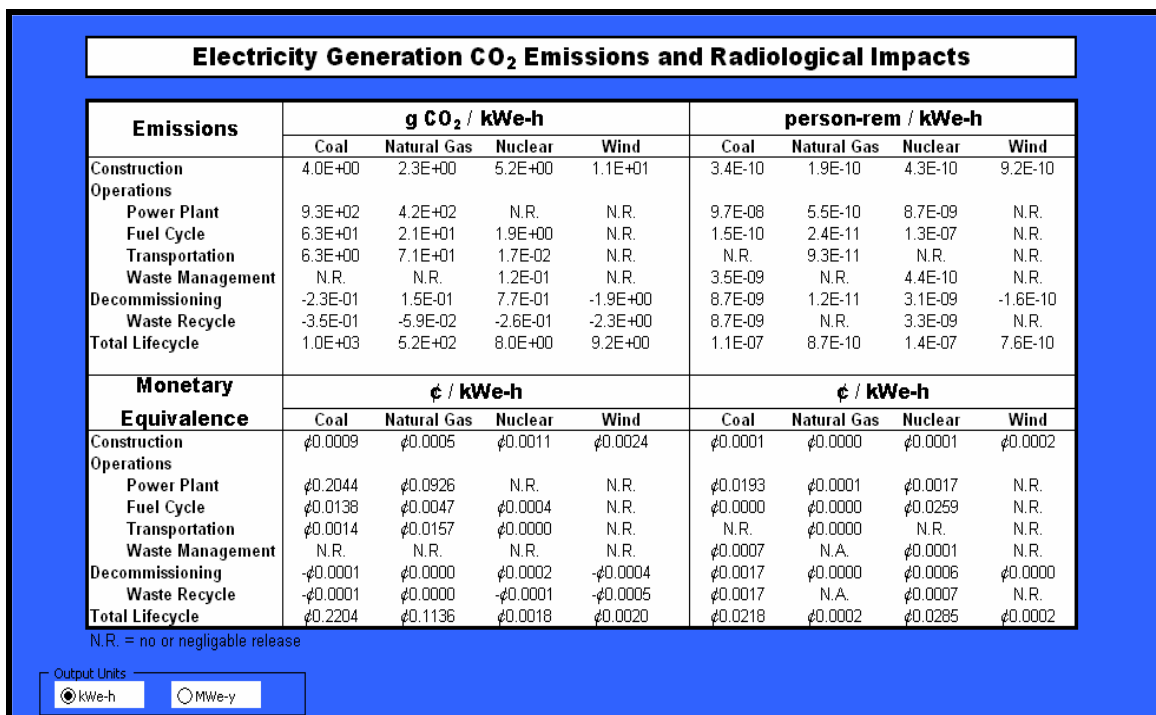


Figure 4: Base Case GHG and Radiological Results from the Energy Technology - Life Cycle Analysis Tool (ET-LCAT)

REFERENCES

U.S. Atomic Energy Commission (AEC), “Environmental Survey of Transportation of Radioactive Materials to and From Nuclear Power Plants,” WASH-1238, December 1972.

U.S. Atomic Energy Commission (AEC), “Environmental Survey of the Uranium Fuel Cycle,” WASH-1248, April 1974.

Bauer C., Dones R., Heck T., Hirschberg S., “Comparative Environmental Assessment of Current and Future Electricity Supply Technologies for Switzerland”, Proceedings 3rd International Conference on Life Cycle Management, August 27-29, 2007.

S. Cohen and Associates, Inc. (SC&A), 2009, “Use of Integrated Environmental Decision-Making to Combine Greenhouse Gas and Radiological Hazards on Energy Alternatives Using Life Cycle Analyses,” Prepared for U.S. Environmental Protection Agency, October 14.

WM2011 Conference, February 27 – March 3, 2011, Phoenix, AZ

Cohen, Bernard L., “Comparison of Radiological Risks from Coal Burning and Nuclear Power,” *Health Physics*, Volume 48, pp 342-343, March 1984.

Cooper, John R., Keith Randle, and Ranjeet S. Sokhi, *Radioactive Releases in the Environment, Impact and Assessment*, Wiley, May 23, 2003.

Corbett, J.O., “The Radiation Dose from Coal Burning: A Review of Pathways and Data,” *Radiation Protection Dosimetry*, Volume 4, No. 1983, pp 5-19, February 1993.

U.S. Department of Energy (DOE), “Applying the ALARA Process for Radiation Protection of the Public and Environmental Compliance with 10 CFR Part 834 and DOE 5400.5 ALARA Program Requirements,” DOE-STD-ALARA, Volume 1, Draft, April 1997.

U.S. Department of Transportation (DOT), “Final Environmental Impact Statement, Corporate Average Fuel Economy Standards, Passenger Cars and Light Trucks, Model Years 2011-2015,” National Highway Traffic Safety Administration (NHTSA), October 2008.

De Santis, V. and Longo J., “Coal Energy vs Nuclear Energy: A Comparison of Radiological Risks,” *Health Physics*, Volume 46, No. 1, pp 73-84, January 1984.

U.S. Environmental Protection Agency (EPA), “Compilation of Air Pollutant Emission Factors, Volume I: Stationary Point and Areas Sources,” Office of Air Quality Planning and Standards, AP-42, 5th Ed., January 1995.

U.S. Environmental Protection Agency (EPA), “Regulating Greenhouse Gas Emissions Under the Clean Air Act,” Federal Register, Volume 73, No. 147, pp 44354–44520, July 30, 2008.

U.S. Environmental Protection Agency (EPA), “Tools for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI),” <http://www.epa.gov/nrmrl/std/sab/traci/>, accessed 4/6/09.

U.S. Environmental Protection Agency (EPA), “Emissions & Generation Resource Integrated Database (eGRID),” Version 1.1, <http://www.epa.gov/resources//.html>, accessed: July 27, 2009.

Fabricant, Jacob, “Is Nuclear an Unacceptable Hazard to Health?” *Health Physics*, Volume 45, No. 3, pp 575-578, 1983.

Gabbard, Alex, “Coal Combustion: Nuclear Resource or Danger,” Coal Combustion—ORNL Review, Volume 26, No. 3&4, 1993. (Available at: <http://www.ornl.gov/info/ornlreview/rev26-34/text/colmain.html>)

U.S. Geological Survey (USGS), “National Coal Resources Data System, US Coal Quality Database,” <http://energy.er.usgs.gov/products/databases/CoalQual/intro.htm>, accessed: April 18, 2009.

Goedkoop, Mark, Suzanne Effting, and Marcel Collingnon, “The Eco-indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment – Manual for Designers,” 2nd Ed., PRé Consultants, April 17, 2000.

Gogolak, C.V., “Review of ²²²Rn in Natural Gas Produced From Unconventional Sources,” U.S. Department of Energy, Environmental Measurements Laboratory, DOE/EML-385, November 1980.

ifu Hamburg, “Umberto – The Software for Process Optimization,” <http://www.umberto.de/en/>, accessed: 4/19/2009

Konzek, G.J.; Smith, R.I.; Bierschbach, M.C.; McDuffie, P.N., “Revised Analyses of Decommissioning for the Reference Pressurized Water Reactor Power Station,” Pacific Northwest Laboratory, Prepared for U.S. Nuclear Regulatory Commission, NUREG/CR-5884, PNL-8742, November 1, 1995.

Linkov, I., A. Varghese, S. Jamil, ICF Consulting, T.P. Seager, Center for Contaminated Sediments Research, University of New Hampshire Durham, G. Kiker, T. Bridges, U.S. Army Engineer Research and Development Center, “Multi-Criteria Decision Analysis: A Framework for Structuring Remedial Decisions at Contaminated Sites,” Comparative Risk Assessment and Environmental Decision Making, 2004.

Marlay, Robert Charles, “Radioactivity Releases to the Environment by Nuclear Plants: Locally and for the Total Fuel Cycle,” MIT Energy Laboratory, 1979.

Marvin Shaffer & Associates Ltd., “Incorporation of Environmental and Social Impacts in the Evaluation of Alternative Electricity Resources,” Prepared for Manitoba Hydro, Draft, April 6, 2004.

Mauro, J.J., R. Eng, S. Marschke, W. Chang, T.A. Coleman, “Environmental Consequences of Higher Fuel Burn-up,” Envirosphere Co., Prepared for the Atomic Industrial Forum, Inc., National Environmental Studies Project, AIF/NESP-032, June 1985.

Mc Bride, J.P., et al, “Radiological Impact of Airborne Effluents of Coal and Nuclear Plants,” Science, Volume 202, No. 4372, December 1978.

National Council of Radiation Protection and Measurements (NCRP), “Public Radiation Exposure from Nuclear Power Generation in the United States,” NCRP Report No. 92, 1987.

National Council of Radiation Protection and Measurements (NCRP), “Radiation Exposure of the U.S. Population from Consumer Products and Miscellaneous Sources,” NCRP Report No. 95, 1987.

U.S. Nuclear Regulatory Commission (NRC), “Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors, Chapter IV - Environmental Impact Due to the Implementation of Plutonium Recycle, Section J, Radiological Health Assessment, Appendix A, Dose Calculation Methodology,” Office of Nuclear Material Safety and Safeguards, NUREG-0002, Volume 3, August 1976.

U.S. Nuclear Regulatory Commission (NRC), “Calculation of Releases of Radioactive Materials in Gaseous and Liquid Effluents from Boiling-Water Reactors (BWR-GALE Code),” Office of Nuclear Reactor Regulation, NUREG-0016, Revision 1, January 1979.

U.S. Nuclear Regulatory Commission (NRC), “Final Generic Environmental Impact Statement (GEIS) on Uranium Milling,” NUREG-0706, 1980

U.S. Nuclear Regulatory Commission (NRC), “Calculation of Releases of Radioactive Materials in Gaseous and Liquid Effluents from Pressurized-Water Reactors (PWR-GALE Code),” Office of Nuclear Reactor Regulation, NUREG-0017, Revision 1, April 1985.

U.S. Nuclear Regulatory Commission (NRC), “Reassessment of NRC’s Dollar Per Person-Rem Conversion Factor Policy,” Division of Regulatory Applications, Office of Nuclear Regulatory Research, NUREG-1530, December 1995.

U.S. Nuclear Regulatory Commission (NRC), “Generic Environmental Impact Statement for License Renewal of Nuclear Plants,” NUREG-1437, Vol. 1, Chapter 6: The Uranium Fuel Cycle and Solid Waste Management, May 1996.

U.S. Nuclear Regulatory Commission (NRC), 10 CFR 51.51, “Uranium Fuel Cycle Environmental Data,” Table S-3, Revised as of January 1, 2009.

U.S. Nuclear Regulatory Commission (NRC), 10 CFR 51.51, “Environmental Effects of Transportation of Fuel and Waste,” Table S-4, Revised as of January 1, 2009.

Pigford, Thomas, Michael Keaton, Bruce Mann, Peter Cukor, and Gladys Sessler, “Fuel Cycles for Electric Power Generation,” Teknekron Report No. EEED 101, January 1973 (revised March 1975).

Science Applications International Corporation (SAIC), “Life Cycle Assessment: Principles and Practice,” Prepared for National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, EPA/600/R-06/060, May 2006.

Smith, R.I.; Bierschbach, M.C.; Konzek, G.J.; McDuffie, P.N., “Revised Analyses of Decommissioning for the Reference Boiling Water Reactor Power Station,” Pacific Northwest Laboratory, Prepared for U.S. Nuclear Regulatory Commission, NUREG/CR-6174, PNL-9975, July 1, 1996.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), “Ionizing Radiation: Sources and Biological Effects,” 1982 Report to General Assembly with Annexes.

Westinghouse Electric Company LLC, “AP1000 Design Control Document,” DCP/NRC2266, Revision 17, Docket No. 52-006, September 22, 2008.

World Energy Council, “Comparison of Energy Systems Using Life Cycle Assessment,” London, United Kingdom, July 2004.