NATIONAL ENERGY TECHNOLOGY LABORATORY

Role of Alternative Energy Sources: Nuclear Technology Assessment

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Acronyms and Abbreviations

Al	Aluminum
AEO	Annual Energy Outlook
ASTM	American Society for Testing and Materials
B&W	Babcock & Wilcox
Bq	Becquerel
BRC	Blue Ribbon Commission
BWR	Boiling water reactor
CAP	Criteria air pollutant
CCS	Carbon capture and sequestration
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COE	Cost of electricity
COL	Combined license
D_2O	Deuterium oxide
DOE	Department of Energy
ECF	Energy conversion facility
EIA	Energy Information Administration
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EROI	Energy return on investment
EXPC	Existing pulverized coal
Gen II	Generation II
Gen III+	Generation III+
Gen IV	Generation IV
GHG	Greenhouse gas
GLE	Global laser enrichment
GNEP	Global Nuclear Energy Partnership
GWe	Gigawatt-electric
GWh	Gigawatt-hour
GWth	Gigawatt-thermal
GWP	Global warming potential
H_2O	Water
HCI	Hydrogen chloride
HEU	Highly enriched uranium
HF	Hydrogen fluoride
Hg	Mercury
HLW	High-level waste
HWR	Heavy water reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
IUEC	International Uranium Enrichment Centre
IPCC	Intergovernmental Panel on Climate Change
ISL	In situ leach (mining)
JNFL	Japan Nuclear Fuel Limited
kg	kilogram
kW	kilowatt
LC	Life cycle
LCA	Life cycle assessment
LCC	Life cycle cost
LCOE	Levelized cost of electricity
LLW	Low-level waste
LWR	Light water reactor
MBq	Megabecquerel
MIT	Massachusetts Institute of Technology
MMBtu	Million British thermal units
MW	Megawatt
MWh	Megawatt-hour
NETL	National Energy Technology Laboratory
MOX	Mixed oxide fuel
NEA	Nuclear Energy Agency
NETL	National Energy Technology Laboratory
N	Nitrogen
N/A	Not applicable
NEI	Nuclear Energy Institute
NETL	National Energy Technology Laboratory
NH_3/NH_4	Ammonium/Ammonia
NOx	Nitrogen oxides
N_2O	Nitrous oxide
NRC	Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
O_3	Ozone
O&M	Operating and Maintenance
OP	Open pit
OP	Open pit
P	Phosphorous
Pb	Lead
PM	Particulate matter

PO_4	Phosphate
ppm	Parts per million
PUREX	Plutonium and uranium recovery by extraction
PWR	Pressurized water reactor
PV	Present value
RFS2	Renewable Fuel Standards Final Rule
SF_6	Sulfur hexafluoride
SILEX	Separation of isotopes by laser excitation
SO_2	Sulfur dioxide
SMR	Small modular reactor
SWU	Separative work units
TPC	Total plant cost
TVA	Tennessee Valley Authority
U	Uranium
U-235	Fissile isotope of uranium with isotope mass of 235 amu
U-238	Isotope of uranium with isotope mass of 238 amu
UG	Underground
UO_2	Uranium dioxide
U_3O_8	Yellow cake
UF_6	Uranium hexafluoride
U.S.	United States
USDA	United States Department of Agriculture
VOC	Volatile organic compound
WNA	World Nuclear Association

Executive Summary

This report discusses the role of nuclear power in meeting the energy needs of the United States (U.S.). This includes an analysis of key issues related to nuclear power and, where applicable, the modeling of the environmental aspects of nuclear power.

Nuclear power plays an important role in the electricity mix of the U.S., providing 20.2 percent of electricity generation (EIA, 2010a). Nuclear power plants provide critical baseload power, and steadily increasing net generation, despite a static number of power plants. Historically, this has allowed nuclear power to maintain a relatively steady net generation of 20 percent despite increasing annual demand for power and no new nuclear power plant construction. Nuclear capacity in the U.S. consists of 104 light water reactors located on a total of 65 different sites. The average operating reactor in the U.S. in 2009 had a capacity of 926 Megawatts (MW) and operated with a 90.6 percent capacity factor (EIA, 2010b).

The U.S. resource base of nuclear power includes domestic and imported sources of uranium. The U.S. consumes 16,500 tonnes of uranium per year (IEA/NEA, 2010). With domestic resources of 207,000 tonnes of uranium, current consumption rates would deplete the domestic supply within 12 years, if imports were excluded. However, the majority of the global supply of uranium is politically stable, so the U.S. can continue to be reliant on imported uranium, originating mostly from Australia, Kazakhstan, Canada, and Russia. Based on the current world demand and known recoverable reserves, there are approximately 80 years of virgin supply at a recoverable cost of less than $130/kg U. The supply outlook for uranium is not a key driver in the stability of the nuclear supply chain. If the price of uranium increases by 100 percent, the corresponding cost increase of nuclear power will be only 10 percent.

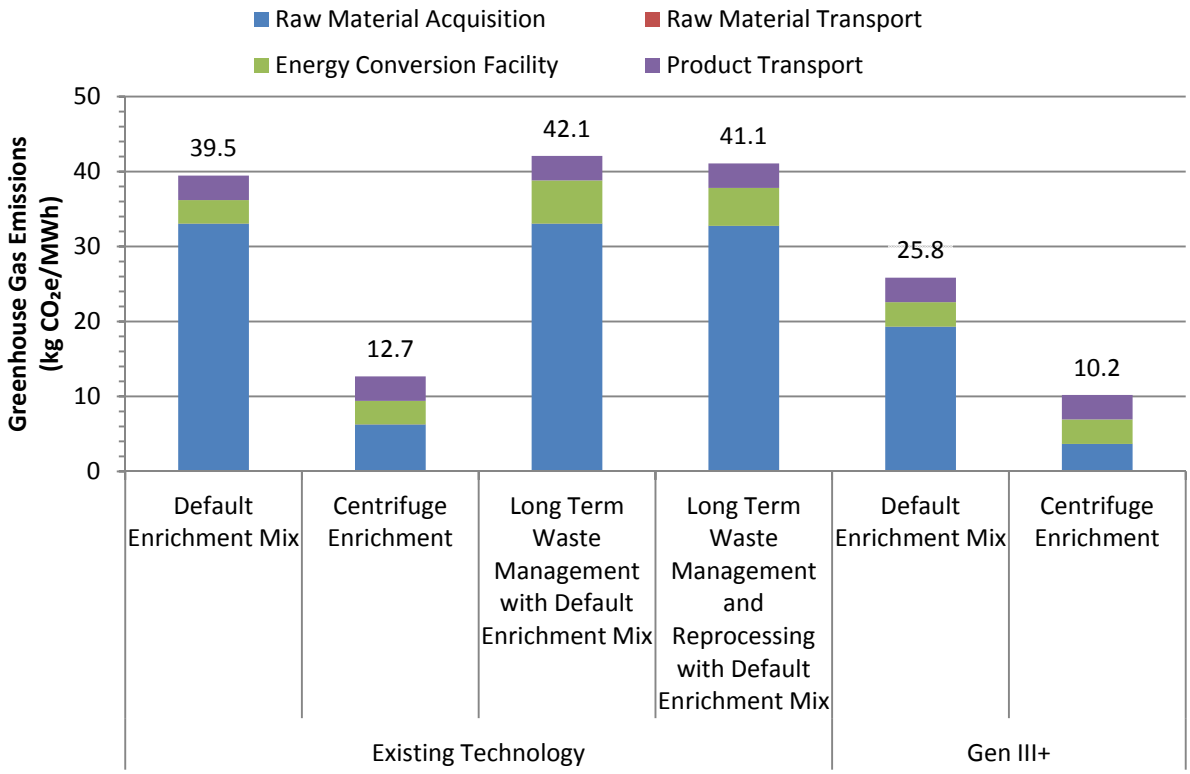
The growth of nuclear power in the U.S. depends on how many existing nuclear power plants will undergo license renewals, how many are commissioned, and how many are decommissioned. Nuclear power forecasts from the Energy Information Administration (EIA), International Atomic Energy Agency (IAEA), IHS Global Insight, and the World Nuclear Association (WNA) range from 110 to 180 GW in 2035 based on a 2010 capacity of approximately 101 GW (EIA, 2011; IAEA, 2010; WNA, 2011c).

A life cycle analysis (LCA) was conducted to assess the environmental characteristics of both existing and Generation III+ (Gen III+) nuclear power technology. The boundaries of the LCA account for the cradle-to-grave energy and material flows for nuclear power. The boundaries include five life cycle (LC) stages: raw material extraction (RMA), raw material transport (RMT), energy conversion facility (ECF), transmission and distribution (T&D), and End Use (EU). The functional unit of this analysis (which serves as the basis of comparison between systems) is one MWh of electricity delivered to the end user. The model also includes the option to include long-term waste management and reprocessing of spent fuel.

The LCA results for greenhouse gas (GHG) emissions, calculated using IPCC 2007 100-year global warming potential factors, are shown in by LC stage **Figure ES-1**. The LC GHG emissions for nuclear power from existing and Gen III+ plants for the default uranium enrichment mix (52 percent gaseous diffusion and 48 percent centrifuge) are 39.5 and 25.8 kg CO_2e/MWh delivered to the end user, respectively. These results do not include long term waste management or reprocessing. The Gen III+ life cycle has lower GHG emissions than the existing plants due to higher uranium dioxide (UO_2) burnup rates of Gen III+ reactors and higher thermal efficiency.

There are two conventional technologies for uranium enrichment: gaseous diffusion and gas centrifuge. Currently, almost all uranium enriched domestically is done so by gaseous diffusion technology with the remainder of the enriched uranium demand supplied by imports from Europe where centrifuge enrichment is prevalent. The U.S. does have a centrifuge enrichment facility owned by URENCO USA and located in Lea County, New Mexico. The facility began operating in June 2010 with current production output at only 3 percent of the 2015 planned capacity of 5.8 million separative work units/year, which is enough to supply enough enriched uranium to meet 10 percent of the total U.S. electricity demand (WNA, 2011e).

Figure ES-1: Life Cycle GHG Profile for Existing and Gen III+ Nuclear Power Including Various Enrichment and Waste Management Scenarios



The addition of long-term waste (which includes low-level waste (LLW) and high-level waste (HLW)) disposition to the existing nuclear power case increases the GHG results of nuclear power by 6.6 percent (42.1 compared to 39.5 kg CO_2e/MWh). As shown by the bars in **Figure ES-1**, the GHG results for RMA, RMT, and PT are identical. The only difference between the baseline scenario and the long-term waste management scenario is the transport and construction requirements of long-term waste management. The addition of fuel reprocessing to the nuclear fuel cycle reduces the consumption of uranium 20 to 30 percent (IAEA, 2008b). However, this reduction only reduces the burdens contributed by uranium mining and milling. Reprocessed uranium requires re-enrichment in order to increase its U-235 concentration to a level appropriate for light water reactor (LWR) operation. The total reduction in the GHG emissions of the RMA LC stage is only 1.0 percent. This percent decrease is representative of the RMA LC stage only, not the total LC of nuclear power. When the entire LC is considered, reprocessing of nuclear fuel increases the GHG results by 4.1 percent (41.1 compared to 39.5 kg CO_2e/MWh). A choice to construct a centrifuge enrichment

facility in the U.S. would be much more effective at reducing nuclear power LC GHG emissions than constructing a PUREX reprocessing facility. Nuclear waste management scenarios were not modeled for the Gen III+ facility, but the incremental increase in emissions as seen with the existing facilities would be expected.

Because the electricity use of diffusion enrichment is the largest contributor to LC GHG emissions, it is worthwhile to investigate the savings in emissions possible through use of centrifuge enrichment for U.S. enriched uranium hexafluoride (UF_6). **Figure ES-1** shows a comparison of LC emissions between the current enrichment mix (52 percent gaseous diffusion and 48 percent centrifuge) and a scenario in which all uranium is enriched using centrifuge technology. The LC emissions of the current reactor fleet could be reduced by 68 percent (12.7 compared to 39.5 kg CO_2e/MWh) through use of centrifuge enrichment in the U.S. For Gen III+ reactors, the switch to 100 percent centrifuge enrichment would yield an LC GHG reduction of 61 percent (10.2 compared to 25.8 kg CO_2e/MWh). The improvement is smaller for Gen III+ reactors due to higher UO_2 burnup rates of Gen III+ reactors and higher thermal efficiency.

These results do not account for the GHG emissions from land use change. The GHG emissions from direct and indirect land use change range from 0.094 – 0.65 kg CO_2e/MWh depending for Gen III+ and existing plants, respectively. Thus, the land use GHG emissions for nuclear power increases the baseline scenario GHG emissions by 2 percent from 39.5 to 40.2 kg CO_2e/MWh.

To validate and improve the accuracy of the cost parameter inputs specific to the nuclear life cycle cost (LCC) results, a survey was sent to a cross section of nuclear experts from academia, government laboratories, industry, and trade associations requesting input on the nuclear specific cost parameters. Based on that input, the cost profile of Gen III+ power was based on a discounted cash flow analysis that calculated an expected COE of $85.9/MWh. This result is based on a capital cost of $4,267/kW, a capacity factor of 90.6 percent, and a seven percent loss of electricity during transmission and delivery. Nuclear power is capital intensive and the breakdown of the expected COE indicates that the capital portion accounts for 81 percent. The remaining cost components compose the remaining 19 percent of the $85.9/MWh, with 11 percent coming from fixed O&M, 1 percent from variable O&M, and 7 percent from fuel costs. The COE ranges from $42.8 to $186.2/MWh across the range of financial and operations parameters.

The barriers to implementation are rooted in the uncertainties surrounding the handling of waste from nuclear power. Current U.S. nuclear policy has not resolved the long-term uncertainties for spent fuel disposition and reprocessing. In 2008, the U.S. Department of Energy (DOE) submitted the license application to the U.S. Nuclear Regulatory Commission (NRC) for authorization to construct a repository at Yucca Mountain (NRC, 2012). NRC started the years-long licensing proceeding. In March 2010, DOE filed a motion with the NRC's Atomic Safety and Licensing Board seeking permission to withdraw its 2008 application. In October 2010, the NRC began closure of its Yucca Mountain activities, and in 2011 suspended the licensing proceeding (NRC, 2011c).

In early 2010, President Obama directed the Secretary of Energy to form a Blue Ribbon Commission (BRC) on America's Nuclear Future. The BRC was to "conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle, including all alternatives for the storage, processing, and disposal of civilian and defense used nuclear fuel and nuclear waste" (Obama, 2010). The BRC final report released in January 2012 (BRC, 2012) included an estimate, prepared by EPRI, of current and projected amounts of spent nuclear fuel from commercial nuclear power plants. The EPRI estimate was 65,000 metric tons uranium (MTU) in 2010, increasing to 133,000 MTU by 2050 (BRC, 2012).

The perception of nuclear power is anchored in three nuclear events that have occurred within recent history: the 1979 Three Mile Island accident, the 1986 Chernobyl accident, and the 2011 Fukushima accident. A review of the international best practices for nuclear safety has identified some measures that the U.S. implemented following the 9/11 terrorist attacks that may have reduced or mitigated the impact of the Fukushima disaster had they been implemented in Japan (Acton & Hibbs, 2012). Public concerns about nuclear power are also rooted in fears of terrorist attacks and nuclear weapon proliferation. The levels of radiation from steady-state nuclear power are the same magnitude as radiation from natural sources and are hundreds of times lower than the exposure threshold for cancer risks (NRC, 2011b). However, the potentially high impacts of adverse nuclear events overshadow the fact that radiation levels from normal operations are very low.

The risks of implementation include failures of nuclear power systems which could lead to radiological releases or other nuclear events. While the chances of adverse nuclear events are small and newer nuclear technologies are inherently safer than older technologies, the scale of a nuclear event can have far-reaching environmental and societal risks.

The WNA has seen interest in small modular reactors (SMRs) grow substantially in the U.S. and around the world as small and large utilities anticipate the need to replace and augment existing electricity generation assets (WNA, 2011d). The U.S. DOE has acknowledged the potential for SMRs to replace aging coal facilities (DOE, 2011). According to Christopher Mowry, Vice President of Babcock and Wilcox Nuclear Energy, SMRs may utilize some of the existing site infrastructure when used to replace existing generating assets, which further reduces costs (Mowry, 2011).

Overnight capital costs for nuclear facilities range from $3,000-5,000/kW, and the installation of cooling systems and other site-specific requirements can push those costs to as high as $6,000/kW. According to the MIT study on the Future of Nuclear Power, estimated construction costs have been increasing at a rate of 15 percent per year (MIT, 2009). These high costs, driven by risk and associated financing structure, have halted several projects and resulted in temporary setbacks at proposed new nuclear installations. The other dominant factor that has stalled the nuclear renaissance has been the low cost of natural gas. According to nuclear market analysts at Standard & Poor’s (Standard & Poor's, 2010), the cost of natural gas needs to be higher than $6/MMBtu for new nuclear power generation to be economically favorable.

Nuclear power provides a stable source of baseload power in the U.S. with a GHG emissions footprint that is similar to that of most renewable power sources. In the last decade, nuclear power plants have had an average capacity factor 90 percent. Maintaining the existing share of the U.S. electricity demand with nuclear power depends on the number of existing facilities that receive operating license extensions and the number of planned and approved new reactors that are actually constructed. While the global supply of uranium is large and stable, the high initial capital investment required for the construction of new reactors, historically low natural gas prices have slowed the nuclear renaissance in the U.S. The storage of spent nuclear fuel also continues to be a major concern since progress on the Yucca Mountain nuclear repository was officially halted in 2010. The growth and perception of nuclear power is also impacted by the three nuclear events that have occurred within recent history: the 1979 Three Mile Island accident, the 1986 Chernobyl accident, and the 2011 Fukushima accident. While the chances of adverse nuclear events are small and newer nuclear technologies are inherently safer than older technologies, the scale of a nuclear event can have far-reaching environmental and societal risks.

1 Introduction

This analysis evaluates the role of nuclear power in the energy supply of the United States (U.S.). This objective is met by focusing on the resource base, growth, environmental characteristics, costs, barriers, and expert opinions surrounding nuclear power. The criteria used by the National Energy Technology Laboratory (NETL) to evaluate the roles of energy sources are summarized in **Table 1-1**.

Table 1-1: Criteria for Evaluating Roles of Energy Sources

Criteria	Description
Resource Base	Availability and accessibility of natural resources for the production of energy feedstocks
Growth	Current market direction of the energy system – this could mean emerging, mature, increasing, or declining growth scenarios
Environmental Profile	Life cycle (LC) resource consumption (including raw material and water), emissions to air and water, solid waste burdens, and land use
Cost Profile	Capital costs of new infrastructure and equipment, operating and maintenance (O&M) costs, and cost of electricity (COE)
Barriers	Technical barriers that could prevent the successful implementation of a technology
Risks of Implementation	Non-technical barriers such as financial, environmental, regulatory, and/or public perception concerns that are obstacles to implementation
Expert Opinion	Opinions of stakeholders in industry, academia, and government

Nuclear power has maintained a 20 percent share of total electricity production in the U.S. since 1988. The U.S. has 104 commercial nuclear reactors, which generated 807 million MWh of electricity in 2010 (EIA, 2011). The nuclear supply chain has a long series of material processing and waste management steps, but the central activity of nuclear power is the splitting of atoms to produce smaller atoms and energy – a process known as nuclear fission. Most nuclear power plants use uranium fuel with high concentrations of uranium (U)-235 isotope. U-235 is more fissile than other isotopes of uranium, which means it is easier to split and can sustain a chain reaction (WNA, 2011f). The energy produced by nuclear fission is used to produce steam for a Rankine power cycle similar to other thermoelectric power plants.

The front end of the nuclear fuel cycle includes all steps for the extraction and processing of nuclear fuel. Naturally-occurring uranium has a low concentration of U-235 and must go through a series of processing and separation steps to transform uranium ore to fissile uranium fuel. Enrichment is the most energy intensive step in the uranium supply chain and isolates U-235 by running a gaseous form of uranium (uranium hexafluoride) through a series of semi-permeable membranes or centrifuges. When delivered to a nuclear power plant, uranium is in the form of uranium oxide, a black ceramic material with enriched levels of U-235 (EIA, 2011).

The back end of the nuclear fuel cycle includes all steps for the storage and disposal of spent nuclear fuel. Spent fuel that is removed from nuclear reactors is highly radioactive and must be stored in water-filled pools that shield plant operators from radiation and allow residual heat to dissipate. The spent fuel is then moved to concrete or steel containers for interim storage. A permanent underground repository is necessary for final disposal of spent nuclear fuel, but such a repository has not been built in the U.S. It is possible to process spent fuel to recover unused U-235 or other fissionable elements, but the U.S. prohibits the reprocessing of nuclear fuel due to concerns with security and nuclear weapons proliferation (EIA, 2011).

2 Nuclear Power Technology Performance

The performance characteristics of nuclear power systems are described below.

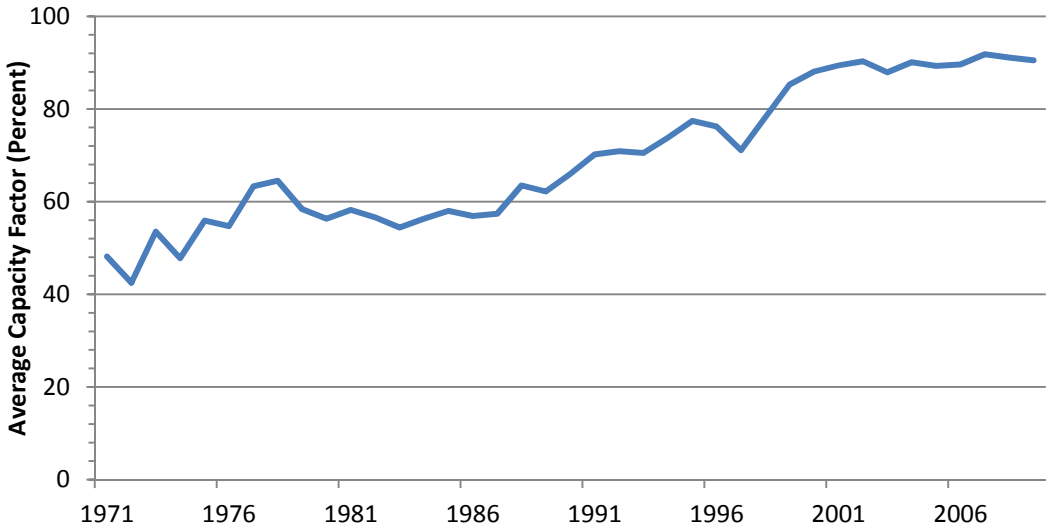
2.1 Existing and Generation III+ Reactor Performance

The nuclear power systems of NETL's existing work include existing Generation II/Generation III (Gen II/III) reactors and Generation III+ (Gen III+) advanced nuclear power reactors. For the remainder of this report, all references to existing plants refer to Gen II/III designs.

Nuclear capacity in the U.S. consists of 104 light water reactors located on a total of 65 different sites. For the remainder of this report, the terms plant and reactor will be used synonymously. These reactors use ordinary water (H_2O) as a moderator to reduce the kinetic energy of neutrons released during fission, enabling a sustained nuclear reaction. In contrast, heavy water reactors, used primarily in Canada, moderate neutrons with deuterium oxide (D_2O) and can operate using uranium that has not been enriched, or even using recycled fuel from light water reactors (LWR) (Ragheb, 2008). A water-filled steel pressure vessel holds the reactor core of an LWR, allowing the water to serve both as moderator for the reaction and as coolant for the reactor core. Sixty-six percent of operating nuclear reactors in the U.S. are pressurized water reactors (PWR), and the remaining 34 percent are boiling water reactors (BWR) (EIA, 2010b). In a BWR, steam produced in the reactor vessel is fed directly to a turbine, condenser, and feedwater pump. In a PWR, hot water from the reactor vessel is fed through a pressurized loop that passes through a heat exchanger that transfers heat to a secondary steam loop. Steam from the secondary loop is used to drive the turbine, thus isolating water that comes into contact with the reactor core from water used for the steam cycle (Nave, 2010).

The average operating reactor in the U.S. in 2009 had a capacity of 926 MW and operated with a 90.6 percent capacity factor (EIA, 2010b). Variation in plant size ranges from 482 MW to 1,314 MW, with 3.5 GWh to 10.7 GWh of electricity production per year. Significant increases in nuclear capacity factors since the 1990s are due in part to power uprating at many plants, which resulted in increased steam output from reactors (NEI, 2011). The average capacity factor of plants operating over the last 40 years is 70.7 percent. Increases of the average fleet capacity factor between 1971 and 2009 are shown in **Figure 2-1.**

Figure 2-1: Average Capacity Factor of Existing Plants (1971-2009) (EIA, 2010b)



Gen III+ plant designs build upon existing technology by incorporating passive safety systems such that no operator control or auxiliary power is necessary in the event of a malfunction. The plants have higher fuel burn-up rates and higher thermal efficiencies. Makers of Gen III+ plants also claim that the designs are favorable because of reduced capital cost, reduced construction time, easier operation, and reduced likelihood of operational problems or failure incidents. Gen III+ plants also have a longer reactor life (60 years).

No Gen III+ reactors are currently in operation in the U.S., but a small number are operating abroad. NETL's LCA of Gen III+ is representative of proposed plants that have pending license applications with the NRC.

The performance characteristics of existing and Gen III+ nuclear power plants are shown in **Table 2-1**, which includes the mass and energy flows per 1 MWh of electricity produced.

Table 2-1: Performance Characteristics of Nuclear Power Technologies

Parameter	Units	Existing Average (1969-2009)	Gen III+
Initial Construction Design Lifetimes	Years	40	60
Average Thermal Efficiency	%	31.6	34.2
Average Net Power Output of a Single Reactor	MW	976	1,475
Average Annual Capacity Factor (2009 Average)	%	70.7 (90.6)	94
Average Annual Electricity Output of a Single Reactor	MWh/year	4.93E+06	1.70E+07
Plant Inputs per Unit Electricity Produced			
Uranium Fuel (UO_2)	kg/MWh	4.33E-03	2.53E-03
Water	m^3/MWh	103.67	2.79E-06
Plant Outputs per Electricity Output			
Electricity (Operation)	MWh	1.0	1.0
Spent fuel (UO_2)	kg/MWh	4.34E-03	2.53E-03
Radionuclides (Radioactive Emissions to Air)	Bq/MWh	3.01E+06	6.02E+05
Carbon Dioxide (Inorganic Emissions to Air)	kg/MWh	0	0
Methane (Organic Emissions to Air [Group VOC])	kg/MWh	0	0
Nitrous Oxide (Inorganic Emissions to Air)	kg/MWh	0	0
Water	m^3/MWh	1.01E+02	1.37E+00
Solid Waste	kg/MWh	5.71E-05	4.26E-05
Mixed Waste (Hazardous or Radioactive)	m^3/MWh	2.70E-06	1.20E-07

The data in **Table 2-1** show the efficiency of nuclear power plants as well as the ancillary inputs and select environmental emissions directly related to nuclear power plants. The performance of nuclear power plants is not the only determinant of the environmental burdens of nuclear power. An understanding of the energy and material flows that occur upstream and downstream of nuclear power plants is necessary to evaluate the overall environmental burdens of nuclear power. Key upstream activities include the energy and emissions associated with uranium mining, milling, conversion, enrichment, and transport; the key downstream activity is electricity transmission and distribution. LCA is necessary for understanding the environmental burdens of the entire life cycle (LC) of nuclear power.

2.2 Nuclear Waste Management

The spent fuel from U.S. nuclear reactors, known as high-level waste (HLW), is currently stockpiled at power plants. Two options for managing this waste are final disposition in a specially-designed repository or reprocessing of spent fuel. Other waste materials from nuclear power plants include low-level radioactive wastes (LLW), such as retired equipment or maintenance wastes. The following discussion provides details on the long-term disposition methods for both categories of nuclear waste, as well as the technologies required for reprocessing of spent fuel.

2.2.1 HLW Disposition

The U.S. Department of Energy (DOE) was in the process of licensing a HLW Geologic Repository at Yucca Mountain, but this action was suspended in early 2010 by the Obama administration (Garvey, 2011). Since then, the U.S. has continued a "wait and see" approach, opting for interim storage of spent fuel on site at nuclear power plants. Interim storage was thus modeled through containment of spent fuel in storage casks with no transport to external sites.

Ultimately, spent fuel must be transferred to permanent disposition sites and contained indefinitely. New data were collected to estimate the environmental significance of spent fuel disposition. Key material requirements for spent fuel disposition include concrete, steel, and other metals used for containment units. Final disposition also requires energy for construction and maintenance and transport of spent fuel casks to the final disposition site. The data used for modeling long-term HLW are discussed in detail in **Appendix B**.

2.2.2 LLW Disposition

LLW consists of items that have become radioactive through exposure to radiation. A list of low level waste items provided by the NRC (2002) includes: "contaminated protective shoe covers and clothing, wiping rags, mops, filters, reactor water treatment residues, equipment and tools, luminous dials, medical tubes, swabs, injection needles, syringes, laboratory animal carcasses, and tissues." Water treatment residues, discarded parts from nuclear reactors, and small gauges containing radioactive material are the most intensely radioactive of low level waste materials (NRC, 2002). Because low level waste from decommissioning is an appreciable quantity in comparison to low level waste from plant maintenance, both sources of low level waste are included in the analysis.

Procedures for handling low level waste include at least three options:

1. Storage until radioactive decay reduces hazard to background radiation levels, then disposal with non-radioactive solid waste
2. Storage until decommissioning of the facility
3. Transport of low-level radioactive waste to a long-term disposition site

This analysis uses the third option (transport to a disposition site) to estimate the LC burdens of long-term low level waste disposition. The data used for modeling long-term LLW are discussed in detail in **Appendix B**.

2.2.3 Spent Fuel Reprocessing

Early development of commercial nuclear power systems in the U.S. (1940s through 1970s) envisioned a closed fuel cycle in which spent fuel would be reprocessed and recycled. Closed fuel cycles reuse the uranium and plutonium portions of spent fuel (96 percent and 1 percent of spent fuel by mass, respectively) by first partitioning these elements from fission products (3 percent by mass) (DOE, 2003). Because some isotopes in the separated plutonium can be suitable for use in nuclear weapons, debate over the danger of proliferation potential from infiltrated reprocessing facilities or transport operations led to the suspension of all commercial reprocessing by the Carter administration in 1977. President Reagan reversed the ban in 1981, but engagement in reprocessing development or infrastructure construction was not supported by future administrations. President George W. Bush's 2001 National Energy Policy included a recommendation that the U.S. work with international partners to "develop reprocessing and fuel treatment technologies that are cleaner, more efficient, less waste intensive, and more proliferation-resistant" (Andrews, 2008). This political shift led to the initiation of the Global Nuclear Energy Partnership (GNEP), collaboration between the U.S. and 25 nations involved in the nuclear fuel cycle. A Draft Programmatic environmental impact statement (EIS) of the GNEP serves as a primary data source for the current evaluation of nuclear spent fuel reprocessing (DOE, 2008). The EIS considers several closed fuel cycle options, including recycling of fuel for use in heavy water reactors, light water reactors, and fast reactors.

It is noted that for any of the options considered in the EIS to be implemented, the following obstacles would have to be overcome (DOE, 2008):

- Demonstration of adequate return on capital investment (competitive with alternative power production facilities) to utilities, regulatory bodies, and financial markets
- Licensing of any new commercial facilities enabled by changes to the regulatory framework to allow for first-of-a-kind facilities
- Regulatory public health, safety, and environmental protections to address potential new waste categories
- Potential government involvement or encouragement (financial and other incentives), for research and development and/or demonstration of technologies

The spent fuel cycle reprocessing approach in the current assessment is based on the plutonium and uranium recovery by extraction (PUREX) separation process and recycling of plutonium as MOX. The first step of the PUREX process is the grinding of spent fuel rods into small pieces, followed by acid extraction and separation of uranium. Recovered uranium is then returned to the front end of the nuclear fuel cycle, where it must undergo conversion to UF_6, re-enrichment, and subsequent fuel production steps in order to make it suitable for use by an existing LWR.

A detailed discussion of the data used to characterize spent fuel reprocessing is provided in **Appendix B**.

3 Nuclear Power Resource, Capacity, and Growth

The future of nuclear power production depends on the resource base for nuclear fuel as well as the sustainability of installed nuclear power plants. Projections of the uranium resource base and nuclear power plant capacity are discussed below.

3.1 Uranium Resource Base

According to the World Nuclear Association (WNA), known world resources of uranium extractable by conventional (mining) methods are approximately 5.4 million metric tonnes. Current annual use is approximately 68,000 metric tonnes, ensuring about 80 years of supply for current world infrastructure (WNA, 2010b). Unconventional sources of uranium, primarily extraction from seawater, are not economically feasible at this time since a metric tonne of seawater contains only three milligrams of uranium (Lenzen, 2008).

Uranium resources in the U.S. total only about 207,000 metric tonnes as shown in **Table 3-1**. Currently the country consumes about 16,500 metric tonnes per year (IEA/NEA, 2010); thus, if the U. S. were to use domestic supply alone for all current plants, the supply would last for only the next 12 years. Consequently, without use of unconventional sources, the U.S. will continue to be reliant upon foreign countries for its uranium supply. The proportion of known resources by nation is provided in **Table 3-1**, showing a dependence on the largest resources in Australia, Kazakhstan, Canada, and Russia.

Table 3-1: Known Recoverable Resources of Uranium (WNA, 2010b)

Nation	Metric Tonnes U	Percent of World Total	DOE Sensitive Country (DOE, 2011a)
Australia	1,673,000	31%	No
Kazakhstan	651,000	12%	Yes
Canada	485,000	9%	No
Russia	480,000	9%	Yes
South Africa	295,000	5%	No
Namibia	284,000	5%	No
Brazil	279,000	5%	No
Niger	272,000	5%	No
USA	207,000	4%	No
China	171,000	3%	Yes
Jordan	112,000	2%	No
Uzbekistan	111,000	2%	Yes
Ukraine	105,000	2%	Yes
India	80,000	1.5%	Yes
Mongolia	49,000	1%	No
Other	150,000	3%	N/A
World Total	**5,404,000**		

As shown by the distribution of countries in **Table 3-1**, the majority of the global supply of uranium does not pose significant political barriers, so the long-term U.S. uranium supply does not need to be restricted to domestic sources only. Approximately 70 percent of the recoverable reserves are in countries that are not considered “sensitive” by the U.S. DOE (2011a). The world’s reactor requirement is about 66,000 tonnes uranium (t U) annually for a production capacity of 370 GWe

(IAEA, 2010). Based on the current world demand and known recoverable reserves, there are approximately 80 years of virgin supply at a recoverable cost of less than $130/kg U. If demand were to increase to the level of the International Atomic Energy Agency (IAEA) 2030 forecasted high of 807 GWe of nuclear generating capacity, there would be 40 years of virgin supply at a recoverable cost of less than $130/kg U based on known recoverable reserves.

The nuclear industry has conducted studies that forecast identified conventional uranium resources. Recent studies have shown that the identified supply of uranium has been increasing. A study in 2008 estimated this supply to be about 5.5 million tonnes uranium (Mt U) and that the recoverable cost of this supply was less than $130/kg U. This was an increase of 17 percent (800,000) tonnes uranium (t U) over 2005 estimates, due mainly to increases reported by Australia, the Russian Federation, South Africa and Ukraine (IAEA, 2008a). Although uranium prices have shown volatility in past years, (spot market uranium prices have reached almost $360/kg), prices should stabilize as supplies increase in the long term, and prices in the $130-200/kg U range would not be a significant detrimental factor regarding the nuclear generation option.

The nuclear industry has also made projections of the extent of undiscovered conventional resources. A 2008 study estimated this category to be about 7.3 Mt U at a recoverable cost of less than $130/kg U. This includes both resources that are expected to occur either in or near known deposits, and more speculative resources that are thought to exist in geologically favorable, yet unexplored areas. If these undiscovered resources are added to the known recoverable reserves, there would be nearly 90 years of virgin supply at a recoverable cost of less than $130/kg U based on the IAEA 2030 forecasted high capacity of 807 GWe.

Driven by increases in the uranium spot price, uranium exploration and development increased significantly in the latter part of the last decade. This increase has occurred in countries that have explored and developed uranium deposits in the past and in many countries new to uranium exploration. Australia and Canada alone accounted for 44 percent of world production in 2006. Together with six other countries (Kazakhstan, Namibia, Niger, the Russian Federation, the U.S. and Uzbekistan) they accounted for 92 percent of production.

New uranium production in 2006 covered only about 60 percent of the world's reactor requirement. The remainder was covered by the following five secondary sources:

- Stockpiles of natural uranium
- Stockpiles of enriched uranium
- Reprocessed uranium from spent fuel
- Mixed oxide (MOX) fuel from reprocessed spent fuel
- Re-enrichment of depleted uranium tails

The supply of uranium is also affected by the total capacity of uranium conversion operations. Supply capacity typically expands as needed to meet expected growth. Recent developments indicate the industry's capability to increase fuel conversion capacity as needed:

- The U.S. NRC renewed the license of the Metropolis, Illinois UF_6 conversion plant for an additional ten years to May 2017, and the plant's capacity was increased by 20 percent.
- AREVA announced the launch of the Comurhex II project, a new uranium conversion facility in southern France with first industrial production planned for 2012 (Areva, 2012).

There has been some overcapacity in world fuel enrichment capacity. In response to this overcapacity, older diffusion plants will close and be replaced by more efficient centrifuge plants. In 2007, the U.S. NRC issued a construction license for USEC's new American Centrifuge Plant. Japan Nuclear Fuel Limited (JNFL) is expanding enrichment capacity at their Rokkasho facility. GE–Hitachi Nuclear Energy is working to commercialize the next generation laser enrichment technology: separation of isotopes by laser excitation (SILEX), now known as Global Laser Enrichment (GLE) technology. Kazakhstan and the Russian Federation established the International Uranium Enrichment Centre (IUEC) in East Siberia to create "a system of international centers providing nuclear fuel cycle services, including enrichment, on a non-discriminatory basis and under the control of the International Atomic Energy Agency (IAEA)" (IAEA, 2008a).

The supply of uranium fuel should match market demand well into the future given there is adequate room for price increases to incentivize the market as needed. An idea of the sensitivity of nuclear power costs to uranium supply is shown in a recent report by the World Nuclear Association (WNA). A doubling of the uranium price increases the cost of UO_2 fuel from 0.50 to 0.62 cents/kWh. In turn, this cost increase in UO_2 fuel would increase the cost of electricity generation of the U.S. nuclear power plants from 1.3 cents/kWh to 1.42 cents/kWh. Thus, a 100 percent increase in the price of uranium results in a 10 percent increase in the cost of nuclear power (WNA, 2011b). These figures are consistent with the life cycle cost (LCC) results from the 2010 NETL Nuclear Power LCA. In that study, the levelized cost of electricity (LCOE) from existing nuclear power plants increased from 8.99 to 9.86 cents/kWh, approximately 10 percent, over the range of fuel costs.

3.2 Baseload Capacity Outlook

Nuclear power plays an important role in the electricity mix of the U.S., providing 20.2 percent of electricity generation (**Figure 3-1**). Nuclear power plants provide critical baseload power and steadily increasing net generation, despite a static number of power plants. The existing fleet of U.S. nuclear power plants includes 104 plants that were permitted for construction between 1964 and 1978 and were initially licensed to operate for 40 years. Most of these plants have been granted 20-year license extensions and have undergone refurbishments and/or power uprating. This has allowed nuclear power to maintain a relatively steady 20 percent of net generation despite increasing annual demand for power and no new power plant construction (**Figure 3-2**). However, questions surrounding the permitting of new plants, costs of advanced reactor construction, and willingness of investors to absorb uncertain financial burdens indicate that the U.S. is not likely to maintain the historical proportion of nuclear power for its baseload electricity generation.

Figure 3-1: Share of Nuclear Power in the 2009 U.S. Generation Mix (EIA, 2010a)

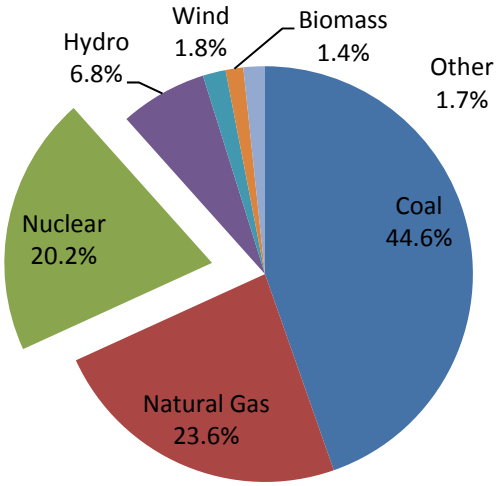
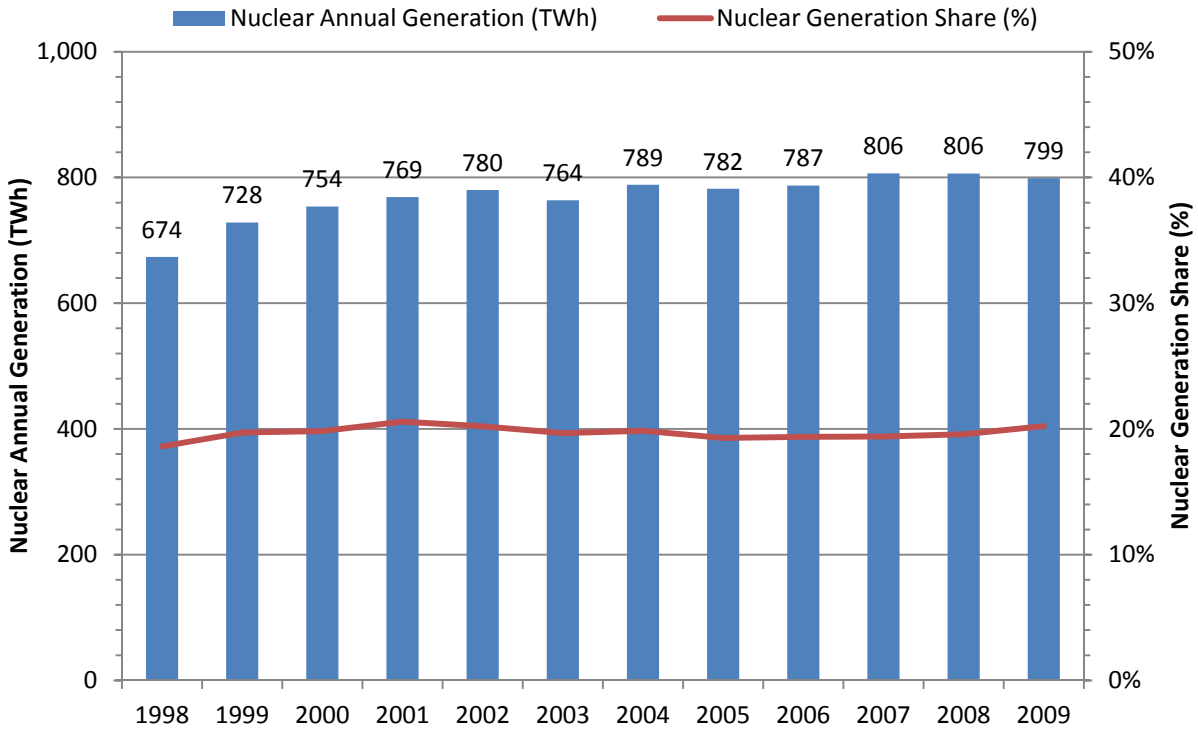


Figure 3-2: Historic Nuclear Annual Generation with Share of U.S. Generation Mix (EIA, 2010a)



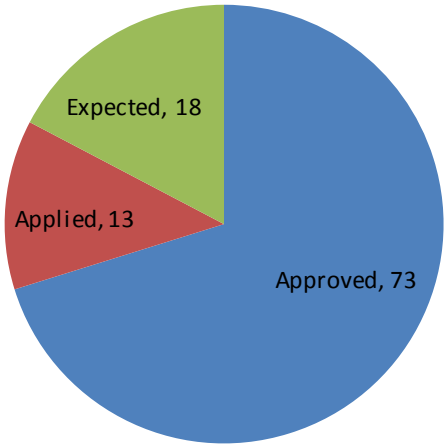
It is also important to understand the regulatory environment that surrounds nuclear power. Increasingly stringent safety and environmental regulations stretch construction times (**Table 3-2**) creating increased financial risk. As a result, it may be financially safer to extend the operating licenses of existing nuclear power plants, rather than build newer advanced units.

Table 3-2: Time to Operation for Nuclear Plants in the U.S. (EIA, 2009)

Operation Begins Prior To:	Average Construction Time (Years)	Number of Plants
2000	18.5	5
1990	12.5	29
1985	10.7	17
1980	7.5	21
1975	5.6	32

There are 104 nuclear reactors licensed by the NRC in the U.S. located on a total of 65 different sites. These reactors were granted original licenses of 40 years, with renewal application review beginning in 1998. Seventy-three of 104 reactors (70 percent) in the U.S. have received 20 year operating renewals from the NRC (**Figure 3-3**). Thirteen of 104 (an additional 13 percent) have submitted renewal applications. Operators have submitted intentions to submit applications for 17 reactors. This is a total of 103 out of 104 reactors, or 99 percent. The NRC and Nuclear Energy Institute (NEI) both expect that eventually, 100 percent of reactors will apply for renewal. Nuclear reactors are, on average, about 27-28 years old when renewal applications are submitted.

Figure 3-3: U.S. Nuclear Reactor Operating License Renewals (NEI, 2012)



The future capacity of nuclear power and its share of the electricity generation mix in the U.S. are affected by many variables including the extension of current operating licenses and the construction of new reactors. Several organizations, including the Energy Information Administration (EIA), IAEA, IHS, and WNA, have published forecasts of nuclear power capacity in the U.S. out to the year 2035. All of the forecasts indicate an increase in nuclear capacity, but some scenarios project a decline in the share of the U.S. electricity generation mix. The EIA Annual Energy Outlook (AEO) 2011 includes three projections (a reference case, low cost case, and high cost case) for nuclear generating capacity. The capacity projections for the high cost scenario were the same as the reference case with both forecasting a nuclear capacity of 110.5 GW in 2035. The low cost scenario

yields a forecast of 129 GW of nuclear capacity in 2035. The IHS projection was included as a comparison in the EIA AEO 2011. IHS provided nuclear generation capacity projections for 2015, 2025, and 2035. For illustration purposes, those three points were connected by straight lines in the figures to aid in comparison to the other forecasts. IHS forecasts a nuclear capacity of 147 GW in 2035.

Figure 3-4 graphs each of the capacity projection scenarios together and **Figure 3-5** shows the portion of U.S. power that needs supported by nuclear electricity generation for each of the projection scenarios. The WNA projection forecasts nuclear growth through 2030 (IAEA, 2010; WNA, 2011c). The WNA provided a range of projected nuclear generating capacity in the U.S. in 2030 between 120-180 GWe. This projection is shown as a band over the range in **Figure 3-4** and **Figure 3-5** because WNA does not provide annual projections similar to those in AEO 2011.

Figure 3-4: U.S. Baseload Nuclear Power Capacity Projections

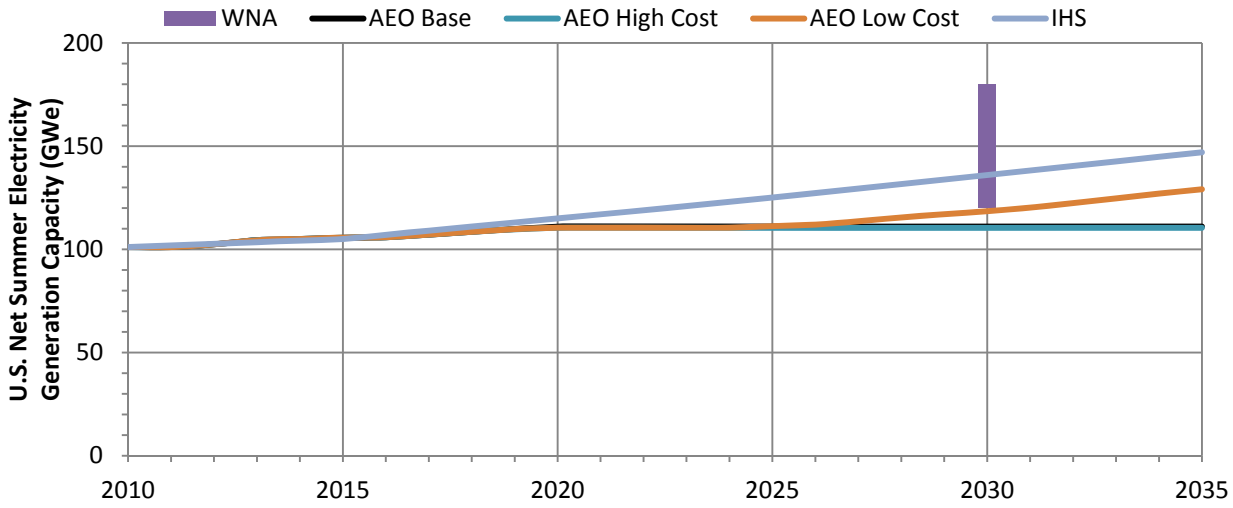
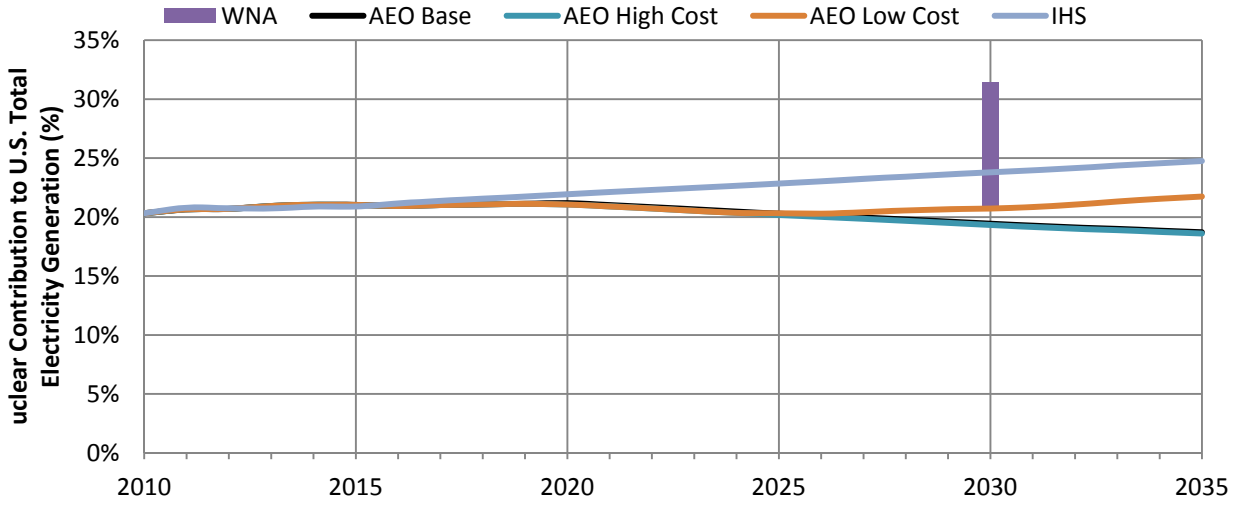


Figure 3-5: Portion of U.S. Power Supported by Nuclear Capacity



IAEA also projected the growth of nuclear power through 2030. However, the forecast was broken down by continent, not country, so no direct comparison could be made to the projections made by other organizations. The IAEA projects the nuclear generating capacity in North America to be between 127-168 GWe in 2030. According to the WNA, the current generating capacity in Canada is 13 GWe and 1 GWe in Mexico. Based on the assumption of modest increases of nuclear generating capacity in those countries, it is likely that the U.S. portion of the IAEA 2030 projection is consistent with the other forecasts by EIA, WNA, and IHS. It is important to note that all of the projections referenced in this analysis were made prior to the events at the Fukushima nuclear plant.

4 Environmental Analysis of Nuclear Power

The operation of a nuclear power plant does not result in significant direct emissions of greenhouse gases (GHG) or other air emissions; however, indirect environmental burdens are associated with the construction and operation of a power plant as well as with the acquisition, processing, and enrichment of uranium. This LCA accounts for all significant processes associated with the LC of nuclear power and inventoried the environmental metrics for GHG emissions, criteria and other air pollutants of concern, water use, water quality, solid waste, energy return on investment, radionuclides, and land use. The boundaries of NETL's LCA of nuclear power begin with the extraction of uranium ore and end with electricity delivered to the consumer. The study examines both existing and Gen III+ nuclear reactors.

4.1 LCA Scope and Boundaries

The goal of this analysis is to determine the cradle-to-grave LC burdens of nuclear power in the U.S. The boundaries of the nuclear power system were carefully selected in order to establish a fair basis of comparison among the scenarios of this analysis and the scenarios of other energy LCAs conducted by NETL. The scope and boundaries for accomplishing this goal are described below.

The environmental flows include GHG emissions; criteria air pollutants (CAP), mercury (Hg), ammonia (NH_3), and heavy metal emissions to air; water quality; water withdrawal and consumption; radionuclides to air, water, and soil; solid waste; energy return on investment (EROI); and land use (acres transformed). The GHG inventories were further analyzed using 2007 100-year global warming potential (GWP) values from the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007).

The cost metrics of this analysis included the constant dollar levelized cost of delivered electricity (LCOE) and the total plant cost (TPC) over the study period.

The LC of the nuclear electricity production pathways begins with the extraction of uranium ore and ends with electricity delivered to the consumer. The system boundaries include:

- Upstream and downstream operations processes associated with a cradle-to-grave LC including uranium fuel processing, power plant operation, and produced electricity transmission and distribution; operations processes include, where significant, the energy, materials and ancillary substances used in operation activities, and subsequent emissions
- Process facility construction energy, materials, installation emissions, and land use change
- Process facility decommissioning energy, end-of-life disposal material management (landfilling, recycling, temporary storage of spent fuel, etc.), and emissions associated with removing the processing facility and returning the land to its original state
- National and international transportation of fuel flows within the uranium fuel cycle
- Construction and operation of switchyard and internal transmission & distribution lines (line between nuclear plant and existing transmission)
- Refurbishment and uprating of existing plants

There are some activities that are associated with nuclear power that are either outside the scope of this analysis or are determined to be insignificant in comparison to other activities. Examples of activities that are *not* included in the boundaries of this analysis are:

- Transportation of raw materials to component manufacturing companies and transportation of components from sub-suppliers to primary manufacturing companies

- Manufacturing of components for power plant and uranium fuel cycle processing facilities
- Maintenance, repair, and replacement of uranium fuel cycle process components during facility operational lifetime
- Construction of existing infrastructure for electricity transmission and distribution
- Human factors and indirect effects of facility construction
- Permanent storage of spent fuel and depleted UF_6

The boundaries of the LCA account for the cradle-to-grave energy and material flows for nuclear power. The boundaries include five LC stages:

LC Stage #1: Raw Material Acquisition (RMA) accounts for the raw material acquisition and processing requirements for uranium fuel. The first step in this stage is the extraction of uranium ore from mines. Intermediate steps include the milling of ore to isolate yellow cake (U_3O_8), conversion of yellow cake to uranium hexafluoride (UF_6), and enrichment of UF_6 so that it has a higher concentration of U-235, which is the fissile isotope of uranium that is naturally occurring. (Transport between each of these steps is also included.) The final step of this stage is the fabrication of uranium dioxide (UO_2) fuel assemblies. This stage ends when the fuel assemblies are loaded onto trucks for transportation to the nuclear power plant.

LC Stage #2: Raw Material Transport (RMT) accounts for the transportation requirements of UO_2 fuel assemblies from the fuel fabrication facility to the energy conversion facility. The boundaries of LC Stage #2 begin with fuel assemblies ready for transport by truck and end with unloading of the assemblies at the energy conversion facility.

LC Stage #3: Energy Conversion Facility (ECF) includes all construction, operation, and decommissioning activities at a nuclear power plant. This analysis models existing and Gen III+ reactor technologies. The model also includes the option to include long-term waste management and reprocessing of spent fuel. The output of this stage is electricity that is ready for transmission.

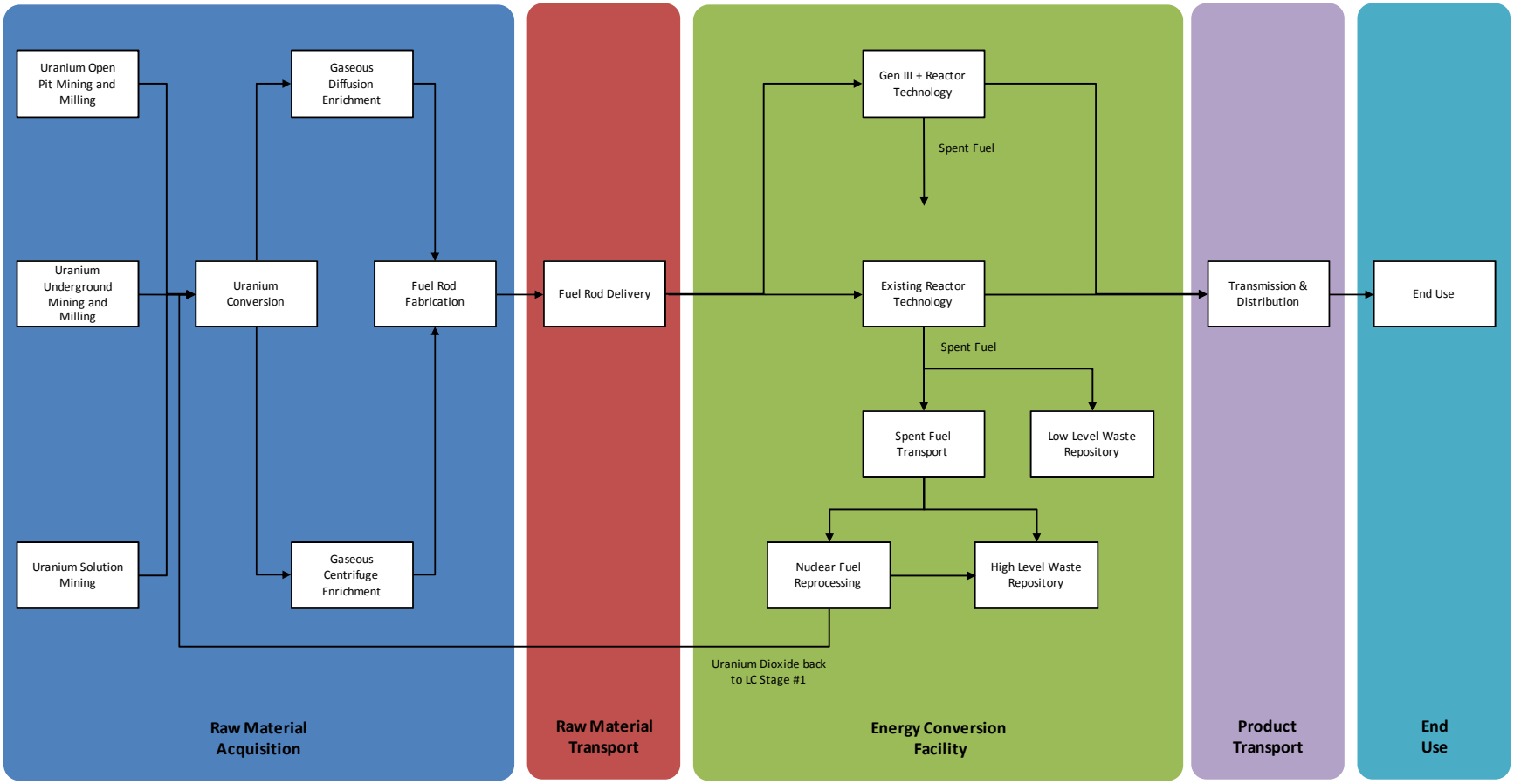
LC Stage #4: Product Transport (PT) accounts for the transmission of electricity from the point of generation to the final consumer. There is a seven percent loss associated with transmission and distribution of electricity (representative of the U.S. average electricity grid). The only emission associated with this stage is the sulfur hexafluoride (SF_6) that is released by transmission and distribution electrical equipment.

LC Stage #5: End Use represents the use of electricity by the consumer. The unit process of this stage represents a generic energy consumption application with no losses or environmental burdens.

The use of a consistent functional unit is another convention that enforces comparability between LCAs. The functional unit of this analysis and other NETL power LCAs is the delivery of 1 MWh of electricity to the consumer.

An LCA model is an interconnected network of unit processes. The throughput of one unit process is dependent on the throughputs of upstream and downstream unit processes. These processes were assembled using the GaBi 4.0 software tool. **Figure 4-1** shows NETL's approach to modeling nuclear power.

Figure 4-1: LCA Modeling Framework for Nuclear Power



4.2 Timeframe

The timeframe of the existing reactor LCA includes technology and changes that have occurred between 1969 and 2009, and predicts that existing power plants will continue to operate through 2029. Uranium fuel cycle facilities are expected to be replaced or refurbished in accordance with plant lifetimes supported by literature.

The timeframe of the Gen III+ LCA addresses the changes that would occur now and in the near future. The technology modeled sets a temporal boundary of the analysis from 2012 through 2072. This timeline covers proposed current technology and addresses technology changes that are likely to occur in the next 60 years.

4.3 Geographical Coverage

The average existing and proposed (Gen III+) industry average nuclear energy conversion facility in the U.S. is modeled. This analysis does not focus on a specific location for the nuclear plant in the U.S.

Uranium fuel cycle process facility locations are modeled according to owner and operator fuel purchase records provided by the EIA Uranium Marketing Report (EIA, 2010b). Location choices for international mines and uranium processing facilities are based upon the largest producing plants in appropriate nations. **Table 4-1** shows the locations of facilities included in the model.

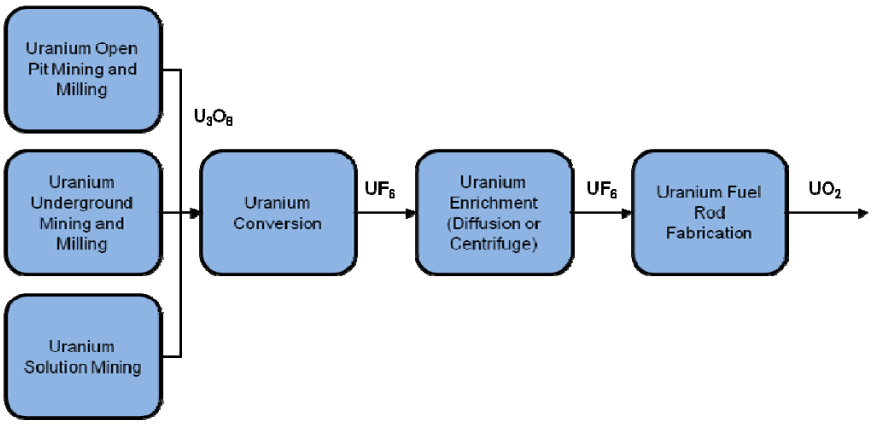
Table 4-1: Geographical Coverage of Modeled Life Cycle

LC Stage	Facility	Location
LC Stage #1	Underground Uranium Mine and Mill	Olympic Dam Mine, Australia; Rabbit Lake, Canada; Priargunsky Mines, Russia
	Open-pit Uranium Mine and Mill	Northern Saskatchewan, Canada; Ranger Mine, Australia; Namibia; South Africa
	In-situ Uranium Mine and Mill	United States; Kazakhstan; Uzbekistan
	Conversion Facility	Port Hope, Ontario; Metropolis, IL; Pierrelatte, France; Springfields, Lancashire, UK
	U.S. Enrichment Facility	Paducah, KY
	European Enrichment Facility	Tricastin, France; Almelo, Netherlands; Capenhurst, UK
	Fuel Fabrication Facility	Columbia, SC; Wilmington, NC; Richland, WA; Lynchburg, VA; Erwin, TN
LC Stage #2	Fuel Assembly Transport	N/A
LC Stage #3	Generation III+ ECF	United States Industry Average
		United States Average
LC Stage #4	Transmission and Distribution	United States
LC Stage #5	End Use	N/A

4.4 Life Cycle Stage #1: Nuclear Fuel Acquisition

The first LC stage of this analysis accounts for the acquisition of uranium and the transformation of uranium into fuel. The boundaries of this LC stage start with the extraction of uranium ore from the earth, include chemical and physical processes for uranium processing and enrichment, and end with the fabrication of uranium fuel rod assemblies. The key processes for the extraction and processing of uranium fuel are represented in **Figure 4-2**.

Figure 4-2: Nuclear Fuel Acquisition



The boundary begins with the construction of three types of uranium mines: underground, open pit, and in situ leaching. Construction materials are included within the boundary for all well known components of uranium mines, conversion facilities, enrichment facilities, and fuel fabrication facilities. Installation and operation material and energy requirements are included for all facilities, as well as transport intermediate to processing facilities. The boundary of this LC stage concludes with loading of finished fuel assemblies onto trucks for distribution to nuclear power plants.

4.4.1 Life Cycle Stage #1 Intermediate Fuel Flows and Transport

Uranium fuel is both extracted within the U.S. and imported from foreign countries to supply U.S. nuclear power plants. The origins of fuel purchased in 2009 by owners and operators of U.S. nuclear reactors are provided in **Table 4-2** (EIA, 2010b). A separate extraction profile was developed for uranium mined in each of the listed countries.

The uranium extraction model for each country in **Table 4-2** is distinguished by the uranium extraction method(s) in use and the transport requirements for produced yellowcake. An extraction model was built for a single underground mine, an in situ leach mine, and an open pit uranium mine. For each country, production data was then used to determine the mass proportion of uranium mined by each method. Production data for individual mines was taken from the industry project summaries on Mining-Technology.com (Mining-Technology, 2010) and from world production data reported by the World Nuclear Association (WNA, 2009). The calculated proportions of total country uranium exports ultimately purchased by U.S. nuclear power plants owners and operators are shown in **Table 4-2.**

The model of LC Stage #1 involves transport of fuel products between each of the fuel production processes in **Figure 4-2**. **Table 4-2** outlines the modeled supply chain of facility locations and transport distances through yellowcake export to the U.S. or Europe for conversion and enrichment. **Table 4-3** provides the modeled supply chain for both European and U.S. enrichment.

Table 4-2: Uranium Yellowcake Supply Chain (EIA, 2010b; Google, 2010; Mining-Technology, 2010; Portworld, 2010; WNA, 2011e)

Region of Uranium Origin	Australia			Canada			Former Soviet Union			United States		Africa	
Mining and Milling Site	Olympic Dam	Beverley	Ranger	McArthur River	McClean Lake	Rabbit Lake	Russia Priar-gunsky Mines	Kazak.	Uzbek.	WY	South TX	Nambia	South Africa
Mining Type (UG, ISL, OP)	UG	ISL	OP	OP	OP	UG	UG	ISL	ISL	ISL		OP	OP
Modeled Portion of Uranium Exports Originating from Mine	0.37	0.07	0.56	0.72	0.14	0.14	0.73	0.16	0.10	1		1	
Truck Transport Distance to Port (km)	560	600	250	2,250 (U.S. Enrichment Chain Only)			N/A			2,032	380	N/A	
Weighted Avg Truck Transport Distance to Port (km)	390			N/A			N/A			1,200		N/A	
Train Transport Distance Port (km)	N/A	N/A	N/A	2,900	3,970	3,550	2,253	4,023	2,500	N/A		N/A	
Weighted Avg Train Transport Distance to Port (km)	N/A	N/A	N/A	3,140 (European Enrichment Chain Only)			2,570			1,206		100	
Export Port Location	Adelaide		Darwin	New York			Vanino	N/A	N/A	Houston, TX		Cape Town, South Africa	
Weighted Avg Ocean Freighter Transport Distance to Houston, TX (km)	19,000			N/A			17,100	N/A	N/A	N/A		13,900	
Average Ocean Freighter Transport Distance to Europe (km)	18,900			5,770			4,960	N/A	N/A	8,855		11,000	
Yellowcake imports for U.S. Enriched UO_2 (EIA, 2010b)	0.11			0.14			0.50			0.20		0.05	
Yellowcake imports for Europe Enriched UO_2 (EIA, 2010b)	0.28			0.33			0.23			0.07		0.09	

Table 4-3: Enrichment Supply Chains: U.S. and European Enrichment

Enrichment Chain Process/ Location	U.S. Enrichment Supply Chain		European Enrichment Supply Chain
Arriving Port	Houston, TX (assumed)	Port Hope, Ontario	Le Havre, FR (Assumed)
Truck Transport Distance from Port to Conversion Facility (km)	1,230	0	620
Conversion Facility Locations	Metropolis, IL	Port Hope, Ontario	Pierrelatte, FR; Springfields, Lancashire, UK
Average Truck Transport Distance (km)	23	1,460	420
Enrichment Facility Locations (Gaseous Diffusion)	Paducah, KY (Gaseous Diffusion)		Tricastin, FR; Almelo, Netherlands; Capenhurst, UK (Centrifuge)
Truck Transport Distance to Fuel Fabrication (km)	1,390		2,130
Fuel Fabrication Locations	Columbia, SC; Wilmington, NC; Richland, WA; Lynchburg, VA; Erwin, TN		Romans-sur-Isère, FR; Lancashire, UK
Ship Transport Distance to Houston, TX (km)	N/A		8,850

Transport of milled yellowcake from countries of origin to conversion facility sites was conducted by one or more of water carrier, train, and truck, as outlined in **Table 4-3**. Water carrier transport distances were estimated through the PortWorld Ship Voyage Distance Calculator (Portworld, 2010). Truck and train transport distances were calculated using Google Earth (Google, 2010). The details of operation unit processes for water carrier, truck, and train transport are available in **Appendix B**.

4.4.2 Mining and Milling

Uranium ore can be extracted using underground, open pit, or in situ leach mining techniques. The key activities for these three uranium mining technologies are described below.

4.4.2.1 Uranium Open Pit Mining and Milling

Open mining of uranium ore is similar to techniques used for the surface mining of coal. Key open pit mining activities include the blasting and blading of overburden, hauling of overburden, removal of ore, and transport of ore to the milling facility. The energy requirements for open pit mining of uranium are based on data for the Ranger Mine, which is located in Australia and currently produces 12 percent of the world's uranium (Leeuwen, 2007). Other emissions are taken from the Government of Saskatchewan, Canada (Acott & Polloc, 2004).

Milling is necessary to extract uranium, in the form of U_3O_8, from ore. The milling of uranium includes a series of crushing, grinding, and leaching processes. The leaching processes use liquid separation methods and thus produce uranium-rich waste sludge (tailings). The product of the milling

process is a solid powder known as yellowcake with an approximate composition of 80 percent U_3O_8 by weight.

This analysis includes data for the construction, operation, and decommissioning of uranium mills. Key construction and installation activities include the concrete and steel requirements for the uranium mill as well as the diesel consumption and combustion emissions associated with the use of trucks and construction equipment. The significant operation activities for milling include the input of uranium ore and the combustion of process fuels. The decommissioning of a uranium mill is assumed to have ten percent of the burdens of the initial construction and installation of the facility.

Milling of uranium ore into yellowcake almost always occurs at the site of the uranium mine. Where this is not the case, transport distances between mines and mills are minimized because of the relatively high mass of mined ore to the mass of uranium produced.

The material and energy inputs used in modeling open pit uranium mine construction, operation, and milling are available in **Appendix B**.

4.4.2.2 Uranium Underground Mining and Milling

Underground mining of uranium was modeled based on the construction of a room and pillar mine, similar to that previously developed by NETL for Illinois No. 6 coal mines (NETL, 2010b). Construction material inputs for the underground mine were based on material lists provided in the Energy Technology Characterizations Handbook (DOE, 1983). Additional materials that are common to uranium and Illinois No. 6 coal mines were added to the model (NETL, 2010b). The milling process for uranium from underground mining is the same as that from open pit mining.

The material and energy inputs used in modeling underground mining operation and construction processes are available in **Appendix B**.

4.4.2.3 Uranium Solution Mining

Solution mining, or in situ leach mining (ISL), injects water-based fluid into an underground mineral formation and extracts uranium ore from the recovered solution. The energy requirements for solution mining include electricity and natural gas used for injection and recovery of the fluid, as well as for the remediation of process water by reverse osmosis before it is returned to the ground (NRC, 2009a). Key chemicals that are used to facilitate the absorption and recovery of uranium are carbon dioxide, sodium carbonate, sodium chloride, hydrogen peroxide, and ion-exchange resins (NRC, 2009b). The water quality burdens incurred by solution mining include the release of heavy metals, radionuclides, and salts (USGS, 2009).

The material and energy inputs used in modeling in situ leach mining operation and construction processes are available in **Appendix B**.

4.4.3 Uranium Conversion

Uranium conversion is the process of converting solid U_3O_8 to UF_6. Conversion is necessary in order to convert solid U_3O_8 to gaseous UF_6, which is easier to enrich to elevated levels of U-235. The conversion process uses strong acid and alkali reagents to purify U_3O_8, which is then combined with fluorine to produce UF_6.

This analysis includes data for the construction, operation, and decommissioning of uranium conversion facilities. Key construction and installation activities include the concrete and steel requirements for the facility (DOE, 1983). The significant operation activities for uranium

conversion include the input of U_3O_8 (yellowcake) and the combustion of process fuels (Rotty, Perry, & Reister, 1975), while air emissions from operations are based on an annual environmental compliance report for a uranium conversion facility in Canada (Cameco, 2009). The decommissioning of a uranium conversion facility is assumed to have ten percent of the energy consumption and environmental emissions as the initial construction of the facility.

North American conversion facilities exist in Port Hope, Ontario (Cameco, 2010), and Metropolis, Illinois (NRC, 2010b). All Canadian and U.S. extracted uranium is assumed to flow through these facilities, respectively. While it is known that some portion of foreign extracted uranium is also converted in foreign countries (some Australian yellowcake is converted in China, for instance), the difference in operations between conversion facilities is expected to be small. Therefore, U.S. and Canadian conversion data is used to represent this process.

The material and energy inputs used in modeling conversion facility operation and construction processes are available in **Appendix B**.

4.4.4 Uranium Enrichment

There are two conventional technologies for uranium enrichment[1]: gaseous diffusion and gas centrifuge. Both technologies exploit the mass differences between molecules composed of U-235 or U-238 isotopes. Currently, almost all uranium enriched domestically is done so by gaseous diffusion technology. The U.S. does have a centrifuge enrichment facility owned by URENCO USA and located in Lea County, New Mexico. The facility began operating in June 2010 with current production output at only 3 percent of the 2015 planned capacity of 5.8 million separative work units/year, which is enough to supply enough enriched uranium to meet 10 percent of the total U.S. electricity demand (WNA, 2011e).

Gaseous diffusion is currently used in the U.S. and uses a long series of semi-permeable membranes. In gaseous diffusion, all UF_6 molecules have the same energy, but the lighter UF_6 molecules (those composed of U-235 isotopes) move faster than the heavier molecules (UF_6 composed of U-238 isotope) and thus collide with the diffusion membrane more frequently than heavier UF_6 molecules. This relatively higher collision rate for the lighter UF_6 molecules results in an elevated concentration of U-235 isotope on the product side of the membrane.

Gas centrifugation is the predominant enrichment technology in Europe and uses a long series of rotating centrifuges to exploit the mass difference between U-235 and U-238 isotopes. Many diffusion stages are required to enrich uranium from its naturally occurring U-235 concentration (approximately 0.7 percent U-235) to a concentration suitable for nuclear fuel (5 percent U-235).

This analysis includes data for the construction and installation, operation, and decommissioning of uranium enrichment facilities. Key construction and installation activities include the concrete, steel, copper, and aluminum materials used for structural and electrical systems, as well as the diesel consumption and combustion emissions associated with the use of trucks and construction equipment. Most of this data was derived from an environmental impact statement (EIS) for a proposed enrichment facility (NRC, 2005). This analysis assumes that the construction and installation requirements of gaseous diffusion and gas centrifuge enrichment facilities are equal.

[1] There are other enrichment technologies, for example laser isotope separation, however none have achieved commercial production. Therefore, this study focuses only on gaseous diffusion and gas centrifuge enrichment.

The significant operation activities for uranium enrichment are the input of natural UF_6, electricity consumption, the combustion of process fuels, and the storage of uranium waste. The operation activities for gas centrifuge enrichment are based on an EIS for a proposed enrichment facility (NRC, 2005), which provides the enrichment capacity, electricity requirements, natural gas consumption, and emission of hydrogen fluoride and solvents. The operation activities for gaseous diffusion enrichment are based on the profiles of the gaseous diffusion facility in Paducah, Kentucky, which is the only operating gaseous diffusion facility in the U.S. (ATSDR, 2001; DOE, 2004). Gaseous diffusion consumes relatively high amounts of electricity. In fact, the Paducah gaseous enrichment facility requires a 1,600 MW supply of electricity and relies on electricity produced by a dedicated, coal-fired power plant in Joppa, Illinois (DOE, 2004; EPA, 2008).

The storage of depleted uranium is a key operation activity for uranium enrichment. No permanent storage solutions for depleted uranium or other radioactive wastes from the nuclear fuel cycle have been implemented in the U.S. Thus, uranium enrichment facilities store depleted uranium onsite in steel containers. In the future, it is possible that on-site storage may no longer be acceptable in which case enrichment plant tails will likely be processed and buried as LLW. This analysis assumes the current storage scenario and models the construction of steel containers used for the stockpiling of depleted uranium on-site (DWMEP, 2005).

The decommissioning of a uranium enrichment facility is a multi-year process that requires careful handling and processing of contaminated equipment (Anigstein, Thruber, Mauro, Marschke, & Behling, 2001). The decommissioning process that is currently underway at the Oak Ridge enrichment facility was used as a basis for estimating the environmental burdens from the decommissioning of a uranium enrichment facility (DOE, 2010). This analysis assumes that the decommissioning requirements of gaseous diffusion and gas centrifuge enrichment facilities are equal. The portion of uranium fuel delivered to owners and operators of U.S. civilian reactors in 2009 enriched in the U.S. by gaseous diffusion was 52 percent (EIA, 2010b). The remainder was enriched in foreign countries, primarily by centrifuge.

4.4.5 Uranium Fuel Fabrication

Uranium fuel fabrication converts gaseous UF_6 to solid UO_2, and then sinters the UO_2 into cylindrical pellets that are assembled into metal-encased fuel rods.

This analysis includes data for the construction and installation, operation, and decommissioning of uranium fuel fabrication facilities. Key construction and installation activities include the concrete and steel requirements for the facility as well as the diesel use and combustion emissions from the use of trucks and construction equipment. The significant operation activities for uranium fuel fabrication are the input of enriched UF_6 and the combustion of process fuels; the LC burdens for the other components of a fuel rod assembly are assumed to be negligible in comparison to the LC burdens of the uranium supply chain and are thus not accounted for in this analysis. The decommissioning of a uranium fuel fabrication facility is assumed to have ten percent of the burdens of the initial construction and installation of the facility.

The material and energy inputs used in modeling fuel fabrication facility operation, construction, and installation processes are available in **Appendix B**.

4.5 Life Cycle Stage #2: Fuel Assembly Transport

U.S. enriched fuel assemblies are loaded onto trucks at U.S. fuel fabrication facilities in Columbia, South Carolina; Wilmington, North Carolina; Richland, Washington; Lynchburg, Virginia; and

Erwin, Tennessee (NRC, 2010a). The average transport distance between these facilities and existing nuclear power plants is weighted by the production capacity of each facility. European enriched fuel is assumed to be delivered to ports in New York City and Houston, Texas.

As with other transport processes within the uranium fuel cycle, no loss of UO_2 is assumed for this stage. The containment structure of the fuel assemblies and the inherent risk in their exposure to the public is assumed to preclude loss of fuel during fuel assembly transport.

With the exception of truck transport distance, material and energy inputs used in modeling truck operation in LC Stage #2 are identical to those used in LC Stage #1 intermediate transport. A detailed description of the truck operation process is available in **Appendix B**.

4.6 Life Cycle Stage #3: Nuclear Power Plant

LC Stage #3 begins when uranium fuel assemblies are unloaded from trucks at the energy conversion facility. The energy conversion facility is described as either as an existing or Gen III+ (proposed) plant in the following sections. These plants have independent construction and operation processes. A common decommissioning process and a common spent fuel storage process are used to characterize the power plants. The details of unit processes used in modeling LC Stage #3 are provided in **Appendix B**.

4.6.1 Existing Plant

The current fleet of nuclear power plants is designated Generation II/III. The model of existing plants considers the average MWh generated by the U.S. installed nuclear capacity since 1969.

U.S. nuclear capacity consists of 104 light water reactors (LWRs), as opposed to heavy water reactors. These reactors use ordinary water (H_2O) as a moderator to reduce the kinetic energy of neutrons released during fission, enabling a sustained nuclear reaction. Heavy water reactors, used primarily in Canada, moderate neutrons with deuterium dioxide (D_2O) and can operate using uranium that has not been enriched, or even using recycled fuel from LWRs (Ragheb, 2008).

A water-filled steel pressure vessel contains the reactor core of an LWR, allowing the water to serve both as moderator for the reaction and as coolant for the reactor core. In a boiling water reactor (BWR), steam generated by the thermal energy from controlled fission is fed directly to a turbine, condenser, and feedwater pump to complete the thermodynamic cycle. The turbine drives an electric generator. In a pressurized water reactor (PWR), by contrast, steam produced in the reactor vessel is fed through a pressurized loop to then transfer heat to a secondary steam loop. Steam from the secondary loop is used to drive the turbine, isolating water in contact with the reactor core from carrying radioactive contamination to the secondary steam loop, turbine, or condenser (Nave, 2010). 66 percent of operating nuclear reactors in the U.S. are PWRs, and the remaining 34 percent are BWRs (EIA, 2010b).

EIA records are used for all plant electricity production, fuel use and capacity factor data in the model of the existing plant (EIA, 2010b). The average operating reactor in the U.S. in 2009 was 926 MW operating with a 90.6 percent capacity factor. Variation in plant size ranged from 482 MW to 1,314 MW, with 3.5 GWh to 10.7 GWh of electricity production per year. Variation in current capacity factors range from 64 percent to 108 percent. The average capacity factor of operating plants since 1969 is 70.7 percent. Increases to the average fleet capacity factor between 1971 and 2009 are shown in **Figure 4-3**. Uprating of existing nuclear power plants is included implicitly in the

model through the averaging of reported power output of all plants between 1969 and 2009 (EIA, 2010b). Operating parameters of the average existing nuclear power plant are shown in **Table 4-4**.

Figure 4-3: Average Capacity Factor of Existing Nuclear Power Plants (1971-2009) (EIA, 2009)

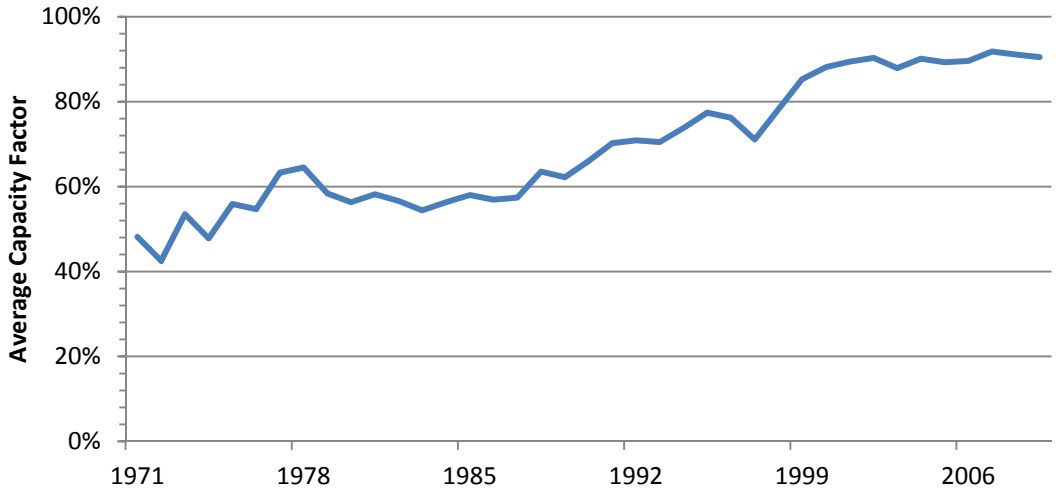


Table 4-4: Existing Nuclear Power Plant Operating Parameters

Parameter	Value	Source
Average Thermal Efficiency of Existing Reactors (%)	31.6	(WNA, 2010a)
Average Annual Electric Output of a Single Reactor, 1969-2009 (MWh/ year)	4.93E+06	(EIA, 2010b)
Uranium Fuel Input per Electricity Output (kg/MWh)	4.33E-03	DOE 1983
Number of Operating Nuclear Reactors in 2009	104	(EIA, 2010b)
Number of Operating PWR Reactors in 2009	69	(EIA, 2010b)
Number of Operating BWR Reactors in 2009	35	(EIA, 2010b)

The construction and installation emissions included in the study are based on the asset lifetime of the plant: known refurbishment of existing facilities are included. The average reactor capacity factor from 1969 to 2009 of 70.7 percent was used to scale the reactor construction impacts to the functional unit of one MWh. Initial construction design lifetimes were between 20 and 30 years for existing plants (NRC, 1996).

4.6.2 Generation III+ Plant

Generation III+ is the next wave of light water reactors. No Gen III+ reactors are currently in operation in the U.S., but a small number have been constructed and are operating abroad. The Gen III+ model uses the average of proposed plants which have submitted application for licensure to the NRC.

Gen III+ plant designs build upon existing reactor technology by incorporating passive safety systems such that no operator control or auxiliary power is necessary in the event of a malfunction. The plants have higher fuel burn-up rates and higher thermal efficiencies, resulting in lower uranium fuel upstream emissions and less radioactive waste than existing plants. Makers of Gen III+ plants

also claim that the designs require reduced capital cost, reduced construction time, easier operation, and reduced likelihood of both operational problems and failure incidents.

Gen III+ plants also have a longer reactor lifetime after initial construction and startup (60 years). While Gen III+ plants may go through refurbishment and uprating within their lifetime, only known replacement of components are included. This method is consistent with an attributional LCA.

4.6.3 Waste Management

This analysis models three scenarios for understanding the LC burdens of nuclear waste management:

- A **baseline scenario**, representative of the existing facility LC without long-term waste management or fuel reprocessing.
- A **long-term waste management scenario**, in which the LLW and HLW from nuclear power are transported to a long-term disposition site.
- A **reprocessing scenario** that includes the reprocessing of spent fuel in addition to long-term disposition of LLW and HLW.

4.7 Life Cycle Stage #4: Electricity Transmission and Distribution

The boundary for LC Stage #4 (electricity transmission and distribution) begins and ends when the power is pulled from the grid. All NETL power generation LCI&C studies assume electricity is used by a non-specific, 100 percent-efficient process. A seven percent loss is assumed for electricity transmission (Bergerson, 2005). The transmission line is considered existing infrastructure, therefore the construction of the line, along with the associated costs, emissions, and land use changes, are not included within the system boundaries of this study.

Sulfur hexafluoride leakage rates from the U.S. transmission and distribution grid are estimated using information collected and compiled from EPA's "SF_6 Emission Reduction Partnership for Electric Power Systems" (EPA, 2007). Data is collected and compiled from various members of the partnership, which in 2006 represented 42 percent of the U.S. grid in terms of U.S. transmission mileage. EPA utilizes the aforementioned data to develop the "Inventory of U.S. Greenhouse Gas Emissions and Sinks" (EPA, 2010a). In preparing the national SF_6 leakage estimate, EPA assumes that "partners commit to reducing SF_6 emissions through technically and economically feasible means. However, non-partners were assumed not to have implemented any changes that would have reduced emissions over time."

It was noted that in 2007 and 2008 the partnership continued to grow but there was no quantification of the percent representation of the U.S. power grid. Therefore, it has been assumed that in 2007, the partnership represented 42 percent of the U.S. grid (conservative estimate which will result in slightly higher SF_6 emissions estimate). For this analysis, it is assumed that the SF_6 leak rate for non-partners (remaining 58 percent of the U.S. grid transmission mileage) will be twice that of partners. Note that SF_6 emissions calculated in this manner exceed EPA's estimates by five percent (EPA, 2007).

4.8 Life Cycle Stage #5: End Use

All NETL power generation LCA studies assume electricity is used by a non-specific, 100 percent efficient process. This assumption avoids the need to define a unique user profile, and allows all

power generation studies to be compared on equal footing. Therefore, no environmental inventories were collected for Stage #5.

4.9 Land Use

Analysis of associated land use effects is considered a central component of an LCA under both International Organization for Standardization (ISO) 14044 and American Society for Testing and Materials (ASTM) standards. Additionally, the U.S. Environmental Protection Agency (EPA) released a final version of the Renewable Fuel Standard Program 2 (RFS2) (EPA, 2010b). Included in RFS2 is a method for assessing land use change and associated GHG emissions that are relevant to this LCA. The land use analysis presented in this study is consistent with the method presented in RFS2. It quantifies both the area of land changed, as well as the GHG emissions associated with that change, for direct and select indirect land use impacts. The land use analysis does not account for long-term waste management or reprocessing.

4.9.1 Definition of Direct and Indirect Impacts

Land use effects can be roughly divided into direct and indirect. In the context of this study, direct land use effects occur as a direct result of the LC processes needed to produce electricity via geothermal power production. Direct land use change is determined by tracking the change from an existing land use type (native vegetation or agricultural lands) to a new land use that supports production.

Indirect land use effects are changes in land use that occur as a result of the direct land use effects. For instance, if the direct effect is the conversion of agricultural land to land used for energy production or conversion, an indirect effect might be the conversion of native vegetation to new farmland, but at a remote location, in order to meet ongoing food supply/demand. This specific case of indirect land use change has been studied in detail by the U.S. EPA (EPA, 2009) and other investigators, and sufficient data are available to enable its consideration within this study. There are also many other types of indirect land use change that could result from installation and operation of new energy production and conversion facilities. For instance, the installation of a large new power generation facility in a rural location could result in the migration of employees closer to the site, causing increased urbanization in surrounding areas. However, due to high uncertainty in predicting and quantifying this and other less studied indirect effects, only the displacement of agricultural lands resulting in conversion of other land uses to agriculture was considered within the scope of this study.

4.9.2 Land Use Metrics

A variety of land use metrics, which seek to numerically quantify changes in land use, have been devised in support of LCAs. Two common metrics in support of a process-oriented LCA are transformed land area (square meters of land transformed) and GHG emissions (kg CO_2e). The transformed land area metric estimates the area of land that is altered from a reference state, while the GHG metric quantifies the amount of carbon emitted in association with that change. **Table 4-5** summarizes the land use metrics included in this study.

Table 4-5: Primary Land Use Change Metrics Considered in this Study

Metric Title	Description	Units	Type of Impact
Transformed Land Area	Area of land that is altered from its original state to a transformed state during construction and operation of the advanced energy conversion facilities	m^2 (acres)	Direct and Indirect
Greenhouse Gas Emissions	Emissions of GHGs associated with land clearing/transformation, including emissions from aboveground biomass, belowground biomass, soil organic matter, and lost forest sequestration	kg CO_2e (lbs. CO_2e)	Direct and Indirect

For this study, the assessment of land use GHG emissions includes those emissions that would result from the following, for each LC Stage and direct and indirect GHG emissions as relevant:

- Quantity of GHGs emitted due to biomass clearing during construction of each facility
- Quantity of GHGs emitted due to oxidation of soil carbon and underground biomass following land transformation
- Evaluation of ongoing carbon sequestration that would have occurred under existing conditions, but did not occur, under study/transformed land use conditions

Additional land use metrics, such as potential damage to ecosystems or species, water quality changes, changes in human population densities, quantification of land quality (e.g. farmland quality), and many other land use metrics may conceivably be included in the land use analysis of an LCA. However, data needed to support accurate analysis of these metrics are severely limited in availability (Canals et al., 2007; Koellner & Scholz, 2007), or otherwise outside the scope of this study. Therefore, only transformed land area and GHG emissions are quantified for this study.

4.9.3 Land Use Calculation Method

As previously discussed, the land use metrics used for this analysis quantify the land area that is transformed from its original state due to construction and operation of the facilities required for the geothermal case considered in this study. Results from the analysis are presented as per the reference flow for each relevant LC stage, or per MWh when considering the additive results of all stages.

4.9.3.1 Transformed Land Area

The transformed land area metric was assessed using data available from the U.S. Bureau of Land For indirect land use change, consistent with EPA's RFS2 analysis, it was assumed that 30 percent of all agricultural land that was lost as a result of the installation of facilities within the study resulted in the creation of new agricultural land at a remote location, within the U.S. The creation of new agricultural land, in turn, was assumed to result in the conversion of either forest or grassland/pasture to farmland, according to regional land use characteristics identified in USDA (2005).

Specific locations for the facilities considered in this study are not identified within this study. Instead, generalized facility locations were used, indicating the region in which a facility would be installed. Regions used for the installation of specific facilities were assessed based on locations of existing, real-world facilities and study assumptions discussed elsewhere in this report. Existing regional land use was assessed based on data available through the U.S. Department of Agriculture (USDA) (2005) and Earthtrends (2010). These data include land use breakdowns for each region for four categories: Cropland, Grassland (including pasture and rangeland), Forest (including various forest types), and Barren (including bare rock, snow/ice, and urban areas). Other minor land use

types, such as water and wetlands, were also included in some of the source data. However, it was assumed that facilities would not be installed into these areas. **Table 4-6** shows a breakdown of the proportions of existing land use types that would be converted from grassland, forest, cropland, or barren, for each region.

Table 4-6: Existing Regional Land Use Categories

Region	Forest	Cropland	Grassland	Barren
Australia	4%	6%	90%	0%
Africa (Sub-Saharan)	15%	15%	51%	18%
Canada	42%	5%	31%	23%
Europe	44%	29%	23%	4%
Russia	49%	16%	29%	5%
United States	36%	25%	34%	3%

Note: Some values may not add to 100% due to rounding

4.9.3.2 Greenhouse Gas Emissions

GHG emissions due to land use change were evaluated based upon the U.S. EPA's method for the quantification of GHG emissions, in support of the RFS (EPA, 2010b). EPA's analysis quantifies GHG emissions that are expected to result from land use changes from forest, grassland, savanna, shrubland, wetland, perennial, or mixed land use types to agricultural cropland, grassland, savanna, or perennial land use types. Relying on an evaluation of historic land use change completed by Winrock, EPA calculated a series of GHG emission factors for the following criteria: change in biomass carbon stocks, lost forest sequestration, annual soil carbon flux, CH_4 emissions, NO_X emissions, annual peat emissions, and fire emissions, that would result from land conversion over a range of timeframes. EPA's analysis also includes calculated reversion factors, for the reversion of land use from agricultural cropland, grassland, savanna, and perennial, to forest, grassland, savanna, shrub, wetland, perennial, or mixed land uses. Emission factors considered for reversion were change in biomass carbon stocks, change in soil carbon stocks, and annual soil carbon uptake over a variety of timeframes. Each of these emission factors, for land conversion and reversion, was included for a total of 756 global countries and regions within countries, including the 48 contiguous states. Based on the land use categories (forest, grassland, and agriculture/cropland) that were affected by study facilities, EPA's emission factors were applied on a statewide or regional basis.

GHG emissions from indirect land use were quantified only for the displacement of agriculture, and not for the displacement of other land uses. Indirect land use GHG emissions were calculated based on estimated indirect land transformation values, as discussed previously. Then, EPA's GHG emission factors for land use conversion were applied to the indirect land transformation values, according to transformed land type and region, and total indirect land use GHG emissions were calculated.

4.10 LCA Results

The environmental results include a comprehensive list of inventory metrics (GHG emissions, criteria and other air pollutants of concern, water use, water quality, EROI, solid waste, and land use). Greenhouse gas emissions, criteria and other air pollutant emissions, water use, radionuclide emissions, and EROI are discussed within this section because their relative importance within

activities in the LC provides the most revealing discussion. A full inventory of environmental metrics for the nuclear power LC is available in **Appendix C**.

4.10.1 Greenhouse Gases

All results of an LCA are expressed on the basis of a functional unit, which describes a service that is provided by each alternative and serves as the basis for comparison. The functional unit of NETL's LCA of nuclear power is the delivery of 1 MWh of electricity to the end user. The LCA results for GHG emissions by LC stage are shown in **Figure 4-4**.

The LC GHG emissions for nuclear power from existing and Gen III+ plants for the default uranium enrichment mix (52 percent gaseous diffusion and 48 percent centrifuge) are 39.5 and 25.8 kg CO_2e/MWh generated and delivered to the end user, respectively. These results do not include long term waste management or reprocessing. The Gen III+ life cycle has lower GHG emissions than the existing plants due to higher UO_2 burnup rates of Gen III+ reactors and higher thermal efficiency.

The addition of long-term waste (which includes LLW and HLW) disposition to the existing nuclear power case increases the GHG results of nuclear power by 6.6 percent (42.1 compared to 39.5 kg CO_2e/MWh). As shown by the bars in **Figure 4-4**, the GHG results for RMA, RMT, and PT are identical. The only difference between the baseline scenario and the long-term waste management scenario is the transport and construction requirements of long-term waste management.

The addition of fuel reprocessing to the nuclear fuel cycle reduces the consumption of uranium 20 to 30 percent (IAEA, 2008b). However, this reduction only reduces the burdens contributed by uranium mining and milling. Reprocessed uranium requires re-enrichment in order to increase its U-235 concentration to a level appropriate for LWR operation. The total reduction in the GHG emissions of LC Stage #1 is only 1.0 percent. This percent decrease is representative of LC Stage #1 only, not the total LC of nuclear power. When the entire LC is considered, reprocessing of nuclear fuel increases the GHG results by 4.1 percent (41.1 compared to 39.5 kg CO_2e/MWh). A choice to construct a centrifuge enrichment facility in the U.S. would be much more effective at reducing nuclear power LC GHG emissions than constructing a PUREX reprocessing facility. Nuclear waste management scenarios were not modeled for the Gen III+ facility, but the incremental increase in emissions as seen with the existing facilities would be expected.

Because the electricity use of diffusion enrichment is the largest contributor to LC GHG emissions, it is worthwhile to investigate the savings in emissions possible through use of centrifuge enrichment for U.S. enriched UF_6. **Figure 4-4** shows a comparison of LC emissions between gaseous diffusion and centrifuge enrichment. The LC emissions of the current reactor fleet could be reduced by 68 percent (12.7 compared to 39.5 kg CO_2e/MWh) through use of centrifuge enrichment in the U.S. For Gen III+ reactors, the switch to 100 percent centrifuge enrichment would yield an LC GHG reduction of 61 percent (10.2 compared to 25.8 kg CO_2e/MWh). The improvement is smaller for Gen III+ reactors due to higher UO_2 burnup rates of Gen III+ reactors and higher thermal efficiency.

It is worth noting that the transportation requirements for nuclear waste, which includes transport from the nuclear power plant to the disposition site, generate negligible GHG emissions in comparison to other activities of the nuclear LC. (More details on the data used for truck transport are provided in **Appendix B**). These transportation results do not account for the security and safety concerns associated with the transport of radioactive materials. The safety and security concerns related to the transport of nuclear waste would likely have a greater effect on the cost of nuclear power, not the environmental burdens of nuclear power.

Figure 4-4: Life Cycle GHG Profile for Existing and Gen III+ Nuclear Power Including Various Enrichment and Waste Management Scenarios

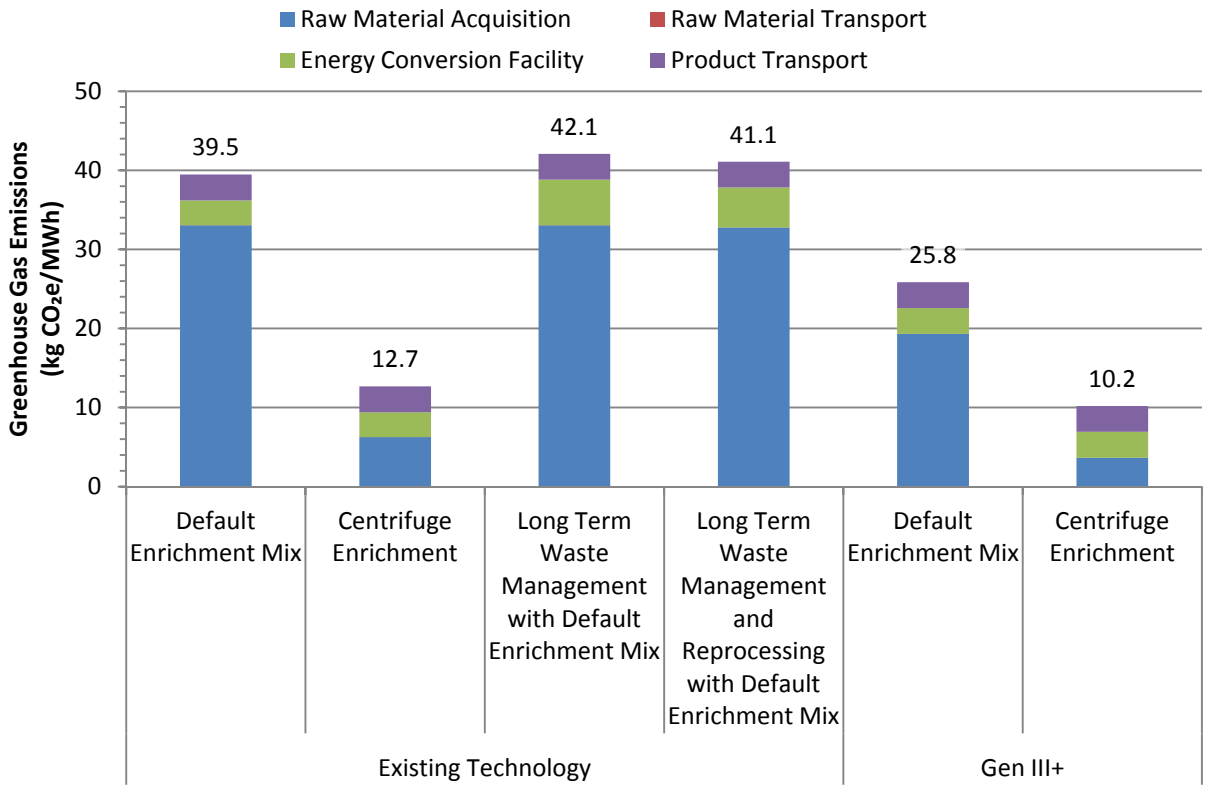


Figure 4-5 and **Figure 4-6** show the detailed stage and sub-stage contributions to the LC GHG emissions of existing and Gen III+ nuclear power for the default uranium enrichment mix with no long term waste management or reprocessing. The GHG profile for nuclear power is dominated by carbon dioxide, which is attributable to combustion of coal, natural gas, and diesel for construction of the power plant and energy for uranium fuel processing. The electricity required for enrichment of uranium fuel accounts for the majority of LC GHG emissions in the existing U.S. nuclear reactor fleet. The enrichment facility in Paducah, KY is powered by an adjacent coal power plant and thus, electricity production emissions were modeled accordingly. Emissions from the gaseous diffusion enrichment process for U.S. enriched fuel are 70 percent of existing plant LC GHG emissions, and 63 percent of Gen III+ life cycle emissions.

The release of SF_6 during the transmission and distribution of electricity is the second most significant GHG contributor. Significant SF_6 emissions are not released directly by power plants, but SF_6 is released by the electrical equipment used for the transmission and distribution of electricity. Sulfur hexafluoride is 8 percent and 13 percent of the LC GHG profile for existing and Gen III+ power, respectively. **Figure 4-5** and **Figure 4-6** show that transport processes within the uranium fuel cycle and from fuel fabrication to the nuclear power plant do not contribute significantly to the LC GHG emissions of nuclear power.

The high energy density of uranium, and the resulting high electricity output per unit input fuel (0.0043 kg UO_2/ MWh for existing facilities), results in a high significance of GHG emissions from construction and decommissioning of the nuclear power plant. The significance of these emissions in the nuclear power LC is approximately 8 percent for existing facilities and 13 percent for Gen III+.

Further, decommissioning of a nuclear plant is nearly as energy intensive as construction because of the care taken in proper isolation of radioactive materials.

Figure 4-5: GHG Emissions for Existing Nuclear

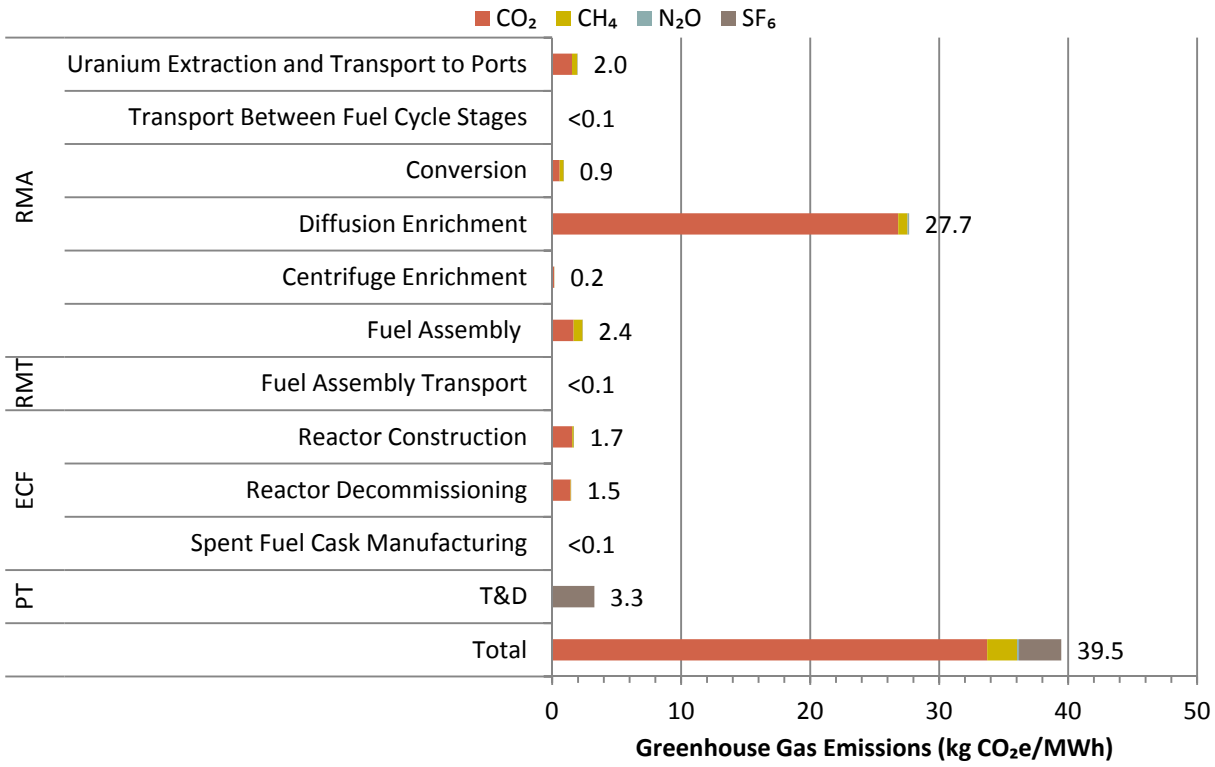
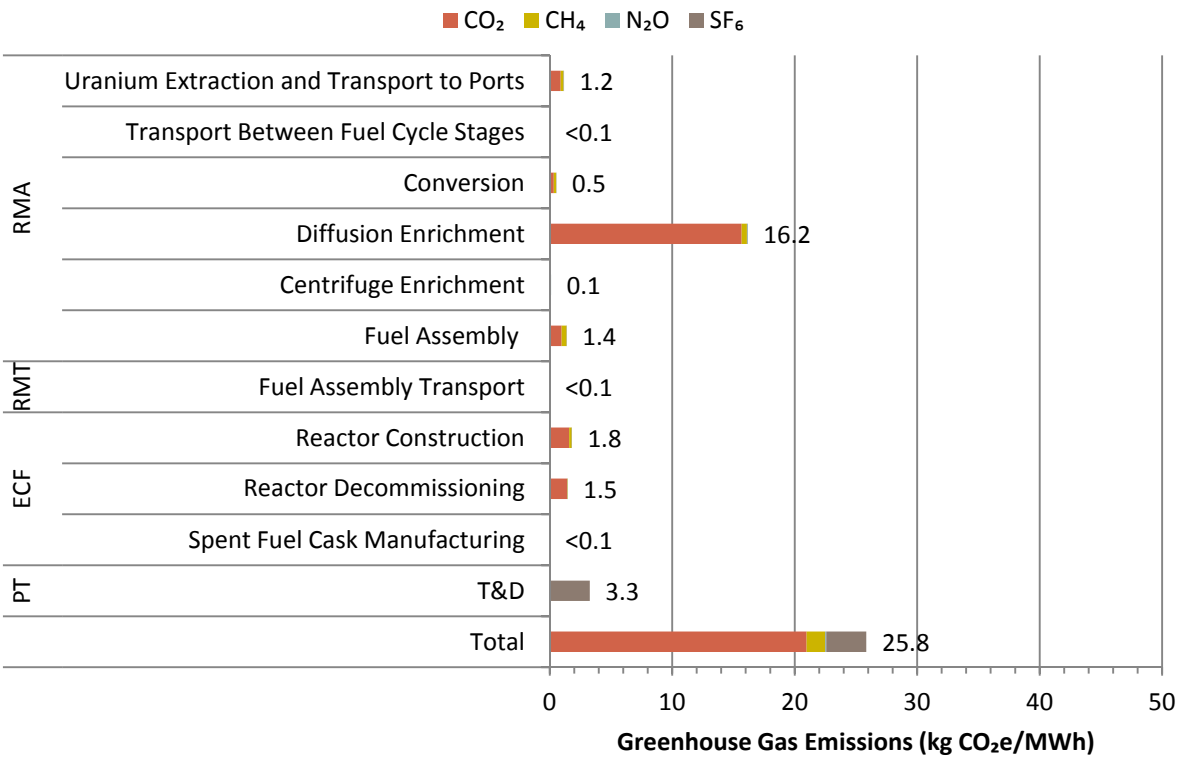


Figure 4-6: GHG Emissions for Gen III+ Nuclear



4.10.2 Land Use

The total transformed land area for all LC Stages combined, on a square meters per MWh delivered to the end user basis, is shown in **Figure 4-7**, with additional details reported in **Table 4-7** and **Table 4-8**. As shown, the total transformed land area for the existing plant pathway is approximately five times that for Gen III+ pathway. This is due in large part to a reduced total footprint area for the energy conversion facility under the Gen III+ pathway (482 acres), as compared to the existing pathway (existing PWR: 1,850 acres; existing BWR: 3,380 acres; existing PWR and BWR pathway total: 2,360 acres). This contributes to an order of magnitude reduction in the transformed land area for the Gen III+ energy conversion facility (0.00262 m^2/MWh), as compared to the existing plant energy conversion facility (0.0267 m^2/MWh). However, because the results shown are normalized per MWh, the reduced transformed land area for Gen III+ is also caused by the substantially higher efficiency of the Gen III+ plant (31.6 versus 34.2 percent). As efficiency increases, more MWh can be produced based on the same total facility footprint areas. Thus, the higher efficiency of the Gen III+ plant accounts for an approximate 40 percent decrease in transformed land area per MWh (total transformed land area for all facilities was compared between existing and Gen III+ pathways except for the energy conversion facility).

Of the four land use types considered, grassland and forest would incur the largest proportion of land transformation. Together, grassland and forest account for 72 percent of the total transformed land area for the existing pathway and 73 percent for the Gen III+ pathway. Agriculture accounts for most of the remaining transformed land area, while barren land use represents only 4 percent of total transformed land area for both the existing and Gen III+ pathways.

Figure 4-7: Total Transformed Land Area

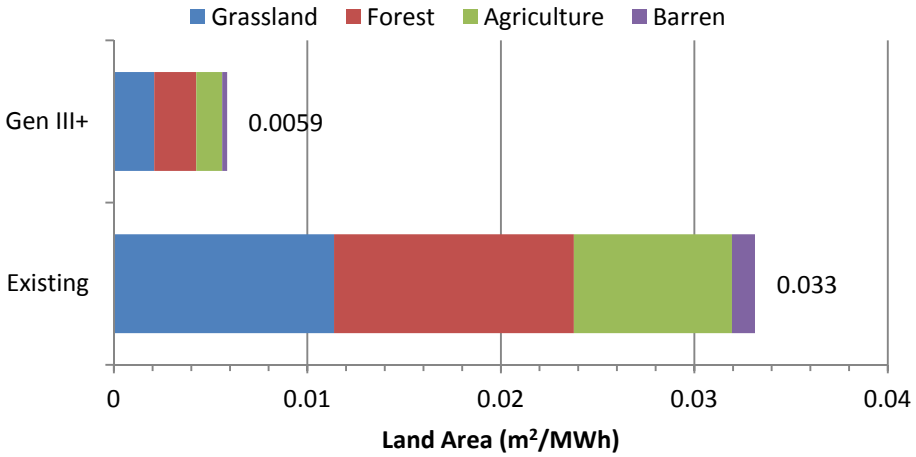


Table 4-7: Existing Plant Total Transformed Land Area (m^2/MWh)

Category	LC Stage #1: Mining	LC Stage #1: Conversion	LC Stage #1: Enrichment	LC Stage #1: Fabrication	LC Stage #3: ECF	LC Stage #3: Trunkline	LC Stage #3: Repository	Total
Grassland	1.29E-03	9.88E-06	1.05E-04	3.33E-05	9.34E-03	5.99E-04	0.00E+00	1.14E-02
Forest	1.15E-03	1.44E-05	1.52E-04	4.85E-05	1.04E-02	6.65E-04	0.00E+00	1.24E-02
Agriculture	5.46E-04	9.59E-06	1.01E-04	3.23E-05	7.03E-03	4.51E-04	0.00E+00	8.17E-03
Barren	2.08E-04	1.34E-06	1.42E-05	4.53E-06	9.09E-04	5.83E-04	0.00E+00	1.72E-03
Total	3.19E-03	3.52E-05	3.72E-04	1.19E-04	2.77E-02	2.30E-03	0.00E+00	3.37E-02

Table 4-8: Gen III+ Total Transformed Land Area (m^2/MWh)

Category	LC Stage #1: Mining	LC Stage #1: Conversion	LC Stage #1: Enrichment	LC Stage #1: Fabrication	LC Stage #3: ECF	LC Stage #3: Trunkline	LC Stage #3: Repository	Total
Grassland	7.54E-04	5.77E-06	6.11E-05	1.94E-05	8.84E-04	3.57E-04	0.00E+00	2.08E-03
Forest	6.74E-04	8.40E-06	8.90E-05	2.83E-05	9.82E-04	3.97E-04	0.00E+00	2.18E-03
Agriculture	3.19E-04	5.60E-06	5.93E-05	1.89E-05	6.66E-04	2.69E-04	0.00E+00	1.34E-03
Barren	1.21E-04	7.86E-07	8.32E-06	2.65E-06	8.61E-05	3.48E-05	0.00E+00	2.54E-04
Total	1.87E-03	2.06E-05	2.18E-04	6.93E-05	2.62E-03	1.06E-03	0.00E+00	5.86E-03

The total land use GHG emissions for all LC stages combined, on a square meters per MWh delivered to the end user basis, are shown in **Figure 4-8** with additional details reported in **Table 4-9** and **Table 4-10**. As shown, the total land use GHG emissions for the existing and Gen III+ pathways reflect the trends in transformed land area as discussed above. In total, the Gen III+ pathway land use GHG emissions are 0.094 kg CO_2e/MWh, which represents an 86 percent reduction in land use GHG emissions in comparison to the existing pathway (0.65 kg CO_2e/MWh). The magnitude of land use GHG emissions in comparison to total LC GHG emissions is small, but not negligible. As shown in **Figure 4-4** total LC GHG emissions (excluding land use) range from 39.5 kg CO_2e/MWh for the

existing pathway with the default enrichment mix and no long term waste management to 10.2 kg CO_2e/MWh for the Gen III+ pathway with centrifuge enrichment and no long term waste management. In comparison to total LC GHG emissions (excluding land use), land use GHG emissions represent 1.6 percent of LC emissions (excluding land use) for existing plants with the default enrichment mix, 0.36 percent for Gen III+ with the default enrichment mix, 4.9 percent for existing plants with centrifuge enrichment, and 0.9 percent for Gen III+ with centrifuge enrichment.

Forest and grassland are shown as the sole contributors to land use GHG emissions in **Figure 4-8**, **Table 4-9**, and **Table 4-10**. This is based on the assumptions that (1) land use GHG emissions for conversion of barren land (which includes urban land, rock outcroppings, and ice) to facilities would not result in emission of land use GHGs; and (2) conversion of agricultural land to facilities would not result in emission of land use GHGs. The second assumption results from data limitations of the land use change data included in the final RFS2 documentation, upon which the land use GHG emissions calculated here are based. However, the second assumption is not unreasonable. Most agricultural cropping does not result in the accumulation of aboveground biomass. For comparison, note that loss of aboveground biomass in forests accounts for over 90 percent of forest related land use GHG emissions shown in **Figure 4-8**. Also, construction activities for most facilities (except surface mines) would result in one-time disturbance to existing soil. But after the initial disturbance, further disturbances to soils on site would be exceptionally rare or limited in extent. Thus, the second assumption likely adds a relatively small level of uncertainty 10 percent at the highest, but most likely less than 5 percent). **Figure 4-8** shows substantially greater forest related emissions as compared to grassland emissions, even though transformed land areas for forest and grassland are very similar. Greater forest emissions result primarily from the loss of existing aboveground biomass that occurs as a result of land clearing for facility installation, and to a much lesser extent, from loss of soil carbon. GHG emissions due to loss of grassland are much smaller and represent a much smaller loss of aboveground biomass, and consequently a proportionally larger share of soil carbon losses, as compared to forest related emissions.

Figure 4-8: Total Land Use GHG Emissions

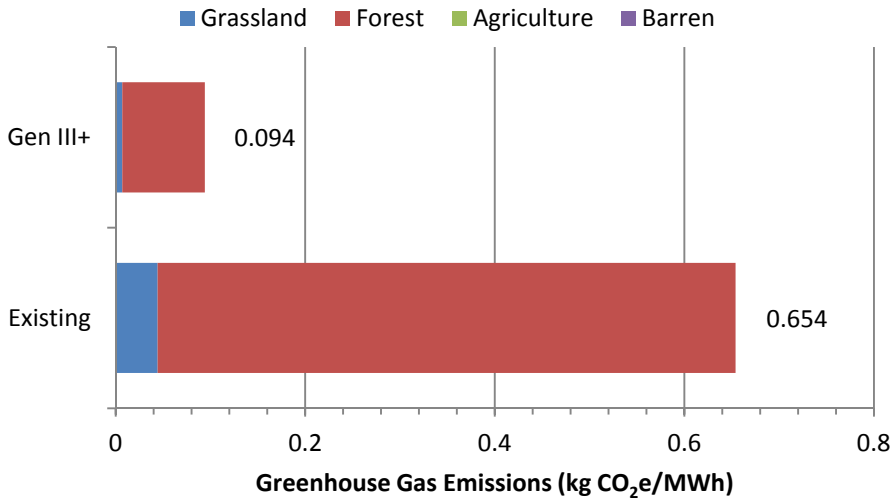


Table 4-9: Existing Plant Total Land Use GHG Emissions (kg CO_2e/MWh)

Category	LC Stage #1: Mining	LC Stage #1: Conversion	LC Stage #1: Enrichment	LC Stage #1: Fabrication	LC Stage #3: ECF	LC Stage #3: Trunkline	LC Stage #3: Repository	Total
Grassland	6.66E-03	6.01E-05	6.37E-04	2.03E-04	3.87E-02	-1.86E-03	0.00E+00	4.44E-02
Forest	4.44E-02	7.29E-04	7.72E-03	2.46E-03	5.50E-01	4.56E-03	0.00E+00	6.10E-01
Agriculture	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Barren	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total GHG	5.11E-02	7.89E-04	8.36E-03	2.66E-03	5.89E-01	2.70E-03	0.00E+00	6.55E-01

Table 4-10: Gen III+ Total Land Use Emissions (kg CO_2e/MWh)

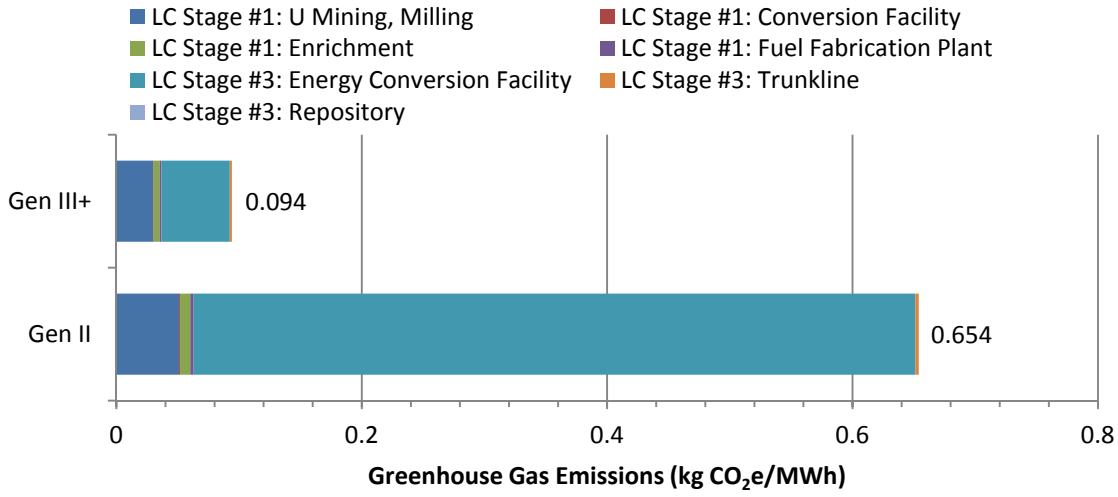
Category	LC Stage #1: Mining	LC Stage #1: Conversion	LC Stage #1: Enrichment	LC Stage #1: Fabrication	LC Stage #3: ECF	LC Stage #3: Trunkline	LC Stage #3: Repository	Total
Grassland	3.89E-03	3.51E-05	3.72E-04	1.18E-04	3.66E-03	-1.11E-03	0.00E+00	6.97E-03
Forest	2.60E-02	4.26E-04	4.51E-03	1.44E-03	5.21E-02	2.72E-03	0.00E+00	8.72E-02
Agriculture	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Barren	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total GHG	2.99E-02	4.61E-04	4.88E-03	1.56E-03	5.58E-02	1.61E-03	0.00E+00	9.72E-02

Figure 4-9 shows total land use GHG emissions, broken down by facility. As shown, the energy conversion facility under LC Stage #3 would result in the largest land use GHG emissions for both the existing and Gen III+ pathways. This result occurs for two primary reasons. First, the total land area required for the energy conversion facility, and especially for existing energy conversion facilities, is large, especially for the existing pathway: 2,360 acres for the existing pathway, and 482 acres for the Gen III+ pathway. However, the primary reason that emissions for LC Stage #1 facilities are not higher is related to the amount of material that could be handled by these facilities. Operation of a single nuclear power plant would not be sufficient to require the full capacity of mining, milling, uranium conversion, enrichment, or fuel fabrication facilities. The analysis presented here accounts for only those land use GHG emissions under LC Stage #1 that would be directly related to the study.

Also worth noting, over 50 percent of the land use GHG emissions from mining and milling results from operation of ISL mines. This is initially counter-intuitive: a single ISL installation requires much less land than an open pit mine. However, total lifetime production capacities for ISL mines are typically much less than for open pit or underground mines. While an open pit or underground mine may remain in operation for 30 years or more, a typical ISL mine remains viable for less than a decade, and produces substantially less uranium over that decade, as compared to most surface or underground mines. Therefore, within the 60 year lifetime of the nuclear power plant considered in this study, many ISL mines will have progressed from initial startup through remediation phases. When considering all of the roads, wells, pipelines, and other facilities required for operation of an ISL mine, which would be installed at many facilities over the study period, combined with comparatively low production rates from a single ISL installation, this results in a relatively higher proportion of emissions from ISL mining as compared to other mining types considered in this study.

Finally, no separate land use GHG emissions are shown for the spent fuels repository, because, according to the assumptions of this study, the spent fuels repository LC Cycle Stage #3 energy conversion facility can be considered to represent the energy conversion facility inclusive of the spent fuels repository. The repository is separated out here for consistency with other sections of this report.

Figure 4-9: Total Land Use GHG Emissions, by Facility



4.10.3 Water Use

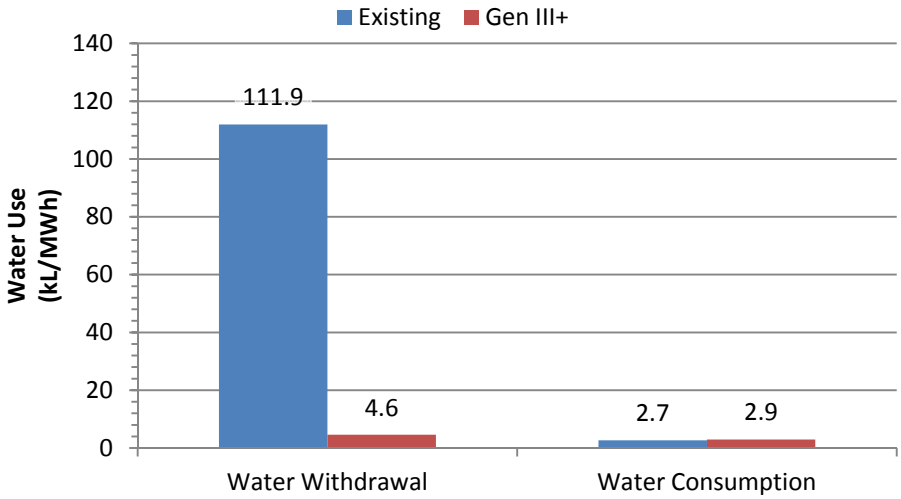
As shown in **Table 4-11** and **Figure 4-10**, water withdrawal is significantly higher for existing plants than for Gen III+ technologies. Of the 104 LWRs operating in the U.S., 35 utilize wet recirculating cooling, 60 use once through cooling, and the remaining 9 use hybrid cooling systems (NEI, 2009). The water use for existing plants is based on the weighted average of cooling technologies in place. It is assumed that Gen III+ facilities would be designed with cooling towers. While closed-loop cooling requires significantly less water withdrawal than once-through, the consumption is almost a factor of five higher (NETL, 2011).

In general, the consumption of water for once-through cooling is higher for nuclear plants than for fossil fuel plants. The LC water consumption value for existing pulverized coal (EXPC) plants was determined to be 2000 L/MWh, which is 35 percent lower than the value determined for nuclear. This difference is consistent with the results of a 2002 Electric Power Research Institute (EPRI) study that compared the water consumption of various types of electricity generation (EPRI, 2002). In comparison to coal-fired power plants, nuclear plants consume more water because of the thermodynamic constraints of the fuel assemblies. Therefore, nuclear plants have higher steam circulation rates and corresponding water withdrawal rates to satisfy a given power output.

Table 4-11: Average Life Cycle Water Use for Nuclear Power Technologies (kL water/MWh)

Reactor Generation	Water Withdrawal	Water Discharge	Net Water Consumption
Existing	111.9	109.2	2.7
Gen III+	4.6	1.7	2.9

Figure 4-10: Average Life Cycle Water Use for Nuclear Power Technologies



4.10.4 Radionuclide Emissions

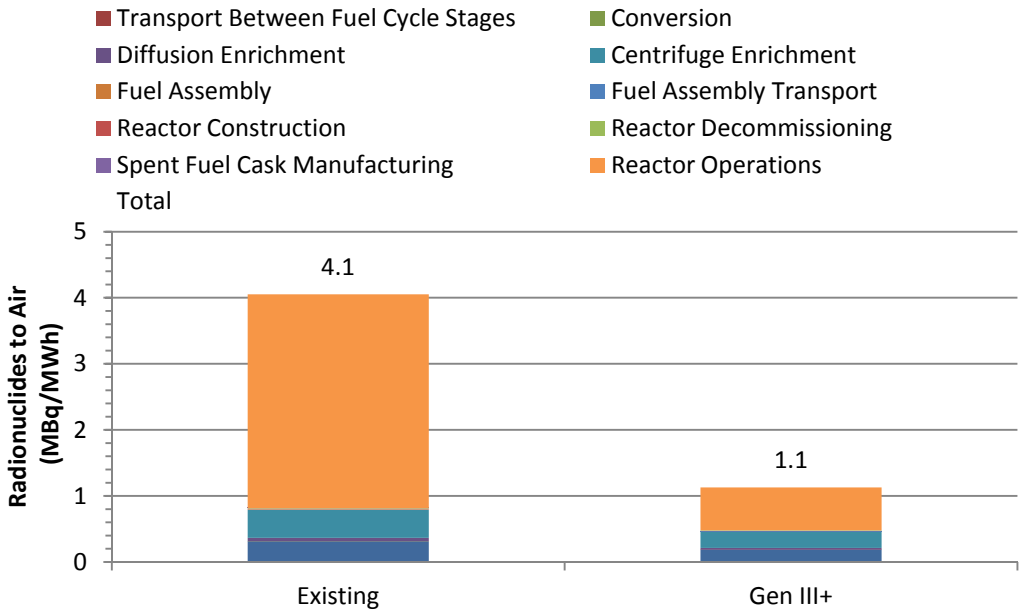
Radionuclide emissions are radioactive emissions to air inventoried by activity level rather than mass. These emissions are frequently of the most interest to regulatory and industry stakeholders because of their potential for human impact and public perception of their danger.

The inventory of radionuclide emissions to air, water, and soil are inventoried in **Table 4-12**. **Figure 4-11** shows radionuclides to air for processes of the existing and Gen III+ life cycles. The table demonstrates that radionuclides to water show similar relative contributions from LC processes, though these emissions are of different magnitudes and should not be directly compared to LC air emissions. The three major LC processes responsible for the majority of radionuclide emissions to air are uranium extraction, uranium enrichment, and nuclear reactor operations. Radionuclide emissions are lower for Gen III+ nuclear power because of reduced consumption of UO_2 fuel due to a higher burnup rate and higher thermal efficiency in combination with and reduced emissions resulting directly from the operation of the facility.

Table 4-12: Radionuclide Emissions for Major Processes of Existing and Gen III+ Life Cycles (Bq/MWh)

Process	Existing Reactors			Gen III+ Reactors		
	Air	Water	Soil	Air	Water	Soil
Uranium Extraction & Transport	3.16E+05	2.46E+03	2.25E+04	1.85E+05	1.44E+03	1.32E+04
Transport Between Fuel Cycle Stages	4.90E+01	1.93E+00	0.00E+00	2.86E+01	1.13E+00	0.00E+00
Conversion	1.28E+03	3.76E+01	1.06E+00	7.46E+02	2.19E+01	6.19E-01
Diffusion Enrichment	4.79E+04	1.84E+03	2.80E-02	2.80E+04	1.07E+03	1.64E-02
Centrifuge Enrichment	4.27E+05	1.69E+04	0.00E+00	2.50E+05	9.85E+03	0.00E+00
Fuel Assembly	6.55E+03	2.52E+02	5.33E-01	3.83E+03	1.47E+02	3.11E-01
Fuel Assembly Transport	1.54E+00	6.08E-02	0.00E+00	9.01E-01	3.55E-02	0.00E+00
Reactor Construction	9.47E+03	3.70E+02	2.88E-01	4.91E+03	1.85E+02	7.23E-01
Reactor Decommissioning	8.68E+03	3.42E+02	1.31E-03	8.68E+03	3.42E+02	1.31E-03
Spent Fuel Cask Manufacturing	4.26E+00	5.50E-02	9.43E-03	2.48E+00	3.21E-02	5.50E-03
Reactor Operations	3.23E+06	0.00E+00	0.00E+00	6.47E+05	2.20E+06	0.00E+00
Total	4.05E+06	2.22E+04	2.25E+04	1.13E+06	2.22E+06	1.32E+04

Figure 4-11: Radionuclide Emissions to Air for Major Processes of Existing and Gen III+



4.10.5 Other Air Emissions

LC criteria and other air pollutant species of interest are also dominated by gaseous diffusion operation and power plant construction emissions. The emissions contribution from these processes relative to all other processes in the lifecycle is shown in **Table 4-13** and **Table 4-14**. Combustion emissions come from hard coal electricity provided to the diffusion enrichment plant as well as diesel combustion in the construction and decommissioning processes. Mercury is heavily emitted as an effect of copper mining for power plant construction materials. Particulate matter is generated in installation and decommissioning activities. Mining emissions also contribute significantly to

particulate matter (PM) and volatile organic compound (VOC) emissions, but are an order of magnitude below enrichment and construction emissions. In general, the Gen III+ life cycle has lower air emissions than the existing plants due to higher UO_2 burnup rates of Gen III+ reactors and higher thermal efficiency.

Table 4-13: Process Contribution to Other Air Emissions for Existing Nuclear Power

Process	Existing Reactors						
	Pb	Hg	CO	NO_X	SO_2	VOC	PM
Uranium Extraction and Transport to Ports	4.70%	4.86%	10.97%	7.07%	1.92%	21.39%	8.26%
Transport Between Fuel Cycle Stages	<0.01%	<0.01%	0.01%	<0.01%	<0.01%	0.04%	<0.01%
Conversion	1.83%	1.91%	2.37%	4.07%	0.60%	16.82%	1.99%
Diffusion Enrichment	60.74%	86.37%	29.84%	70.46%	92.05%	21.56%	79.55%
Centrifuge Enrichment	1.50%	0.42%	0.81%	0.44%	0.20%	1.68%	1.02%
Fuel Assembly	6.56%	1.30%	17.22%	14.86%	2.06%	20.82%	1.51%
Fuel Assembly Transport	<0.01%	<0.01%	<0.01%	<0.01%	<0.01%	<0.01%	<0.01%
Reactor Construction	23.79%	4.85%	19.22%	1.78%	1.68%	10.26%	7.30%
Reactor Decommissioning	0.64%	0.26%	19.20%	0.43%	1.41%	6.75%	0.17%
Spent Fuel Cask Manufacturing	<0.01%	0.02%	0.02%	0.04%	0.01%	0.14%	0.19%
Reactor Operations	0.23%	0.02%	0.34%	0.86%	0.05%	0.53%	<0.01%
Total (kg/MWh)	2.02E-06	3.50E-07	3.68E-02	7.59E-02	1.92E-01	9.95E-03	4.23E-03

Table 4-14: Process Contribution to Other Air Emissions for Gen III+ Nuclear Power

Process	Gen III+ Reactors						
	Pb	Hg	CO	NO_X	SO_2	VOC	PM
Uranium Extraction and Transport to Ports	4.93%	4.71%	9.17%	4.94%	1.86%	15.00%	6.27%
Transport Between Fuel Cycle Stages	<0.01%	<0.01%	0.01%	<0.01%	<0.01%	0.03%	<0.01%
Conversion	1.92%	1.85%	1.98%	2.85%	0.59%	11.79%	1.51%
Diffusion Enrichment	63.72%	83.84%	24.94%	49.22%	89.37%	15.12%	60.42%
Centrifuge Enrichment	1.58%	0.41%	0.67%	0.30%	0.20%	1.18%	0.78%
Fuel Assembly	6.88%	1.26%	14.40%	10.38%	2.00%	14.60%	1.15%
Fuel Assembly Transport	<0.01%	<0.01%	<0.01%	<0.01%	<0.01%	<0.01%	<0.01%
Reactor Construction	19.47%	7.44%	20.93%	30.91%	3.55%	33.55%	29.50%
Reactor Decommissioning	1.14%	0.44%	27.47%	0.51%	2.35%	8.10%	0.23%
Spent Fuel Cask Manufacturing	<0.01%	0.02%	0.01%	0.02%	0.01%	0.10%	0.15%
Reactor Operations	0.35%	0.03%	0.41%	0.86%	0.07%	0.54%	<0.01%
Total (kg/MWh)	1.12E-06	2.11E-07	2.57E-02	6.35E-02	1.16E-01	8.30E-03	3.26E-03

4.11 Energy Return on Investment

The energy return on investment (EROI) is the ratio of energy produced to total energy expended. The functional unit of this LCA is 1 MWh of delivered electricity and represents the amount of energy produced by the system. The total energy expended is the energy content of all resources (crude oil, coals, natural gas, uranium, and renewable resources) that enter the LC boundaries minus the useful energy in the final product (the functional unit).

EROI calculations are often applied to the LC of a primary fuels. For example, if the energy expended on the extraction, processing, and transport of a fuel is 10 percent of the useful energy in the fuel, the EROI can be expressed as a ratio of 10:1. In addition to the extraction and delivery of primary fuels, the boundaries of this analysis include the conversion of primary energy to electrical energy. The EROI for electric power systems is less than one because the conversion of thermal energy to electric energy expends more than half of the energy content of the energy that enters the power plant. For example, if a power plant has an overall efficiency of 33 percent, 67 percent of the energy entering the power plant is expended.

The calculation of energy return on investment (EROI) is presented in **Table 4-15** for the baseline existing and Gen III+ life cycles, plus those that use the centrifuge process for U.S. enrichment. Natural gas and coal are the primary energy sources for the uranium supply chain operations process, thus dominate the LC energy investment. Natural gas is used primarily in fuel fabrication construction and operation processes, conversion operation processes, and to a lesser extent to uranium in situ mining operations processes. Interestingly, though natural gas resource use is more than twice that of coal on an energy basis, emissions from combustion of coal dominate other LC flows such as GHGs and air pollutants. Hard coal feeds the diffusion enrichment process in the U.S., and coal-fired electricity supplies approximately 45 percent of the grid used to power other U.S. fuel cycle facilities. Crude oil resource is input primarily in the form of diesel used for installation and decommissioning activities. On a LC scale, the majority of crude oil resource is from construction and decommissioning of the nuclear plant. The EROI is slightly higher for the Gen III+ scenarios because of the higher burnup rate compared to existing reactors.

Table 4-15: Energy Return on Investment for Existing and Gen III+ Nuclear Power

Resource	Existing Technology		Gen III+	
	Default Enrichment Mix	Centrifuge Enrichment	Default Enrichment Mix	Centrifuge Enrichment
Useful Energy Produced, MJ	**1**	**1**	**1**	**1**
Total System Energy Input, MJ	**3.36**	**3.29**	**3.19**	**3.15**
Crude oil, MJ	0.01	0.01	0.01	0.01
Hard coal, MJ	0.08	<0.01	0.05	<0.01
Lignite, MJ	<0.01	<0.01	<0.01	<0.01
Natural gas, MJ	0.30	0.31	0.18	0.18
Uranium, MJ	2.97	2.97	2.96	2.95
Renewables	<0.01	<0.01	<0.01	<0.01
Total Energy Expended, MJ	**2.36**	**2.29**	**2.19**	**2.15**
EROI	**0.43:1**	**0.44:1**	**0.46:1**	**0.47:1**

If EROI is calculated only around the boundaries of raw material extraction and raw material transport, the EROI of uranium fuel elements is 2.55 for existing reactor technology and 4.43 for Gen III+. The reactor technology matters because the difference in burnup rates affects how much useful energy is extracted from a given mass of uranium fuel. This value represents the useful energy in delivered uranium fuel elements divided by the energy expended during its acquisition and transport. The data used for calculating the upstream uranium EROI values are shown in **Table 4-16**.

Table 4-16: Energy Return on Investment for Upstream Uranium

Resource	Existing Technology	Gen III+
Useful Energy Produced, MJ	**1**	**1**
Total System Energy Input, MJ	1.39	1.23
Crude oil, MJ	0.01	<0.01
Hard coal, MJ	0.08	0.05
Lignite, MJ	<0.01	<0.01
Natural gas, MJ	0.29	0.17
Uranium, MJ	1.01	1.01
Renewables	<0.01	<0.01
Total Energy Expended, MJ	**0.39**	**0.23**
EROI	**2.55:1**	**4.43:1**

4.12 LCA Conclusions

- At 39.5 kg of carbon dioxide equivalents (CO_2e)/MWh generated by existing reactors, and 25.8 kg CO_2e/MWh for Gen III+ reactors, the LC GHG emissions of nuclear power are a factor of 10 lower than integrated gasification combined cycle (IGCC) power plants with carbon capture and sequestration (CCS) and a factor of 30 to 40 lower than existing pulverized coal (EXPC) power plants.
- Gen III+ reactors achieve an approximately 13.7 kg CO_2e/MWh reduction in LC emissions over existing reactors, primarily due to an average of 1.7 times lower fuel input rates and a 2.6 percent higher thermal efficiency.
- The energy required for enrichment of uranium fuel accounts for the majority of LC GHG emissions in the existing U.S. nuclear reactor fleet. Gaseous diffusion enrichment is currently the only type used in the U.S., where 52 percent of uranium dioxide (UO_2) delivered to U.S. reactors is enriched. If the proposed centrifuge enrichment facility in Lea County, New Mexico were used for U.S. enriched fuel, the LC GHG emissions of existing nuclear power would be reduced to approximately 12.7 kg CO_2e/MWh for existing reactors and 10.2 kg CO_2e/MWh for Gen III+ reactors.
- The addition of long-term waste (which includes LLW and HLW) disposition to the existing nuclear power case increases the GHG results of nuclear power by 6.6 percent (42.1 compared to 39.5 kg CO_2e/MWh). The only difference between the baseline scenario and the long-term waste management scenario is the transport and construction requirements of long-term waste management.
- The addition of fuel reprocessing to the nuclear fuel cycle reduces the consumption of uranium 20 to 30 percent (IAEA, 2008b). However, this reduction only reduces the burdens contributed by uranium mining and milling. Reprocessed uranium requires re-enrichment in

order to increase its U-235 concentration to a level appropriate for LWR operation. The total reduction in the GHG emissions of LC Stage #1 is only 1.0 percent. When the entire LC is considered, reprocessing of nuclear fuel increases the GHG results by 4.1 percent (41.1 compared to 39.5 kg CO_2e/MWh). A choice to construct a centrifuge enrichment facility in the U.S. would be much more effective at reducing nuclear power LC GHG emissions than constructing a PUREX reprocessing facility.

- In the LC assessment model for nuclear power, the mass of enriched and fabricated nuclear fuel required to produce 1 MWh of delivered electricity is 4.66E-03 kg UO_2 for existing reactor technology and 2.72E-03 kg UO_2 for Gen III+ reactor technology. The corresponding amount of mined ore required to produce 1 MWh of electricity is 20.0 kg for existing reactor technology and 11.7 kg for Gen III+ reactor technology. The Gen III+ life cycle requires less fuel and ore per MWh of delivered electricity due to higher UO_2 burnup rates of Gen III+ reactors and higher thermal efficiency.
- High water withdrawal rates from existing facilities are the result of the contribution of plants that use once-through cooling. The existing reactor water withdrawal and consumption values are based on a composite of the cooling technologies employed by existing plants. While closed-loop cooling requires significantly less water withdrawal than once-through, the consumption is almost a factor of five higher (NETL, 2011).
- The three major LC processes responsible for the majority of radionuclide emissions to air are uranium extraction, uranium enrichment, and nuclear reactor operations. Radionuclide emissions are lower for Gen III+ nuclear power because of reduced consumption of UO_2 fuel due to a higher burnup rate and higher thermal efficiency in combination with and reduced emissions resulting directly from the operation of the facility.
- LC criteria and other air pollutant species of interest are also dominated by gaseous diffusion operation and power plant construction emissions. Combustion emissions come from hard coal electricity provided to the diffusion enrichment plant as well as diesel combustion in the construction and decommissioning processes. Mercury is heavily emitted as an effect of copper mining for power plant construction materials. Particulate matter is generated in installation and decommissioning activities. In general, the Gen III+ life cycle has lower air emissions than the existing plants due to higher UO_2 burnup rates of Gen III+ reactors and higher thermal efficiency.
- In total, the Gen III+ pathway land use GHG emissions are 0.094 kg CO_2e/MWh, which represents an 86 percent reduction in land use GHG emissions in comparison to the existing pathway (0.65 kg CO_2e/MWh). The magnitude of land use GHG emissions in comparison to total LC GHG emissions is small, but not negligible.

5 Cost Analysis of Nuclear Power

The life cycle costs (LCC) of nuclear power were calculated by performing a discounted cash flow analysis over the lifetime of a nuclear power plant.

5.1 Nuclear Power LCC Approach

The LCC analysis accounts for the significant capital and O&M expenses incurred by the nuclear power systems. The LCC calculates the cost of electricity (COE), which is the revenue received by the generator per net MWh during the first year of operation. The COE is the preferred cost metric of NETL's bituminous baseline (NETL, 2010a); however, the LCOE is also calculated in this analysis to provide a basis of comparison against past LCC analyses. The LCC calculations were performed using NETL's Power Systems Financial Model (PSFM), which calculates the capital charge factors necessary for apportioning capital costs per unit of production.

Cash flow is affected by several factors, including cost (capital, O&M, replacement, and decommissioning or salvage), book-life of equipment, federal and state income taxes, equipment depreciation, interest rates, and discount rates. Modified accelerated cost recovery system (MACRS) depreciation rates are used in this analysis. O&M costs are assumed to be consistent over the study period except for the cost of energy and feedstock materials determined by EIA.

Capital investment costs are defined as equipment, materials, labor (direct and indirect), engineering and construction management, and contingencies (process and project). Capital costs are assumed to be "overnight costs" (not incurring interest charges) and are expressed in 2007 constant dollars. Accordingly, all cost data are normalized to 2007 dollars.

The boundaries of the LCC are consistent with the boundaries of the environmental portion of the LCA as seen in **Table 5-1**, ending with the delivery of 1 MWh of electricity to a consumer. Unlike the LCA portion of the study, the LCC is only applicable to new nuclear power, meaning Gen III+ installations, not existing facilities. The capital costs for the nuclear power facilities account for all upstream economic activities related to the extraction, processing, and delivery of construction materials. The O&M costs of nuclear power account for the cost of fuel as well as labor and maintenance costs. Finally, all costs at the nuclear power facility are scaled according to the delivery of 1 MWh of electricity to the consumer, which includes a seven percent transmission and distribution loss between the power facility and the consumer.

Table 5-1: LCC Boundary Assumptions

Primary Subject	Assumption	Source
Study Boundary Assumptions		
Temporal Boundary	Variable	Present Study
Construction Cost Boundary	"Overnight"	Multiple
LC Stage #1: Raw Material Acquisition		
Extraction Location	Australia, Canada, U.S.	Present Study
Fuel Feedstock	UO_2, Mined in the Form of U_3O_8	Multiple
Uranium Mining and Milling Construction and Operation Costs	Included in Nuclear Fuel Delivery Price	Present Study
LC Stage #3: Power Plant		
Power Plant Location	General	Present Study
Net Electrical Output	Variable	Present Study
Onsite Storage	Plant Location	Present Study
Long Term Storage	Offsite	Present Study
LC Stage #4: Product Transport		
Transmission Line Loss	7%	Present Study
Transmission Grid Construction	Pre-existing	Present Study

5.2 Data Collection for LCC

There are a handful of studies that have examined the LC costs for nuclear power generation. The set below was used extensively in this analysis and provided guidance for calculating the LCC over ranges of input conditions.

INL, 2009 Advanced Fuel Cycle Economic Analysis of Symbiotic Light-Water Reactor Burner and Fast Bruner Systems: Shropshire, et. al., INL, January 2009. Idaho Falls, ID 83415

This analysis combines fuel cycle costs with the reactor costs (with associated uncertainties) to produce a total cost of electricity representing the levelized cost of a system strategy consisting of hundreds of reactors and all the supporting fuel cycle services. The common reactor-related costs consist of capital, operating, and decontamination and decommissioning costs. Fuel cycle costs include front-end and back-end costs, as well as costs associated with fuel recycling. A comparison of the costs used in this study were made to previous economic studies, including the OECD/NEA, "Advanced Nuclear Fuel Cycles and Radioactive Waste Management" report (OECD/NEA 2006) and the Massachusetts Institute of Technology (MIT) report on "The Future of Nuclear Power" (MIT, 2003).

INL, 2008 Advanced Fuel Cycle Cost Basis: Shropshire, et. al., INL, March 2008. Idaho Falls, ID 83415

One of the primary resources developed by the AFCI Systems Analysis is the "2008 Advanced Fuel Cycle Cost Basis" (AFC Cost Basis) report (Shropshire 2008). Since 2004, the AFCI Program has been developing an economic cost basis, and developing capabilities to perform engineering economic comparisons of advanced fuel cycles. The initial "AFC Cost Basis" report was produced in 2004, with annual updates in 2005, 2006, and 2007.

MIT, 2003 *The Future of Nuclear Power.* Massachusetts Institute of Technology (MIT) Cambridge, MA

The MIT study investigates a broad range of issues related to a successful nuclear power industry in the U.S. One area of the study provides a rigorous economic analysis for a number of fuel cycles.

MIT, 2009 *Update of the MIT 2003Future of Nuclear Power.* Massachusetts Institute of Technology (MIT) Cambridge, MA

This study updates the economics from the 2003 study.

5.3 Nuclear Cost Parameter Reconciliation

To validate and improve the accuracy of the cost parameter inputs specific to the nuclear PSFM results, a survey was sent to a cross section of nuclear experts from academia, government laboratories, industry, and trade associations requesting input on the parameters listed in **Table 5-2**.

Detailed responses were received from the following experts:

- **Dr. Edward Hoffman**, Nuclear Engineering Division, Argonne National Laboratory
- **Dr. John E. Parsons**, Executive Director, the MIT Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology
- **Richard J. Myers**, Vice President Policy Development, Nuclear Energy Institute
- **Dr. Kent Williams**, formerly of Oak Ridge National Laboratory
- **Kenneth Chuck Wade and Matthew Crozat**, U.S. Department of Energy, Office of Nuclear Energy

The survey responses, along with the NETL estimates were combined into a single set of low, expected, and high inputs. As opposed to using the highest and lowest values as the extremes of the parameter inputs, a mean and standard deviation were calculated for the unfiltered list of the nuclear cost parameters. Based on these values, potential outliers were identified by filtering values that were outside of the mean plus or minus two standard deviations. After the outliers were removed, a new mean and standard deviation were calculated for each of the parameter values. The expected value parameter input to the PSFM was chosen as the weighted mean, while the low and high values were calculated as the mean plus or minus one standard deviation. These values are also shown in **Table 5-2**.

Input from the survey responders indicated that the debt fraction and interest rate are highly dependent on the existence of federal loan guarantees for new nuclear power plant construction. With loan guarantees in place, the debt fraction is likely to increase and the interest rate decreases. Decommissioning costs were originally modeled in PSFM as a percentage of the total overnight

capital (TOC) cost of the power plant. Therefore, the value can change as either the cost of the plant changes or as the plant capacity changes. Half of the survey respondents recommended using a flat decommissioning fee for nuclear power, while the other half recommended estimating decommissioning as a percentage of TOC. For the purposes of this effort the second approach was modeled.

The cost parameters shown in **Table 5-2** are for an nth-of-a-kind reactor installation, meaning that lessons learned and efficiency improvements from early installations have been incorporated into factors like the TOC. Construction activities are currently underway for the first-of-a-kind Gen III+ reactors to be built in the U.S. and the first reactors to be constructed in nearly three decades. Vogtle units 3 and 4 are 1,100 MWe reactors based on the Westinghouse AP1000 design. The total cost for the project is estimated to be almost $14 billion (approximately $6,300/kW) with proposed staggered reactor startups in April 2016 and April 2017. The project is currently running under budget by $28 million; however, delays in the schedule will ultimately increase the project costs due to financing charges (Swartz, 2012).

Table 5-2: Nuclear Cost Parameter Survey Results

Parameter	Filtered Survey Results		
	Expected COE	Low COE	High COE
Nameplate Capacity (MW)	1,400	1817	983
Capacity Factor (%)	90.6%	94.4%	86.9%
Thermal Efficiency (%)	33.4%	35.8%	31.0%
Construction Time (Years)	5.6	4.2	7.1
Overnight Capital (TOC) Excluding Decommissioning Cost ($/kW)	4,267	3,269	5,264
Decommissioning Cost (%)	9.1%	6.4%	11.8%
Fixed O&M ($/kW/year)	69.1	57.0	81.2
Non-fuel Variable O&M ($/kW/year)	1.0	0.8	1.3
Debt Fraction (1 - Equity)	0.58	0.71	0.44
Interest Rate (%)	6.5%	5.3%	7.8%
Debt Term (Years)	23.1	29.1	17.2
Plant Lifetime (Years)	48.9	59.4	38.3
Depreciation Period (MACRS)	15	10	15
Tax Rate (%)	38.7%	36.4%	41.0%
Working Capital ($/kW/yr.)	30.0	13.3	46.7
O&M Escalation Rate	1.5%	1.0%	2.0%
Capital Cost Escalation During the Capital Expenditure Period (%)	2.2%	1.0%	3.4%
Nuclear Fuel Price ($/MMBtu)	0.61	0.36	0.86
Nuclear Waste Fee ($/kWh)	0.0012	0.0007	0.0017
Fuel Cost Escalation Rate (%)	1.2%	0.7%	1.7%
Waste Fee Escalation Rate (%)	0.38%	0.00%	0.89%
Required Internal Rate of Return on Equity (IRROE)	14%	12%	16%

5.4 Nuclear LCC Results

Results from the LCC analysis of Gen III+ nuclear power are provided in **Figure 5-1**. Scenario A represents a set of financial conditions that minimize COE, Scenario B represents the expected values for those parameters, and Scenario C is based on financial conditions that maximize COE. The financial parameters that were varied across the scenarios are shown in **Table 5-3**. The uncertainty bars on each result are based on the range of LCC plant operations parameters for a given financial scenario. The operations parameters that were varied for each scenario are shown in **Table 5-4**. The expected COE of Gen III+ nuclear power is $85.9/MWh, as shown in **Figure 5-1**. This value accounts for a seven percent electricity loss during transmission and distribution and is expressed in 2007 dollars. Nuclear power is capital intensive and the breakdown of the expected COE indicates that the capital portion accounts for 81 percent. The remaining cost components compose the remaining 19 percent of the $85.9/MWh, with 11 percent coming from fixed O&M, 1 percent from variable O&M, and 7 percent from fuel costs. As illustrated by **Figure 5-1**, the COE ranges from $42.8 to $186.2/MWh across all three financial and operating scenarios.

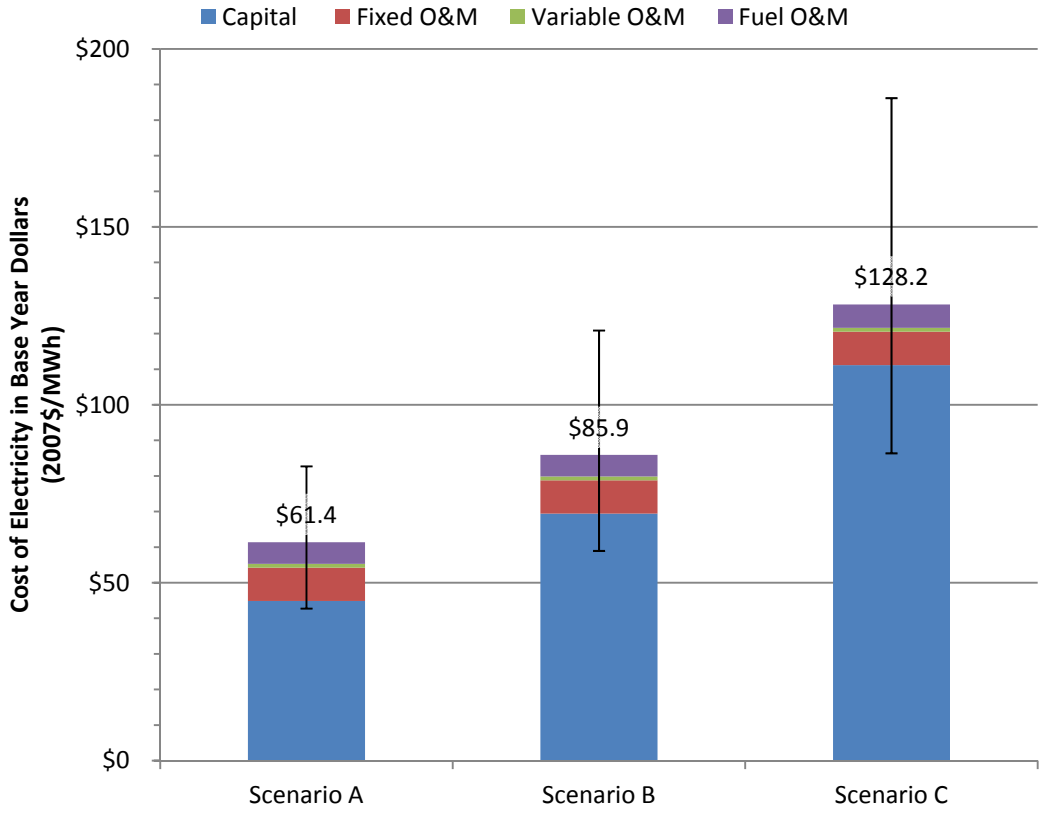
Table 5-3: LCC Financial Parameter Inputs for Gen III+ Nuclear COE Calculation Scenarios

Financial Parameter	Scenario A Minimize COE	Scenario B Expected COE	Scenario C Maximize COE
Interest Rate (%)	5.3%	6.5%	7.8%
Debt Term (Years)	29	23	17
Plant Life (Years)	59	49	38
Depreciation Period (MACRS)	10	15	15
Tax Rate (%)	36%	39%	41%
IRROE (%)	12%	14%	16%

Table 5-4: LCC Operations Parameter Inputs for Gen III+ Nuclear COE Calculation Scenarios

Operations Parameter	Low	Expected	High
Net Plant Capacity (MW Net)	983	1400	1817
Capacity Factor (%)	86.9%	90.6%	94.4%
Thermal Efficiency (%)	31.0%	33.4%	35.8%
Construction Period (Years)	4.2	5.6	7.1
Capital ($/kW)	3,269	4,267	5,264
Decommissioning Costs (% of TOC)	6%	9%	12%
Fixed O&M ($/kW/year)	57.0	69.1	81.2
Non-fuel Variable O&M ($/kW/year)	0.80	1.00	1.30
Fuel Price ($/MMBtu)	0.36	0.61	0.86
Waste Fee ($/kWh)	0.0007	0.0012	0.0017

Figure 5-1: Life Cycle COE for Gen III+ Nuclear Power



A sensitivity analysis was performed to see which financial and operations parameters have the largest impact on the COE. A selection of the parameters in **Table 5-3** and **Table 5-4** were varied one at a time from minimum to maximum, while the rest of the parameters remained at the expected value. **Figure 5-2** and **Figure 5-3** depict the results from the sensitivity analysis, divided into operations and financial parameters. **Figure 5-2** shows that financial parameters can have a more significant impact on the COE than the operational costs. The expected rate of return on investment has the largest impact on the COE for the financial parameters. A longer debt payback period and lower interest rate have significant benefits. An analysis of **Figure 5-3** shows that the installed capital and plant size have the greatest sensitivity and will have the largest impact on the COE, while fuel costs, O&M costs and decommissioning costs are not as sensitive.

Figure 5-2: Sensitivity of Gen III+ Nuclear Power to Financial Parameters

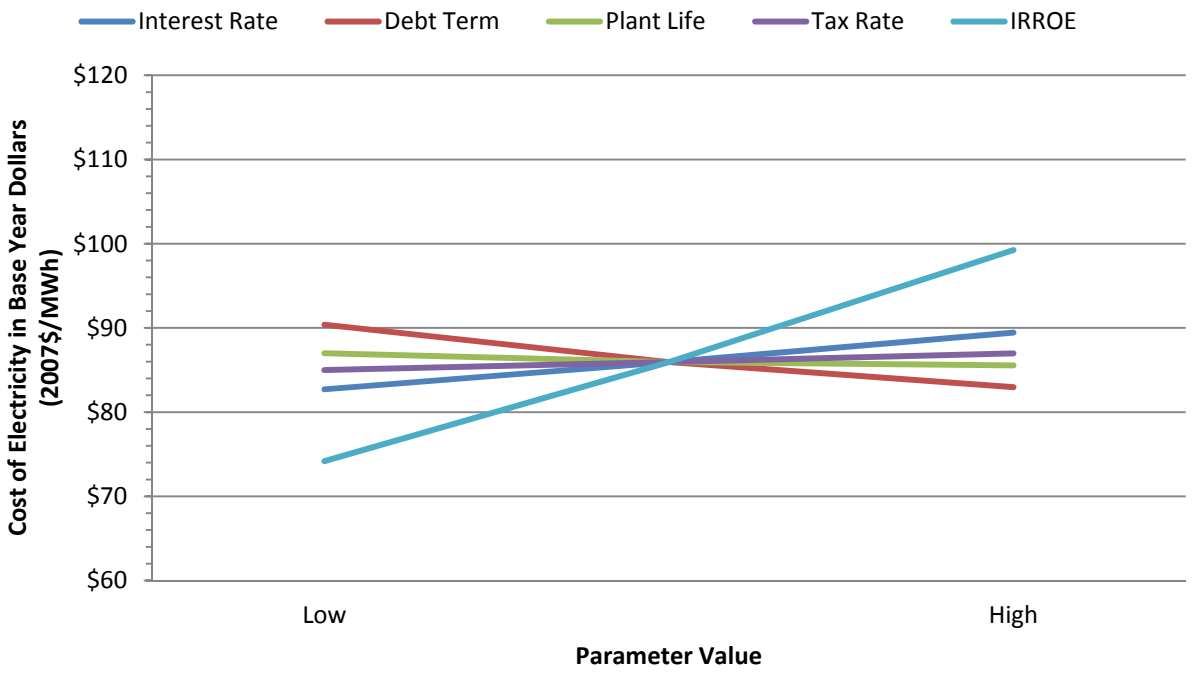
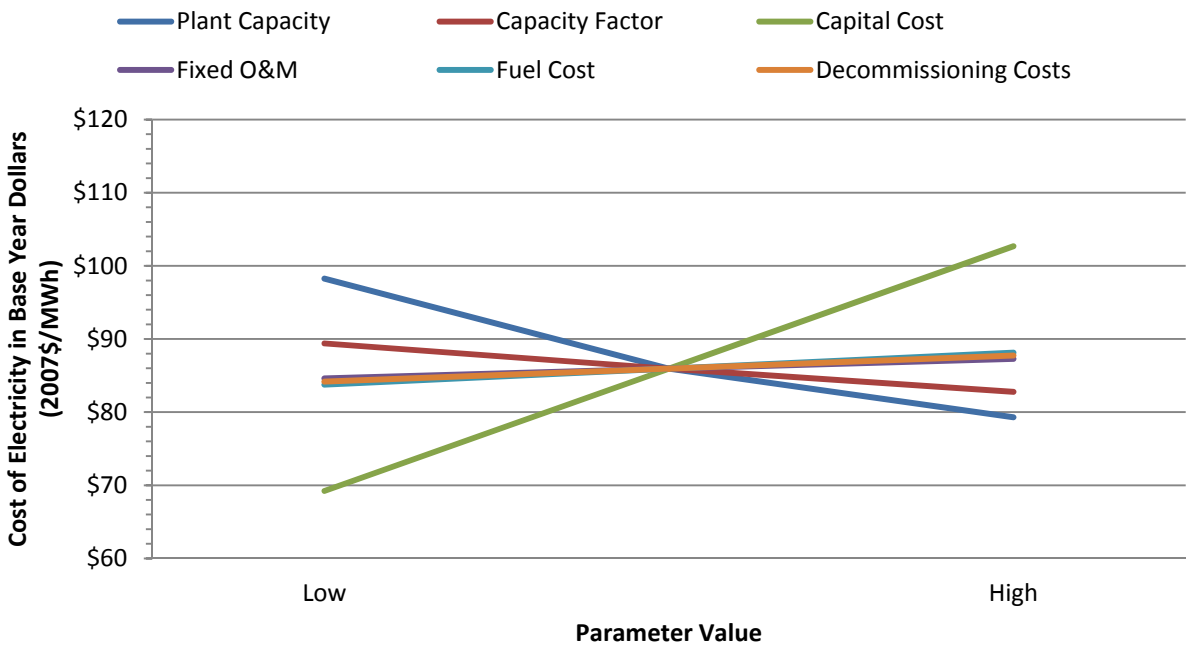


Figure 5-3: Sensitivity of Gen III+ Nuclear Power to Operations Parameters



6 Barriers to Implementation

One potential barrier to additional implementation of new nuclear power is the issue of storage of spent nuclear fuel. The Nuclear Waste Policy Act (NWPA) directed the DOE to site, construct, and operate deep geologic repositories to "provide a reasonable assurance that the public and the environment will be adequately protected from the hazards" of high-level radioactive waste (a by-product of U.S. nuclear weapons production), and spent nuclear fuel (removed from commercial power reactors). The NWPA limited the capacity of the first repository to 70,000 metric tons heavy metal (MTHM). The DOE was required to report to Congress by January 2010 on the need for a second repository (NWPA, 1983).

After a national site screening process in the early 1980s, three sites, in three different geologic media, (Yucca Mountain, Nevada, Deaf Smith County, Texas, and Richland, Washington) were selected by DOE in 1986, as candidates to undergo more detailed site characterization (U.S. Senate Committee on Environment and Public Works, 2006). In 1987, however, Congress amended the NWPA, directing DOE to characterize only Yucca Mountain. Characterization proceeded, and in 2002, President Bush approved Yucca Mountain as suitable for development as a repository, meaning DOE could proceed with developing a license application. In 2008, DOE submitted the license application to the NRC for authorization to construct the repository at Yucca Mountain (NRC, 2012). NRC started the years-long licensing proceeding. In March 2010, DOE filed a motion with the NRC's Atomic Safety and Licensing Board seeking permission to withdraw its 2008 application. In October 2010, the NRC began closure of its Yucca Mountain activities, and in 2011 suspended the licensing proceeding (NRC, 2011c).

In early 2010, President Obama directed the Secretary of Energy to form a Blue Ribbon Commission (BRC) on America's Nuclear Future. The BRC was to "conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle, including all alternatives for the storage, processing, and disposal of civilian and defense used nuclear fuel and nuclear waste" (Obama, 2010). The BRC final report released in January 2012 (BRC, 2012) included an estimate, prepared by EPRI, of current and projected amounts of spent nuclear fuel from commercial nuclear power plants. The EPRI estimate was 65,000 metric tons uranium (MTU) in 2010, increasing to 133,000 MTU by 2050 (BRC, 2012).

The BRC final report (BRC, 2012) contained recommendations for a comprehensive strategy to manage the "back-end" of the nuclear fuel cycle. The major recommendations are:

- A consent-based approach to siting future nuclear waste management facilities
- A new organization dedicated solely to implementing the waste management program and empowered with the authority and resources to succeed
- Access to funds nuclear utility ratepayers are providing for the purpose of waste management
- Prompt efforts to develop one or more geologic disposal facilities
- Prompt efforts to develop one or more consolidated storage facilities
- Prompt efforts to prepare for the eventual large-scale transport of spent nuclear fuel and high-level waste to consolidated storage and disposal facilities when such facilities become available.
- Support for continued innovation in nuclear energy technology and for workforce development.
- Active U.S. leadership in international efforts to address safety, waste management, non-proliferation, and security concerns.

DOE is in process of implementing these recommendations (Tetreault, 2012).

7 Risks of Implementation

Public fears of nuclear power are rooted in the perceived environmental and human health hazards from engineering failures at nuclear power plants, terrorism vulnerability, and nuclear weapons proliferation. This section outlines the technical issues of perceived nuclear power hazards and the potential for revived public resistance that may limit future implementation.

Three significant events in the history of commercial power are likely the strongest drivers for public resistance to the technology: Three Mile Island, Chernobyl, and, most recently, Fukushima. The 1979 Three Mile Island accident was the result of cooling system power failure and instrument malfunction. Overheating of the core caused a meltdown of the nuclear fuel rods, but the melting never breached the reactor containment structure. While the incident was the worst in U.S. nuclear history, according to the NRC, no deaths or injuries resulted. Improvements in safety and regulatory oversight followed the accident, including emergency response planning, reactor operator training, human factors engineering, and radiation protection (NRC, 2009c). In 1986, the Ukraine's Chernobyl accident resulted from flawed reactor control rod and safety system designs, as well as inadequate training of operators (IAEA, 1992). Human errors during a routine shutdown and test led to a steam explosion that released fission products into the atmosphere. Improvements in safety controls, reactor design information sharing across countries, and third- party safety testing ensure that this particular disaster is very unlikely to happen again (WNA, 2011a).

The recent Fukushima accident (March 11, 2011) reinforced fears that the consequences of a nuclear accident can be even more significant when the reactor is located in close proximity to human populations. The Fukushima accident was caused by the combination of an earthquake and tsunami that incapacitated backup power systems for plant cooling. The inadequate coolant flow to the reactors led to hydrogen explosions at three reactors and release of an uncertain volume of radioactive gas (IAEA, 2011). It is very likely that this engineering failure will drive a resurgence of strong and persistent anti-nuclear power activism in the U.S. A spike in reporting activity on nuclear power surrounds the date of the event: a total of seven New York Times articles focused on nuclear power the month before the event (February 2011); 95 articles were published by the same periodical in March. While perceived dangers from this accident were not always consistent with physical realities, the negative effect to public perception of the technology is unambiguous.

A comparison of U.S. and Japanese nuclear engineering strategies provide context in evaluating these perception issues. The U.S. and Japanese commercial nuclear programs have similar plant types (PWRs and BWRs) and regulatory structure. However, the U.S. and Japanese nuclear programs diverged in the 1980s when the U.S. stopped building new reactor technologies and focused on operational improvements and cost savings, while Japan continued to build and design newer reactors. The Japanese approach led to the development of a new reactor type (Advanced Boiling Water Reactor) in the 1990s, and the Japanese nuclear industry expanded its global capability when Toshiba acquired the Westinghouse nuclear division in 2006 (Toshiba is the world's largest reactor manufacturer). It is possible that if the Fukushima facility had adhered to international best practices, the incident may have been avoided (Acton & Hibbs, 2012). One of the international best practices is the use of plant-specific probabilistic safety assessments; however, this practice has only been used on an experimental basis in Japan. Based on this approach, Japanese nuclear power plants were only prepared for a short-term (30 minute) loss of power. Following a flooding event at the Blayais nuclear power plant in France that occurred in 1999, many facilities upgraded the protection measures for emergency plant power supplies, but unfortunately, Japan did not make upgrades to the Fukushima facility. The Fukushima incident is a good example of how engineering exceptions can

sometimes lead to unforeseen problems, such as inappropriate placement and inadequate protection of emergency diesel generators.

In addition to engineering failures, public concerns related to nuclear power are also rooted in fears of terrorist attacks or nuclear weapons proliferation. The reprocessing of spent fuel is the only activity in the LC of nuclear power that could produce a material (specifically, plutonium) that could be easily diverted to weapons use. However, the U.S. does not currently have any nuclear fuel reprocessing plants, which makes the conversion of nuclear material to weapons-grade material prohibitively expensive (IAEA, 2008b). Following the 9/11 terrorist attacks, the NRC issued requirements for security upgrades at licensed facilities including active reactors (NRC, 2008). In addition to physical infrastructure changes including barriers and vehicle checks, the facilities also focused on enhanced training of security forces and added new posts along with restrictions to site entry. The NRC initiated a Threat Advisory and Protective Measures System that provided facilities with actions corresponding to the threat level as assessed by the Department of Homeland Security.

Aside from the perceptions regarding the potential release of radioactive materials in the event a nuclear accident, negative perceptions can also be based on the characteristics of steady-state nuclear systems. The relative impacts of various nuclear events are compared in **Table 7-1**, which is based on NRC data (NRC, 2011b). According to this data, annual exposures due to living in high altitude environments are responsible for higher radiation increases (over average U.S. annual) than the maximum regulated exposure from living near nuclear facilities. Both exposure potentials are orders of magnitude below the threshold generally considered responsible for increased incidences of cancer. Nuclear facility radioactive emissions to air are measured regularly and must report releases above the regulated limit. The National Cancer Institute concluded in 1991 that no increased risk of death resulted in counties adjacent to nuclear facilities (Jablon, Hrubec, & Boice, 1991). Cancer rates in communities surrounding facilities throughout the nuclear fuel cycle are currently being investigated by the National Academy of Sciences (The National Academies, 2011).

Table 7-1: Radiation Exposures and Biological Effects (NRC, 2011b)

Cause	Dose (mrem/year)	Biological Effect
Highest dose to worker/firefighter recorded from Chernobyl accident	1,600,000	Death
Threshold for high dose with potential to cause death	350,000	Potential for 50% of a population to die within thirty days
Threshold for high-dose with high potential to cause cancer	50,000	Leukemia, breast, bladder, colon, liver, lung, esophagus, ovarian, multiple myeloma, and stomach cancers
Threshold below which dose is considered "low"	10,000	No determined effect
Occupational radiation exposure to adults working with radioactive material (in the U.S.)	5,000	
Annual dose in Denver, CO (higher altitude)	1,000	
Average annual U.S. dose	620	
Portion of average annual dose that is from natural sources	310	
NRC limit for maximum radiation exposure from operating facilities to individual members of the public	100	

8 Expert Opinions

The opinions from academic institutions and industry organizations mirror the key issues identified by the literature search of this analysis. Recent statements by researchers and industry experts have focused on safety of existing reactors following the Fukushima event, the potential of small modular reactors, the high capital cost of new reactors, and competitiveness with natural gas.

Following the accident at Fukushima, many questions have been asked about the safety of operating nuclear reactors. Acton and Hibbs of the Carnegie Endowment for International Peace completed a thorough review of the incident at Fukushima and have identified international best practices that may have limited or altogether prevented the accident (Acton & Hibbs, 2012). If the risk assessment conducted by authorities was performed in line with international best practices, it may have predicted the threat of a large-scale tsunami hitting the facility. Acton and Hibbs assert that if the facility implemented safety upgrades following the lessons learned from a flooding incident at a nuclear power plant in France a major accident could have been avoided. The U.S. nuclear industry is in the process of assessing the protective measures across the fleet, especially pertaining to the robustness of backup power sources in the event of flooding or some other loss-of-power event.

The WNA has seen interest in small modular reactors (SMRs) grow substantially in the U.S. and around the world as small and large utilities anticipate the need to replace and augment existing electricity generation assets (WNA, 2011d). The U.S. DOE has acknowledged the potential for SMRs to replace aging coal facilities (DOE, 2011). According to Christopher Mowry, Vice President of Babcock and Wilcox Nuclear Energy, SMRs may utilize some of the existing site infrastructure when used to replace existing generating assets, which further reduces costs (Mowry, 2011).

According to Rosner, Goldberg, and Hezir of the University of Chicago, the cost gap between SMRs and conventional large-scale nuclear reactors has narrowed as the cost of new Gen III+ plants has escalated substantially (Rosner, Goldberg, & Hezir, 2011). SMR designs incorporate passive control systems like natural circulation which makes them inherently safer than the existing nuclear fleet. Another potential advantage of SMRs is that, based on their size, they can be pre-fabricated and shipped by rail and truck to the site. A final advantage compared to conventional plants is a longer operation period between refueling (42-48 months) (WNA, 2011d).

Overnight capital costs for nuclear facilities range from $3,000-5,000/kW, and the installation of cooling systems and other site-specific requirements can push those costs to as high as $6,000/kW. According to the MIT study on the Future of Nuclear Power, estimated construction costs have been increasing at a rate of 15 percent per year (MIT, 2009). These high costs, driven by risk and associated financing structure, have halted several projects and resulted in temporary setbacks at proposed new nuclear installations. In addition to the high capital costs associated with new nuclear reactor construction, the other dominant factor that has stalled the nuclear renaissance has been the low cost of natural gas. According to nuclear market analysts at Standard & Poor’s (Standard & Poor's, 2010), the cost of natural gas needs to be higher than $6/MMBtu for new nuclear power generation to be economically favorable. Further, the recent engineering failures at the Fukushima power plant will likely increase the safety concerns for nuclear power plants, which will lead to high installed costs for nuclear power plants.

8.1 Comparison to Other Nuclear LCAs

There is existing research on the LC impacts of nuclear power published in several peer-reviewed journals. This section reviews the methods and conclusions of a selection of those reports.

Life cycle GHG emission analysis of power generation systems: Japanese case (Hondo, 2005)

Hondo performed an LCA of nuclear power in Japan based on a BWR. Uranium ore was assumed to originate in Canada and Australia; however, there was no mention of modeling differences based on the type of mine. Enrichment of uranium was modeled as a mix of gaseous diffusion (89 percent), occurring in the U.S. and France, and gas centrifuge (11 percent), occurring in Japan, the Netherlands, and the UK. Similar to this study, Hondo found that the majority of LC GHG emissions, 62 percent overall, could be attributed to the energy requirements of the uranium enrichment process. Fuel fabrication facilities were assumed to be located in Japan. Similar to this study, Hondo modeled both the initial construction and decommissioning of the power plant. In addition, low-level waste from enrichment was modeled based on the storage container requirements. The only difference between the work by Hondo and this study was the assumed fuel enrichment and burn up rate in the reactor. Hondo calculated the base case LC GHG emissions to be 24.2 kg CO_2e/MWh. In addition, a future case, which modeled the potential for reprocessing was also considered. The LC GHG emissions for this case were determined to be 22.2 kg CO_2e/MWh. The increase in GHG emissions related to the construction and operations requirements for the reprocessing facility were offset by a reduction in the amount of primary uranium fuels required.

Greenhouse-gas emissions from solar electric- and nuclear power: A life-cycle study (Fthenakis and Kim, 2007)

Fthenakis and Kim completed an LCA for an 1100 MWe nuclear power plant. The study by Fthenakis and Kim considers three cases based on differences in uranium ore grades (0.05 percent U to 12.7 percent U), the carbon intensity of electricity used for the enrichment of uranium, and the replacement frequency of materials associated with ongoing operations of the nuclear power plant. It was assumed that the uranium that was enriched was a mix of gaseous diffusion enrichment in the U.S., imports from Europe, and downblending of nuclear weapons into nuclear grade fuel. Similar to this study, Fthenakis and Kim found that enrichment represented the majority of LC GHG emissions for nuclear power in each case they investigated, representing 11 to 20 kg CO_2e/MWh. Their study included estimates for operations, specifically, fuel use for auxiliary equipment, miscellaneous supplies, makeup materials and chemicals. The range of LC GHG emissions for the operations stage was estimated to be 2.5 to 10.8 kg CO_2e/MWh, depending on replacement frequency and changes in operations. This study did not model the use of fuels and materials during the operation stage of the nuclear power plant, which explains some of the differences in results. Overall, the range of LC GHG emissions calculated by Fthenakis and Kim was 16 to 55 kg CO_2e/MW and the baseline was 25 kg CO_2e/MWh.

Life cycle energy and greenhouse gas emissions of nuclear energy: A review (Lenzen, 2008)

In this study, Lenzen reviewed a number of existing LCA studies regarding nuclear power. Assumptions regarding reactor type, enrichment technology, location, and reactor lifetime differed significantly amongst the studies.

Some of the most notable differences pertained to the mining of uranium. Energy requirements for uranium mining differ by a factor of two for shale and ore, with ore requiring the higher amount of

energy per ton of uranium. As an example, uranium is mined as a byproduct of copper in the Olympic Dam in Australia; if uranium is mined as a co-product and all of the emissions are attributed only to uranium, then those emissions have been inappropriately overstated. This study did not consider mining uranium as a co-product of other valuable materials. Lenzen found that the construction of gas centrifuge enrichment plants requires almost 50 percent more energy than diffusion plants. This study assumed that the construction impacts modeled after the EIS for the gas centrifuge in Lea County, NM, were the same for gaseous diffusion. Another process variable that Lenzen identified has to do with the process of reacting UO_2 with HF can occur in either a dry kiln or via a wet process, which requires considerably less energy. This study used data based on the Cameco facility in Port Hope, which utilizes the wet process.

The majority of the LCA studies reviewed focused on PWRs; however, it is important to note that emissions associated with the construction of advanced designs, like breeder reactors, heavy water reactors, and sodium cooled reactors, are likely higher because of the more complex design and emissions associated with production of advanced coolants. Several of the studies reviewed by Lenzen modeled the energy requirements for high level waste disposal based on costs. This study did not address model high level waste beyond the storage requirements. The range of values for studies reviewed by Lenzen was 10-130 kg CO_2e/MWh with an average of 65 kg CO_2e/MWh. The results of this study are in the lower half of the range found by Lenzen; however, based on the type of reactor and assumptions regarding fuel cycle processes, the differences are explainable.

Valuing the greenhouse gas emissions from nuclear power: A critical survey (Sovacool, 2008)

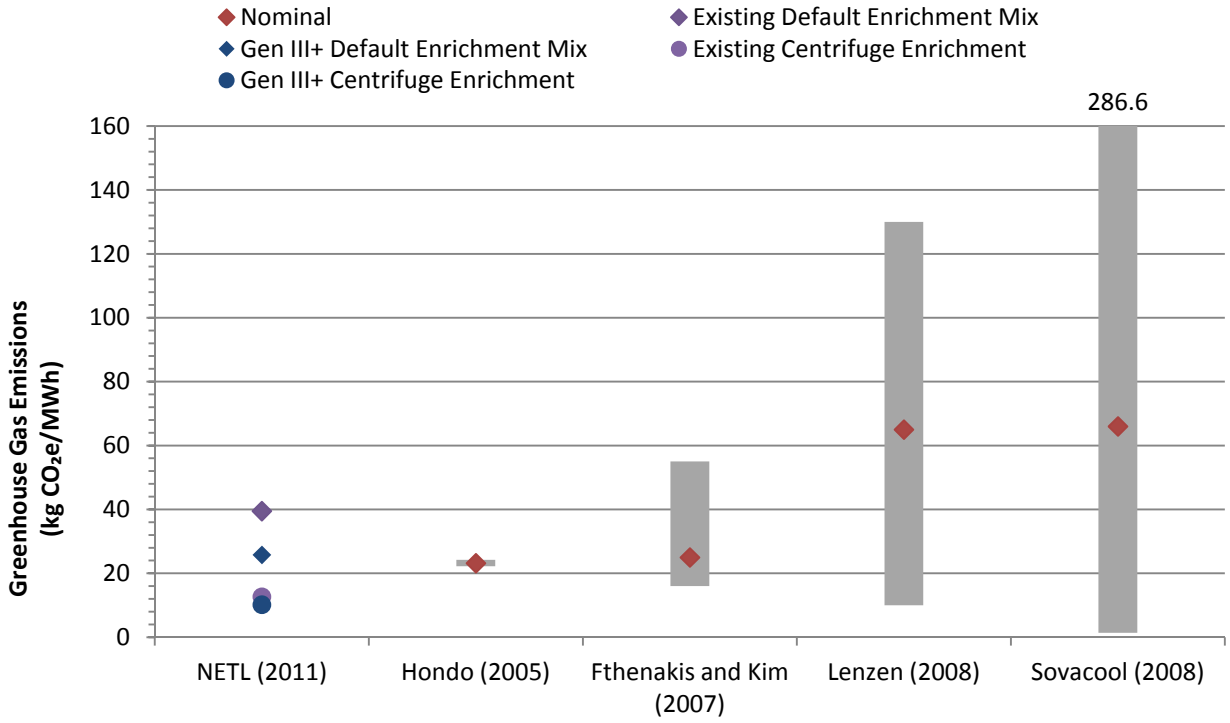
Sovacool reviewed over 100 different LCA studies of the nuclear power generation process dating back to the 1980s. Based on set of criteria regarding the age of the study, accessibility, and research method, he eliminated the majority of the studies and focused on 19 in particular. The average value for LC emissions reported for the nuclear power cycle was 66 kg CO_2e/MWh of energy produced and the range of values from the studies extended from 1.4 to 288 kg CO_2e/MWh. Sovacool identified that open pit mines produce more methane gas than underground excavation activities and this can have a significant impact on GHG emissions because of the increased global warming potential of methane. This study did not account for methane emissions related to open pit uranium mining, which could explain some of the differences in results. The location of the mine influences the types of fuel that are used there, for example diesel generators versus centrally generated power.

Heavy water reactors were found to have significantly lower GHG emissions than PWRs (15 versus 66 kg CO_2e/MWh) because of their ability to utilize low-grade nuclear fuels. This is intuitive based on the discussions regarding the proportion of GHG emissions that are accounted for during the enrichment stage of the nuclear fuel cycle. Other LCA studies found that the production impacts associated with the heavy water required by the CANDU reactors outweighed the savings that were achieved by using lower grade fuel.

Another important assumption regarding the reactor plant operation in the LCA studies reviewed was plant lifetime. Most studies utilized values ranging from 30 to 60 years. With a significant portion of GHG emissions emitted during the plant construction and decommissioning phases it is important to consider differences in plant lifetime between studies. This critical assumption explains a portion of the variability in GHG emissions figures determined from the various studies. Sovacool found that a 10 year change in plant lifetime from 30 to 40 years results in a 23 percent decrease in the GHG emissions factor. This study assumed a plant lifetime of 60 years, which would explain why the LC GHG emissions are on the lower end of the range identified by Sovacool.

Figure 8-1 shows the comparative GHG emissions from the four studies discussed above. There are four results presented for this study based on permutations of Existing and Gen III+ plants and the mix of gaseous diffusion and centrifuge enrichment and 100 percent centrifuge enrichment. These results do not include the nuclear waste management scenarios. The average and range of results are presented for the other studies.

Figure 8-1: Comparison of Nuclear Life Cycle Greenhouse Gas Results with Other Studies



9 Summary

This analysis provides insight into the role of nuclear power as a future energy source in the U.S. The criteria used for evaluating the role of nuclear power are as follows:

- Resource Base
- Growth
- Environmental Profile
- Cost Profile
- Barriers to Implementation
- Risks of Implementation
- Expert Opinions

Key conclusions for these criteria are summarized below.

The U.S. **resource base** of nuclear power includes domestic and imported sources of uranium. The U.S. consumes 16,500 tonnes of uranium per year (IEA/NEA, 2010). With domestic resources of 207,000 tonnes of uranium, current consumption rates will deplete the domestic supply within 12 years, if imports are excluded. Fortunately, the majority of the global supply of uranium is politically stable, so the U.S. can continue to rely on imported uranium originating mostly from Australia, Kazakhstan, Canada, and Russia. Based on the current world demand and known recoverable reserves, there are approximately 80 years of virgin supply at a recoverable cost of less than $130/kg U. If demand were to increase to the level of the IAEA 2030 forecasted high of 807 GWe of nuclear generating capacity, there would be 40 years of virgin supply at a recoverable cost of less than $130/kg U based on known recoverable reserves. Additionally, recent reports by the nuclear industry indicate that the discovery of new conventional sources of uranium is likely. Finally, the supply outlook for uranium is not a key driver in the stability of the nuclear supply chain. This is demonstrated by the sensitivity of the cost of nuclear power to increase in uranium prices; if the price of uranium increases by 100 percent, the corresponding cost increase of nuclear power will be only 10 percent.

The **growth** of nuclear power in the U.S. depends on how many existing nuclear power plants will undergo license renewals, how many are commissioned, and how many are decommissioned, as there is little room for increased output from existing facilities. Based on other projections reviewed (EIA, IAEA, IHS, and WNA), the forecasted nuclear capacity from those organizations ranges from 110 to 180 GW in 2035 based on a 2010 capacity of approximately 101 GW.

The **environmental profile** of this analysis focuses on the LC GHG emissions of existing and Gen III+ nuclear power. At 39.5 kg of carbon dioxide equivalents (CO_2e)/MWh generated by existing reactors, and 25.8 kg CO_2e/MWh for Gen III+ reactors, the LC GHG emissions of nuclear power are a factor of 10 lower than integrated gasification combined cycle (IGCC) power plants with carbon capture and sequestration (CCS) and a factor of 30 to 40 lower than existing pulverized coal (EXPC) power plants. Gen III+ reactors achieve an approximately 13.7 kg CO_2e/MWh reduction in LC emissions over existing reactors, primarily due to an average of 1.7 times lower fuel input rates and a 2.6 percent higher thermal efficiency.

The energy required for enrichment of uranium fuel accounts for the majority of LC GHG emissions in the existing U.S. nuclear reactor fleet. Gaseous diffusion enrichment is currently the only type used in the U.S., where 52 percent of uranium dioxide (UO_2) delivered to U.S. reactors is enriched. If the proposed centrifuge enrichment facility in Lea County, New Mexico were used for U.S. enriched

fuel, the LC GHG emissions of existing nuclear power would be reduced to approximately 12.7 kg CO_2e/MWh for existing reactors and 10.2 kg CO_2e/MWh for Gen III+ reactors.

The addition of long-term waste (which includes LLW and HLW) disposition to the existing nuclear power case increases the GHG results of nuclear power by 6.6 percent (42.1 compared to 39.5 kg CO_2e/MWh). The only difference between the baseline scenario and the long-term waste management scenario is the transport and construction requirements of long-term waste management. The addition of fuel reprocessing to the nuclear fuel cycle reduces the consumption of uranium 20 to 30 percent (IAEA, 2008b). However, this reduction only reduces the burdens contributed by uranium mining and milling. Reprocessed uranium requires re-enrichment in order to increase its U-235 concentration to a level appropriate for LWR operation. The total reduction in the GHG emissions of LC Stage #1 is only 1.0 percent. When the entire LC is considered, reprocessing of nuclear fuel increases the GHG results by 4.1 percent (41.1 compared to 39.5 kg CO_2e/MWh). A choice to construct a centrifuge enrichment facility in the U.S. would be much more effective at reducing nuclear power LC GHG emissions than constructing a PUREX reprocessing facility.

The results in the above paragraph do not account for the GHG emissions from land use change. The GHG emissions from direct and indirect land use change range from 0.094 – 0.65 kg CO_2e/MWh depending for Gen III+ and existing plants, respectively. Thus, the land use GHG emissions for nuclear power increases the baseline scenario GHG emissions from 39.5 to 40.2 kg CO_2e/MWh.

The **cost profile** of Gen III+ nuclear power was based on a discounted cash flow analysis that calculated an expected COE of $85.9/MWh. (COE is defined as the revenue received by the generator per net MWh during the first year of operation). This result is based on a capital cost of $4,267/kW, a capacity factor of 90.6 percent, and a seven percent loss of electricity during transmission and delivery. Nuclear power is capital intensive and the breakdown of the expected COE indicates that the capital portion accounts for 81 percent. The remaining cost components compose the remaining 19 percent of the $85.9/MWh, with 11 percent coming from fixed O&M, 1 percent from variable O&M, and 7 percent from fuel costs. The COE ranges from $42.8 to $186.2/MWh across the range of financial and operations parameters.

The main **barrier to implementation** to new nuclear power is the issue of storage of spent nuclear fuel. The Nuclear Waste Policy Act (NWPA) directed the DOE to site, construct, and operate deep geologic repositories to “provide a reasonable assurance that the public and the environment will be adequately protected from the hazards” of high-level radioactive waste (a by-product of U.S. nuclear weapons production), and spent nuclear fuel (removed from commercial power reactors). The NWPA limited the capacity of the first repository to 70,000 metric tons heavy metal (MTHM).

In 2008, DOE submitted the license application to the NRC for authorization to construct the repository at Yucca Mountain (NRC, 2012). NRC started the years-long licensing proceeding. In March 2010, DOE filed a motion with the NRC’s Atomic Safety and Licensing Board seeking permission to withdraw its 2008 application. In October 2010, the NRC began closure of its Yucca Mountain activities, and in 2011 suspended the licensing proceeding (NRC, 2011c).

In early 2010, President Obama directed the Secretary of Energy to form a Blue Ribbon Commission (BRC) on America’s Nuclear Future. The BRC was to “conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle, including all alternatives for the storage, processing, and disposal of civilian and defense used nuclear fuel and nuclear waste” (Obama, 2010). The BRC final report released in January 2012 (BRC, 2012) included an estimate, prepared by EPRI, of current and projected amounts of spent nuclear fuel from nuclear power plants. The EPRI estimate was 65,000 metric tons uranium (MTU) in 2010, increasing to 133,000 MTU by 2050 (BRC, 2012).

The **risks of implementation** are rooted in the uncertainties surrounding nuclear power. Current U.S. nuclear policy has not resolved the long-term uncertainties for spent fuel disposition and reprocessing. NETL's LCA of nuclear power demonstrates that spent fuel disposition does not introduce significant environmental burdens to the LC of nuclear power, and from a GHG perspective, a change in uranium enrichment technologies would be more beneficial than fuel reprocessing. Other uncertainties include the costs of nuclear power, which are affected by security and safety concerns that are unique to the nuclear fuel cycle. Until there is more certainty on waste management, security, and safety concerns, investors will shy away from nuclear power. Finally, even if the issues of long-term waste disposition and cost uncertainty are resolved, perception-based issues will be the final barrier to additional implementation of nuclear power.

The perception of nuclear power is anchored in three nuclear events that have occurred within recent history: the 1979 Three Mile Island accident, the 1986 Chernobyl accident, and the 2011 Fukushima accident. A comparison of the U.S. and Japanese nuclear programs shows that the U.S. has implemented safety systems that have not yet been implemented in Japan. Public concerns about nuclear power are also rooted in fears of terrorist attacks and nuclear weapon proliferation. Again, LCA demonstrates that the environmental burdens of steady-state nuclear operations do not pose a significant risk. Additionally, the levels of radiation from steady-state nuclear power are the same magnitude as radiation from natural sources and are hundreds of times lower than the exposure threshold for cancer risks (NRC, 2011b). However, the potentially high impacts of adverse nuclear events overshadow the fact that their occurrence is rare.

Risks also include failures of nuclear power systems that could lead to radiological releases or other nuclear events. From an LCA perspective, the environmental burdens of the steady-state nuclear power LC do not pose a significant environmental risk. However, while the chances of adverse nuclear events are small and newer nuclear technologies are inherently safer than older technologies, the scale of a nuclear event can have far-reaching environmental and societal risks.

Expert opinions have focused on safety of existing reactors following the Fukushima event, the potential of small modular reactors, the high capital cost of new reactors, and competitiveness with natural gas. Some experts believe that the incorporation of international best practices for both risk assessment and mitigation can prevent future catastrophic accidents like Fukushima. The nuclear renaissance has slowed due to the increasing capital costs of new reactors and the low price of natural gas.

Nuclear power provides a stable source of baseload power in the U.S. with a GHG emissions footprint that is similar to that of most renewable power sources. In the last decade, nuclear power plants have had an average capacity factor 90 percent. Maintaining the existing share of the U.S. electricity demand with nuclear power depends on the number of existing facilities that receive operating license extensions and the number of planned and approved new reactors that are actually constructed. While the global supply of uranium is large and stable, the high initial capital investment required for the construction of new reactors, historically low natural gas prices have slowed the nuclear renaissance in the U.S. The storage of spent nuclear fuel also continues to be a major concern since progress on the Yucca Mountain nuclear repository was officially halted in 2010. The growth and perception of nuclear power is also impacted by the three nuclear events that have occurred within recent history: the 1979 Three Mile Island accident, the 1986 Chernobyl accident, and the 2011 Fukushima accident. While the chances of adverse nuclear events are small and newer nuclear technologies are inherently safer than older technologies, the scale of a nuclear event can have far-reaching environmental and societal risks.

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Appendix A:
Constants and Unit Conversion Factors

List of Tables

Table A-1: Common Unit Conversions

Category	Input			Output	
	Value	Units		Value	Units
Mass	1	lb.	=	0.454	kg
	1	Short Ton	=	0.907	Tonne
Distance	1	Mile	=	1.609	km
	1	Foot	=	0.305	m
Area	1	$ft.^2$	=	0.093	m^2
	1	Acre	=	43,560	$ft.^2$
Volume	1	Gallon	=	3.785	L
	1	$ft.^3$	=	28.320	L
	1	$ft.^3$	=	7.482	Gallons
Energy	1	Btu	=	1,055.056	J
	1	MJ	=	947.817	Btu
	1	kWh	=	3,412.142	Btu
	1	MWh	=	3,600	MJ

Table A-2: IPCC Global Warming Potential Factors (Forester, et al., 2007)

IPCC GWP Factor	Vintage	20 Year	100 Year	500 Year
CO_2	2007	1	1	1
CH_4	2007	72	25	7.6
N_2O	2007	289	298	153
SF_6	2007	16,300	22,800	32,600
CO_2	2001	1	1	1
CH_4	2001	62	23	7
N_2O	2001	275	296	156
SF_6	2001	15,100	22,200	32,400

Table A-3: Uranium Ore Concentration and Enrichment Parameters

Fuel Cycle Stage	Parameter	Value
Mining	Uranium Concentration in Ore	2580 ppm U
	Ore Uranium Composition	U_3O_8
	Concentration of U-235 in U_3O_8	0.70%
Enrichment	Feed Concentration of U-235	0.70%
	Product Concentration of U-235	5.00%
	Tails Concentration of U-235	0.25%
	Uranium Feed to Product Ratio (kg U feed/kg U product)	10.40
	Separative Work Units Required (kg SWU/kg U product)	7.90
	Uranium Composition During Enrichment	UF_6

Appendix B:
Data for Nuclear Power Modeling

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B.1 Raw Material Acquisition

Raw material acquisition considers several processes, including uranium mining (underground, open pit, or in-situ leach), uranium conversion, uranium enrichment, UF_6 storage and transport, and uranium fuel fabrication. These are described in the following text.

B.1.1 Uranium Mining

The following categories of uranium mines are considered: underground mines, open pit mines, and in-situ leach mines. Mine construction is also considered. These processes are described in the following discussion.

B.1.1.1 Underground Mine

Construction material inputs for the underground uranium mine are based on material lists provided in the Energy Technology Characterizations Handbook (DOE, 1983). Where additional materials are known to be shared between underground mining of coal and uranium, surrogate data was used from existing Illinois No. 6 coal mine DS and DF sheets (NETL, 2010). **Table B-1** lists the materials used in the construction of these mines. Installation of the underground mine is approximated using an existing NETL unit process for installation of an underground coal mine. Because of the low significance of mine installation in the life cycle (LC) emissions of nuclear power, this data limitation is acceptable.

Table B-1: Material Inputs for Underground Uranium Mine Construction (DOE, 1983, NETL, 2010)

Flow Name	Value	Units
Aluminum (Metals)	2.04E-03	kg/kg yellowcake
Asphalt (Concrete_Cement)	1.11E-03	kg/kg yellowcake
Cast iron (Metals)	7.13E-03	kg/kg yellowcake
Concrete, ready mix, R-5-0 (Concrete_Cement)	8.06E-01	kg/kg yellowcake
Copper (Non renewable elements)	2.96E-03	kg/kg yellowcake
Hot-dip Galvanized Steel (Metals)	1.52E-06	kg/kg yellowcake
Polyvinylchloride-tube (PVC) (Plastic parts)	1.30E-07	kg/kg yellowcake
Rebar Wire Rod (Metals)	1.41E-06	kg/kg yellowcake
Steel cold rolled (St) (Metals)	5.15E-01	kg/kg yellowcake
Steel plate, BF (85% Recovery Rate) (Metals)	1.80E-04	kg/kg yellowcake
Steel, Stainless, 316 2B (80% Recycled) (Metals)	6.77E-08	kg/kg yellowcake
Styrene-butadiene-rubber (SBR) (Plastics)	4.45E-07	kg/kg yellowcake

B.1.1.2 Open Pit Mine

Operations for the open pit uranium mine are based primarily upon the operation of the Ranger Mine in Australia. The Ranger Mine produces twelve percent of the world's uranium with an annual production of 5.91 gigagrams of yellowcake in 2005. Energy inputs for the Ranger Mine were reported by Storm van Leeuwen (2007) as electric and thermal energy demands for mining and milling activities.

Water emissions were not publically available for the Ranger Mine, thus, water quality data was taken from the Saskatchewan Surface Water Quality Objectives. These emissions targets must be met by the

four operating uranium mines (SSWQO, 2006). According to a planning description of Cluff Lake uranium mine, water emissions from the mine are very near SSWQO targets (Accott 2004).

With the exception of ore removal emissions, PM Emissions from operation of open pit uranium mines are approximated by the activities of surface coal mines. The substitution overcomes a data limitation with a surrogate data set considered largely similar to open pit uranium mine operation. It is noted, however, that uranium is extracted from hard rock and thus is expected to require considerably more blasting energy, generating more PM, than surface coal mining. Therefore the number of blasts per week is doubled from the 5 blasts per week averaged for a coal mine. Considerations for the blasting, overburden bulldozing, and dragline removal of overburden were considered in the calculation.

Radioactive emissions to the soil and water were calculated from a technical radiological mining emissions report from the United States Environmental Protection Agency (U.S. EPA). The document focused on mining impacts and how to reclaim the land after the mining activities are completed. Emissions to soil include arsenic, iron, lead, mercury, selenium, thallium, and vanadium. **Table B-2** presents the inputs and outputs inventoried for open pit uranium mine operation.

Construction material inputs for the open pit uranium mine are based on material lists provided in the Energy Technology Characterizations Handbook (DOE, 1983). **Table B-3** lists the materials used in the construction of the mine. Installation of the open pit mine is approximated using an existing NETL unit process for installation of an open pit coal mine. Because of the low significance of mine installation in the LC emissions of nuclear power, this data limitation is acceptable.

Table B-2: Open Pit Uranium Mine Operation Inputs and Outputs

Flow Name	Value	Units
Inputs		
Ammonia (Inorganic Intermediate Products)	3.40E+00	kg/kg U_3O_8
Ammonium Nitrate (Inorganic Intermediate Products)	1.54E+01	kg/kg U_3O_8
Hydrated Lime Dry Slaked (Minerals)	4.65E-01	kg/kg U_3O_8
Light Fuel Oil (Crude Oil Products)	1.83E-01	kg/kg U_3O_8
Power (Electric Power)	4.41E+00	MJ/kg U_3O_8
Sodium Chlorate (Inorganic Intermediate Products)	3.66E-01	kg/kg U_3O_8
Sulphuric Acid (100%) (Inorganic Intermediate Products)	2.34E-02	kg/kg U_3O_8
Thermal Energy from Diesel Combusted in Construction Vehicles	2.10E+01	MJ/kg U_3O_8
Thermal Energy from Natural Gas Combusted in Industrial Boiler	2.79E+02	MJ/kg U_3O_8
Water (Ground Water) (Water)	1.53E-02	kg/kg U_3O_8
Outputs		
Uranium Yellowcake (U_3O_8) (Energy Carrier)	1.00E+00	kg
Uranium Tailings (Solid Waste)	1.94E+03	kg/kg U_3O_8
Dust (PM10) (Particles to Air)	3.62E-02	kg/kg U_3O_8
Radionuclide (Radioactive Emissions to Water)	4.70E+01	Bq/kg U_3O_8
Radionuclide (Radioactive Emissions to Soil)	1.15E+06	Bq/kg U_3O_8
Radionuclide (Radioactive Emissions to Air)	3.51E+00	Bq/kg U_3O_8

Flow Name	Value	Units
Arsenic (+V) (Heavy Metals To Industrial Soil)	1.33E+00	kg/kg U_3O_8
Iron (Heavy Metals to Industrial Soil)	2.38E+03	kg/kg U_3O_8
Lead (+II) (Heavy Metals to Industrial Soil)	9.51E+00	kg/kg U_3O_8
Mercury (+II) (Heavy Metals to Industrial Soil)	2.46E-02	kg/kg U_3O_8
Selenium (Heavy Metals to Industrial Soil)	1.58E-01	kg/kg U_3O_8
Thallium (Heavy Metals to Industrial Soil)	1.15E+00	kg/kg U_3O_8
Vanadium (+III) (Heavy Metals to Industrial Soil)	7.26E+00	kg/kg U_3O_8
Aluminum (+III) (Inorganic Emissions to Fresh Water)	2.54E-05	kg/kg U_3O_8
Ammonium / Ammonia (Inorganic Emissions to Fresh Water)	5.86E+01	kg/kg U_3O_8
Arsenic (Heavy Metals to Fresh Water)	1.27E-06	kg/kg U_3O_8
Cadmium (+II) (Heavy Metals to Fresh Water)	2.54E-08	kg/kg U_3O_8
Chromium (+VI) (Heavy Metals to Fresh Water)	2.54E-07	kg/kg U_3O_8
Copper (Heavy Metals to Fresh Water)	1.02E-06	kg/kg U_3O_8
Mercury (+II) (Heavy Metals to Fresh Water)	6.60E-09	kg/kg U_3O_8
Iron (Heavy Metals to Fresh Water)	7.61E-05	kg/kg U_3O_8
Lead (Heavy Metals to Fresh Water)	1.78E-06	kg/kg U_3O_8
Nickel (Heavy Metals to Fresh Water)	2.54E+01	kg/kg U_3O_8
Selenium (Heavy Metals to Fresh Water)	2.54E-07	kg/kg U_3O_8
Silver (Heavy Metals to Fresh Water)	2.54E-09	kg/kg U_3O_8
Zinc (+II) (Heavy Metals to Fresh Water)	7.61E-06	kg/kg U_3O_8
Uranium (Heavy Metals to Fresh Water)	7.61E+01	kg/kg U_3O_8

Table B-3: Material Inputs for Open Pit Uranium Mine Construction (DOE, 1983)

Flow Name	Value	Units
Aluminum (Metals)	1.04E-03	kg/kg yellowcake
Cast iron (Metals)	7.34E-03	kg/kg yellowcake
Concrete, Ready Mix, R-5-0 (Concrete_Cement)	7.81E-04	kg/kg yellowcake
Copper (Non Renewable Elements)	2.19E-03	kg/kg yellowcake
Steel cold rolled (St) (Metals)	1.76E-01	kg/kg yellowcake

B.1.1.3 Milling Facility Construction, Underground and Open Pit Mining

Underground and open pit mining operations include a milling facility for the purpose of separating uranium from uranium ore to produce a fine powder called yellowcake (U_3O_8). Raw uranium or is passed through crushers, leached with acid or alkali solution, dried, and filtered. While the operation of this mill is included in the operations process for the two mines, construction of the facility is inventoried in this separate unit process. Milling facilities are collocated with the mines or separated by negligible transport distances (less than 10 miles).

The high relative mass of uranium ore to produced yellowcake results in milling facilities being co-located with the mine or at the nearest possible neighboring site. Co-location also allows the tailings and waste rock from the milling process to be stored near the extraction point and disposed of in evacuated mines.

The construction process for this milling facility is based on a construction material list provided in the "Energy Technology Characterizations Handbook" (DOE, 1983). Source data for the material list dates from between 1974 and 1976.

The energy requirements for the installation of the milling facility were available from the Rotty Report (1975). The Rotty Report provides values for electricity and fossil energy consumed during milling facility installation. It is assumed that all fossil energy is consumed as diesel in a construction vehicle. The emissions from combustion of diesel in construction vehicles are calculated in a process external to this unit process, entitled "Thermal Energy from Diesel Combusted in Construction Vehicles."

The mass for a selection of materials were used in construction: concrete, copper, aluminum, polyvinylchloride, wood, and steel. These material inputs and installation energy inputs are presented in **Table B-4** for the milling construction unit process.

Table B-4: **Milling Facility Construction Inputs and Outputs**

Flow Name	Value	Units
Aluminum (Metals)	3.78E-03	kg/kg yellowcake
Concrete, ready mix, R-5-0 (Concrete_Cement)	1.85E+00	kg/kg yellowcake
Copper (Non renewable elements)	1.62E-03	kg/kg yellowcake
Polyvinylchloride-tube (PVC) (Plastic parts)	1.84E-03	kg/kg yellowcake
Power (Electric Power)	6.57E-02	MWh/kg yellowcake
Steel cold rolled (St) (Metals)	1.84E-01	kg/kg yellowcake
Thermal Energy from Diesel Combusted in Construction Vehicles (Valuable substances)	4.14E+00	MJ/kg yellowcake
Timber pine (65% humidity / 40% moisture content) (Materials from renewable raw materials)	1.84E-03	kg/kg yellowcake

B.1.1.4 In-Situ Leach (ISL) Mine

The scope of this unit process models an in-situ leach (ISL) uranium mine, along with a processing, or milling, facility. The modeled facility is based on data available for several existing and proposed ISL facilities located in the U.S., as well as existing facilities located in Australia. These facilities have varying capacities, and due to the nature of ISL mining, wherein a single 'mine' may include many drilling sites that are applied over time, a mine production capacity was not specified for this process. The processing facility is assumed to be located on site, in close proximity to ISL mining operations. Groundwater remediation, which occurs following completion of yellowcake extraction, is also included.

This unit process accounts for electricity use for mining, milling, and remediation; natural gas use for milling, chemical use for the injected lixiviant and elution/precipitation phases; air emissions due to natural gas usage, fugitive dust from trucks, and emissions from uranium concentrating and drying; solid waste including mine tailings; water use during mining/milling operations and during remediation; and long term water quality effects, following completion of the groundwater remediation process.

Electricity use for mining, milling, and remediation is calculated based on ISL mining and milling data available for mines located in Australia and Kazakhstan (WNA, 2009), and includes all operations at the mining and processing facilities, totaling 0.0220 MWh electricity per kg yellowcake produced, on average. Groundwater remediation, which is required following completion of mining activity in order to ensure that groundwater contamination with uranium is minimized, also requires electricity to run pumps and drive reverse osmosis or other remediation activities. This results in an additional electricity use of 0.0385 MWh/kg yellowcake (NRC, 2009a).

This ISL mining and processing unit process includes a single adjustable process parameter, which was included due to uncertainty associated with the amount of natural gas used at the processing facility, for milling operations. All available data collected for this parameter were available from a single ISL mining site, located in Australia (WNA, 2009). However these data were substantially variable on a month-to-month basis. The proposed default value for this parameter, 120.9 kg natural gas per kg yellowcake, is the average of available data, while the suggested minimum and maximum are 48.38 and 241.9 kg/kg yellowcake, respectively.

ISL mining and processing requires the use of a substantial amount of chemicals. Various chemicals are mixed and injected into the subsurface, in order to dissolve and mobilize uranium that is trapped in the underground formation. This chemical composition of this solution, which is termed *lixiviant*, varies widely based on formation characteristics and environmental regulatory constraints of overseeing agencies. However, most ISL mines located in the U.S. use a lixiviant that contains a mixture of carbon dioxide, oxygen, soda ash, sodium chloride (e.g., table salt), and chlorine as an anti-fouling agent. During the elution/precipitation circuit, yellowcake is separated from other leached constituents and lixiviant via ion exchange resin. Elution of the resin and precipitation of yellowcake from the eluate involve the use of hydrogen peroxide, soda ash, and sodium chloride. Ion exchange resin is reusable, but must be replaced periodically, resulting in a total ion exchange resin consumption rate of 0.360 kg resin per kg yellowcake produced.

Air emissions are quantified based on fugitive dust emissions from operations traffic (trucks and automobiles at the ISL site), radon-222 emissions associated with yellowcake drying, and natural gas fired boiler emissions that result from yellowcake processing. Air emissions from natural gas fired boilers is calculated based on the amount of natural gas required for uranium processing (discussed previously), and based on a natural gas fired boiler emissions profile calculator that is maintained by the Illinois State EPA (Illinois EPA 2010). The emissions profile calculator generates emission factors based on federal and state emissions regulations and requirements.

Solid waste from the ISL process includes radioactive mine tailings, which require remediation. Mine tailings are generated at a rate of 0.107 kg/kg yellowcake (NRC, 2009a). Other uncontaminated solid wastes generated on site amount to 0.360 kg/kg yellowcake, while low level hazardous wastes (primarily lubricant oil and spent batteries) amount to 8.82E-05 kg/kg yellowcake (NRC, 2009a).

Water is required during mining and processing, and also during remediation. At the ISL mine, a small portion of mine bleed water containing extracted uranium and other materials, is injected into a deep well for disposal. This is done to maintain a negative groundwater gradient, such that migration of groundwater away from mining operations is minimized, reducing the chances for contamination of adjacent aquifers. This amounts to approximately 70.2 kg water per kg yellowcake. During the elution/precipitation circuit, water is consumed at a rate of approximately 224 kg/kg yellowcake. Finally, water is also consumed during groundwater remediation operations, which accounts for an additional 87.0 kg water/kg yellowcake (NRC, 2009a)

No surface water runoff is permitted from the ISL mining and processing site, at least under U.S. regulations. Therefore, no surface water quality contamination is anticipated due to ISL mining. However, ISL mining can degrade groundwater. A study produced by the U.S. Geologic Survey (USGS 2009) indicated potential for increased groundwater contamination following ISL operations, even following remediation activities. Increases in pollutant levels were consistently reported for groundwater concentrations of arsenic, selenium, uranium, sulfate, manganese, molybdenum, and total nitrogen.

Table B-5 summarizes the relevant properties and assumptions used to estimate energy requirements, as well as other key components of the ISL mining and processing unit process. **Table B-6** provides a summary of modeled input and output flows.

Table B-5: **Properties of In Situ Leach Mining and Processing**

Item	Value	Reference
Natural Gas Use, for Processing (Milling) (kg natural gas/kg yellowcake)	120.9 (suggested) 48.38 (min) 241.9 (max)	WNA 2009
Electricity Use, Mining and Processing (MWh/kg yellowcake)	0.0220	WNA 2009
Aquifer Remediation Period (years)	4.25	NRC 2009a
Ion Exchange Resin Replacement (kg resin/kg yellowcake)	0.360	NRC 2009a
Radon-222 Emissions from Yellowcake Drying (Ci/kg yellowcake)	5.33E-04	NRC 2009a

Table B-6: **In Situ Leach Mining Operation Inputs and Outputs**

Flow Name	Value	Units
Inputs		
Power (Electric power)	0.03853	MWh/kg U_3O_8
Natural gas USA (Natural gas (resource))	120.9	kg/kg U_3O_8
Carbon dioxide (Renewable resources)	9.101	kg/kg U_3O_8
Oxygen	1.896	kg/kg U_3O_8
Sodium Carbonate	18.08	kg/kg U_3O_8
Sodium chloride (rock salt) (Non renewable resources)	38.51	kg/kg U_3O_8
Chlorine	0.02275	kg/kg U_3O_8
Hydrogen Peroxide	0.2000	kg/kg U_3O_8
Ion Exchange Resin	0.3602	kg/kg U_3O_8
Water (ground water) (Water)	223.9	kg/kg U_3O_8
Outputs		
Yellowcake (U_3O_8) (Non renewable resource)	1.000E+00	kg
Carbon dioxide (Inorganic emissions to air)	3.454E-01	kg/kg U_3O_8
Methane (Organic emissions to air [group VOC])	6.621E-06	kg/kg U_3O_8
Nitrous oxide (laughing gas) (Inorganic emissions to air)	6.333E-06	kg/kg U_3O_8
Nitrogen oxides (Inorganic emissions to air)	2.879E-04	kg/kg U_3O_8
Sulphur dioxide (Inorganic emissions to air)	1.727E-06	kg/kg U_3O_8
Carbon monoxide (Inorganic emissions to air)	2.418E-04	kg/kg U_3O_8
NMVOC (unspecified) (Group NMVOC to air)	1.583E-05	kg/kg U_3O_8
Dust (unspecified) (Particles to air)	1.242E-02	kg/kg U_3O_8
Radon (Rn_{222}) (Radioactive emissions to air)	5.333E-04	kg/kg U_3O_8
Arsenic (+V) (Heavy metals to fresh water)	2.025E-04	kg/kg U_3O_8
Selenium (Heavy metals to fresh water)	1.179E-04	kg/kg U_3O_8
Uranium (Radioactive emissions to fresh water)	2.243E-03	kg/kg U_3O_8
Sulfate	8.219E+00	kg/kg U_3O_8
Nitrogen (Inorganic emissions to fresh water)	2.468E-01	kg/kg U_3O_8
Manganese (+II) (Heavy metals to fresh water)	9.569E-04	kg/kg U_3O_8
Molybdenum (Heavy metals to sea water)	7.055E-03	kg/kg U_3O_8
Waste (solid) (Waste for disposal)	3.603E-01	kg/kg U_3O_8
Radioactive tailings (Radioactive waste)	1.072E-01	kg/kg U_3O_8

The construction process for an in situ leach uranium mine includes a single well field and processing plant complete with polyvinylchloride (PVC) pipelines. Once the uranium is extracted by the wells, it is transported through the pipelines for processing. The well house, used to combine multiple well outputs into one flow of uranium to the processing plant, has been assumed be insignificant compared to both the construction of the wells and the construction of the pipelines and processing plant.

Specifications for the well field were provided in an Environmental Impact Statement for the Beverley Uranium Mine in Australia (MPINRRD, 1998). The well field is expected to require drilling of one thousand wells for 15 production years. Each of the wells would be drilled to a depth of roughly 110 meters. Each well will have a PVC pipe inserted into it. The pipe will be cemented for stability and longevity of the well.

A processing plant is built to separate the uranium from the extraction solution. The materials specified for the processing plant includes only the amount of concrete needed for the base (MPINRRD, 1998). Additional requirements were not readily available. While it is known that other materials would likely be used in construction of a processing plant, the completeness of these data is considered sufficient for the low significance of this process in the lifecycle emissions of nuclear power (determined by LC screening of relative greenhouse gas [GHG] emissions for all unit processes).

Pipelines are needed for the transportation of the uranium solution from the extraction wells through the well house to the processing plant. The pipes entering the well house will have a smaller diameter than those leaving the well house as the well house combines multiple streams into a larger stream. The pipes will be construction out of PVC (NRC, 2009b).

For the drilling of the wells, it is assumed that fuel consumption is based on the brake specific power. The diesel consumption is estimated at 0.1645 kg/horsepower – hour (EPA, 1995). All combustion emissions based on the diesel consumption are included.

Variable parameters in the in situ leach mining construction process are shown in **Table B-7** with minimum, maximum, and default values. The modeled physical properties of a single well are provided in **Table B-8**. The final input and output materials and energy flows for the in situ mine construction process are in **Table B-9**.

Table B-7: **Variable Parameters in the In Situ Mine Construction Process**

Material	Minimum	Best Estimate	Maximum
Drill Speed (m/h)	14.2	17.8	21.3
Drill Depth (m)	120	150	180
Production Rate (kg/d)	1,245	2,740	53,437
Well Life (year)	12	15	18

Table B-8: Properties of a Single Constructed In Situ Uranium Mine

Property	Value	Reference
Number of Wells	1000 wells	MPINRRD 1998
Mine Lifetime	15 years	MPINRRD 1998
Pipeline Depth	150 meters	Assumed
Concrete for Well	5,499,803 kg	Calculated
Concrete for Processing Plant Base	36,758,880 kg	MPINRRD 1998
Length of Pipeline	8,210 meters	NRC 2009b

Table B-9: Inputs and Outputs for the In Situ Mine Construction Process

Flow Name	Value	Units
Inputs		
Polyvinylchloride part (PVC) (Plastic parts)	3.03E-02	kg/kg yellowcake
Concrete, ready mix, R-5-0 (Concrete_Cement)	2.82	kg/kg yellowcake
Diesel (Crude oil products)	5.55E-05	kg/kg yellowcake
Outputs		
Uranium Yellowcake (U_3O_8) (Construction)	1.00	kg/kg yellowcake
Carbon dioxide (Inorganic emissions to air)	1.78E-04	kg/kg yellowcake
Methane (Organic emissions to air [group VOC])	9.71E-09	kg/kg yellowcake
Nitrogen oxides (Inorganic emissions to air)	3.67E-06	kg/kg yellowcake
Sulphur oxides (Inorganic emissions to air)	6.19E-08	kg/kg yellowcake
Carbon monoxide (Inorganic emissions to air)	8.42E-07	kg/kg yellowcake
NMVOC (unspecified) (Group NMVOC to air)	9.82E-08	kg/kg yellowcake
Dust (PM10) (Particles to air)	1.07E-07	kg/kg yellowcake

B.1.2 Uranium Conversion

The purpose of a uranium conversion facility is to convert milled yellowcake (U_3O_8) into a gaseous state for subsequent fuel enrichment. Because uranium hexafluoride (UF_6) is gaseous at low temperatures, a conversion facility uses strong acids and alkalis to remove impurities and combine uranium with fluorine. The UF_6 is then pressurized and slow cooled to a solid state for transport to an enrichment facility.

Honeywell International Inc. operates the only U.S. conversion facility, located in Metropolis, Illinois. A single Canadian facility is operated by Cameco in Port Hope, Canada. Operation of the conversion facility is based on publicly available information from the Port Hope Conversion Facility in Port Hope, Canada (Cameco, 2010). It is assumed that the conversion facility has a fuel conversion efficiency of 85 percent. The license limit for UF_6 output from the Port Hope facility is 2,119 kg UF_6/hr. (personal contact with Port Hope representative). At an assumed fuel conversion efficiency of 85 percent, the modeled input is 5,058 kg U_3O_8/hr. from an input quantity of 1,891 kg UF_6/hr.

Best estimates for air and water emissions were made using 2009 averages. Variation of these emissions is captured through minimum and maximum emission rates in 2009. Emissions values are provided in kilograms per kilogram of UF_6 produced.

Energy usages for the Port Hope facility were neither provided in the publicly available documents nor available for release through employee contacts. This data limitation required the use of an older source (Rotty et al., 1975) for an estimate of energy inputs. Energy values are provided in an energy unit per kilogram of UF_6 produced.

The Port Hope facility receives the U_3O_8 in large drums from the extraction points. The first step of processing is reducing the size of the compound. It is crushed into a fine powder. Once at the correct size particles, the compound is reacted with hydrogen gas. This forms uranium dioxide (UO_2). To add fluorine to the compound, hydrogen fluoride is mixed with the UO_2. The resulting compound is uranium tetrafluoride (UF_4). The products of this reaction are heated to precipitate out the water from the mixture and purify the UF_4. The remaining UF_4 compound is mixed with fluorine gas. This results in the creation of uranium hexafluoride (UF_6) gas. To transform the gas into a liquid for transportation, the gaseous UF_6 gets passed through cold traps to solidify the compound into crystallized form and collect it. Once the compound is collected, it is heated to liquid form and packaged in steel cylinders for shipment (Cameco, 2010).

Water withdrawal values, but not consumption or discharge values, were available from Cameco. It is assumed that 10 percent of water withdrawal is consumed by the plant.

Inputs and outputs to the conversion facility operation process are available in **Table B-10**.

The construction process for this conversion facility is based on a construction material list provided in the “Energy Technology Characterizations Handbook” (DOE, 1983). Source data for the material list dates from between 1974 and 1976. Newer facilities have not been constructed in the U.S. since this time period, and therefore the construction materials data presented in this unit process represent the best available data. This is noted as a data limitation.

Table B-10: **Conversion Facility Operation Inputs and Outputs**

Flow Name	Value	Units
Inputs		
U_3O_8	2.81	kg/kg UF_6
Power (Electric power)	0.01	MWh/kg UF_6
Thermal Energy from Natural Gas Combusted in Industrial Boiler	885.53	MJ/kg UF_6
Water (lake water) (Water)	331.60	L/kg UF_6
Water (municipal) (Water)	26.86	L/kg UF_6
Outputs		
UF_6 (natural)	1.00E+00	kg
Uranium (total) (Radioactive emissions to air)	4.37E-06	kg/kg UF_6
Nitrogen oxides (Inorganic emissions to air)	2.06E-03	kg/kg UF_6
Ammonia (Inorganic emissions to air)	2.70E-03	kg/kg UF_6
Uranium (total) (Radioactive emissions to water)	2.11E-06	kg/kg UF_6
Fluoride (Inorganic emissions to fresh water)	7.59E-05	kg/kg UF_6
Ammonium / ammonia (Inorganic emissions to fresh water)	3.29E-05	kg/kg UF_6
Nitrate (Inorganic emissions to fresh water)	2.95E-04	kg/kg UF_6
Water (wastewater) (Water)	24.42	L/kg UF_6
Water (lake water) (Water)	301.46	L/kg UF_6

The following materials were assumed to be used in construction: concrete, copper, aluminum, cast iron, and steel. While it is known that other materials would likely be used in construction of a conversion facility, the completeness of these data is considered sufficient for the low significance of this process in the lifecycle emissions of nuclear power (determined by LC screening of relative GHG emissions for all unit processes). All materials are calculated based on the number of kilograms of UF_6 produced during the lifetime of the facility.

Table B-11 shows inputs and outputs of each of the construction materials needed to produce one kilogram of UF_6.

Table B-11: Material Inputs for Conversion Facility Construction

Flow Name	Value	Units
Aluminum (Metals)	3.60E-04	kg/kg UF_6
Cast iron (Metals)	8.90E-04	kg/kg UF_6
Concrete, ready mix, R-5-0 (Concrete_Cement)	2.35E+00	kg/kg UF_6
Copper (Non renewable elements)	1.10E-03	kg/kg UF_6
Steel cold rolled (St) (Metals)	7.43E-02	kg/kg UF_6

B.1.3 Uranium Enrichment

Uranium enrichment considers construction and installation of the uranium enrichment facility, decommissioning of the facility, and operation of both gaseous diffusion and gas centrifuge enrichment. These are discussed in the following text.

B.1.3.1 Enrichment Facility Construction and Installation

Construction of the nuclear enrichment facility is considered to be common between gaseous diffusion and centrifuge enrichment types. Differences between construction material needs for the two facilities are considered insignificant based on a screening analysis of the nuclear power LC.

Construction materials for the facility are based on material list provided in the environmental impact statement for the proposed centrifuge enrichment facility in Lea County, New Mexico (NRC 2005). Selected commodities and resources needed for construction include asphalt paving, chain link fencing, concrete and concrete paving, copper and aluminum wiring, crushed stone, and carbon and stainless steel piping and ductwork. The document also reports air emissions from construction vehicles as well as fugitive dust from installation activity.

Table B-12: Enrichment Facility Construction and Installation Inputs and Outputs

Flow Name	Value	Units
Inputs		
Bitumen (Organic intermediate products)	7.21	kg/kg UF_6
Concrete, ready mix, R-5-0 (Concrete_Cement)	14.05	kg/kg UF_6
Copper (99.999%; electrolyte copper) (Metals)	1.71E-02	kg/kg UF_6
Aluminum sheet (Metals)	2.90E-01	kg/kg UF_6
Steel, pipe welded, BF (85% Recovery Rate) (Metals)	1.56E-04	kg/kg UF_6
Steel plate, BF (85% Recovery Rate) (Metals)	5.09E-05	kg/kg UF_6
Water (Unspecified) (Water)	7.49E-01	kg/kg UF_6
Diesel (Crude oil products)	1.32	kg/kg UF_6
Outputs		
Enriched UF_6 (Construction and Deconstruction)	1.00E+00	kg UF_6
Carbon dioxide (Inorganic emissions to air)	4.1	kg/kg UF_6
Nitrogen oxides (Inorganic emissions to air)	2.63E-02	kg/kg UF_6
Nitrogen oxides (Inorganic emissions to air)	1.49E-02	kg/kg UF_6
Sulphur oxides (Inorganic emissions to air)	5.34E-03	kg/kg UF_6
Carbon monoxide (Inorganic emissions to air)	2.63E-02	kg/kg UF_6
Dust (PM10) (Particles to air)	2.08E-02	kg/kg UF_6
NMVOC (unspecified) (Group NMVOC to air)	4.15E-03	kg/kg UF_6

The weights for a selection of materials were readily available. The materials include: asphalt, concrete, copper, aluminum, and steel plates and pipes. While it is agreed that there must be additional materials, there is no readily available data to add that information so it is assumed that it will be negligible in

comparison to the materials given. All materials are calculated based on the number of kilograms of enriched uranium which will be produced during the lifetime of the facility.

Construction and installation inputs and outputs for the enrichment facility are provided in **Table B-12**.

B.1.3.2 Enrichment Facility Decommissioning

After the useful lifetime of the enrichment facility it is dismantled and disposed of properly. The decommissioning activities for the enrichment plant at Oak Ridge (the "K-25" plant) are assumed to be the same as those for other gaseous diffusion facilities (e.g., Paducah).

Decommissioning of a uranium enrichment facility is a multi-year process; therefore the energy for decommissioning activities is assumed to be equal to the direct energy for construction activities. Direct energy use (electricity and thermal energy) are reported by the Rotty report (1975). The thermal energy portion is assumed to be supplied by diesel combusted in construction vehicles: the amount of diesel consumed is calculated from the heating value of diesel. Air emissions associated with diesel combustion in construction vehicles were calculated using EPA's AP-42 (EPA, 1995).

Electricity for operation of Paducah UF_6 enrichment plant comes from Joppa steam plant, which uses 100% bituminous coal. It is assumed that the electricity demand for decommissioning is from the same plant.

Table B-13: **Enrichment Facility Decommissioning Inputs and Outputs**

Flow Name	Value	Units
Inputs		
Power (Electric power)	8.60E+04	MWh/facility
Diesel (Crude oil products)	4.34E+08	kg/facility
Outputs		
Carbon dioxide (Inorganic emissions to air)	1.37E+09	kg/facility
Nitrogen oxides (Inorganic emissions to air)	3.69E+07	kg/facility
Carbon monoxide (Inorganic emissions to air)	7.96E+06	kg/facility
Sulphur oxides (Inorganic emissions to air)	2.43E+06	kg/facility
Dust (PM10) (Particles to air)	2.60E+06	kg/facility
NMVOC (unspecified) (Group NMVOC to air)	3.02E+06	kg/facility
Waste radioactive (Radioactive Waste)	1.17E+07	kg/facility

Scrap metal from decommissioning of the plant can be recycled for unrestricted use. The majority of this scrap metal is carbon steel. 100 percent of the burdens for metal recycling are assigned to the next generation product, with exception of waste slag, which is assigned to the decommissioning activities of this unit process. The solid waste values were provided by a document which inventorying recycling scrap metals from nuclear facilities (Anigstein, 2001). Any waste concrete from demolition activities is disposed onsite at the EMWMF (Environmental Management Waste Management Facility) and does not exit the boundaries of this unit process. The EMWMF facility has a capacity of nearly 1 million cubic meters (Waldman, 2007).

Inputs and outputs for the enrichment facility decommissioning process are provided in **Table B-13**.

B.1.3.3 Gaseous Diffusion Enrichment Facility Operation

This gaseous diffusion enrichment process is used to increase the concentration of U-235 in UF_6 for effective use of the fuel. Natural concentrations of U-235 are less than one weight percent. For optimal light water nuclear fission in a commercial power plant, the U-235 concentration must be above 3 weight percent.

Gaseous diffusion is the only type of enrichment process used in the U.S. Operations take place at a single plant in Paducah, Kentucky. A similar plant in Piketon, Ohio was shut down in March 2001. Operational parameters for the Paducah plant are given in **Table B-14**.

The diffusion enrichment process filters UF_6 gas through porous membranes to separate heavier U-238 isotopes from lighter U-235 isotopes. The fuel goes through many hundreds of these barriers before the concentration is high enough for commercial fuel use. (NRC, 2010)

Inputs to the unit process include electricity and natural UF_6. A dedicated power plant, the Joppa Steam plant, provides the Paducah facility 1600 MW of power. Electric Energy, Inc. provides a maximum capacity of 3400 MW for use by the enrichment facility. (WNA, 2011)

A public health assessment completed by the Agency for Toxic Substances and Disease Registry provided toxic and radioactive air emissions and water quality data for this inventory (ATSDR, 2001). Water use data was taken from the final environmental impact statement for the Paducah facility (DOE, 2004).

Inputs and outputs for the gaseous diffusion enrichment process are provided in **Table B-15**.

Table B-14: **Gaseous Diffusion Enrichment Operational Parameters**

Property	Value	Units	Reference
Purchased Electric Power: Electrical Need	1,600	MW	WNA 2010
Purchased Electric Power: Maximum Capacity	3,400	MW	WNA 2010
Annual Enrichment Capacity	1.13E+07	SWU/yr.	Laughter 2009
SWU per kg of Enriched UF_6	7.9	SWU/kg	WNA 2010, Spurgeon 2008

Table B-15: **Gaseous Diffusion Enrichment Operation Inputs and Outputs**

Flow Name	Value	Units
Inputs		
UF_6 (natural) (Energy carrier)	10.40	kg/kg UF_6
Power (Electric power)	8.0	MWh/kg UF_6
Water (surface water) (Water)	14488	kg/kg UF_6
Outputs		
UF_6 (enriched) (Energy carrier)	1.00	kg
Chromium (unspecified) (Heavy metals to air)	1.00E-03	kg/kg UF_6
Hydrogen fluoride (Inorganic emissions to air)	3.85E-03	kg/kg UF_6
NMVOC (unspecified) (Group NMVOC to air)	2.24E-02	kg/kg UF_6
Radionuclides (unspecified) (Radioactive emissions to air)	7.11E+02	Bq/kg UF_6
Heavy metals to water (unspecified) (Heavy metals to fresh water)	1.06E-01	kg/kg UF_6
Nitrate (Inorganic emissions to fresh water)	9.63E-03	kg/kg UF_6
Fluoride (Inorganic emissions to fresh water)	4.04E-03	kg/kg UF_6
Chlorinated hydrocarbons (unspecified) (Halogenated organic emissions to fresh water)	3.67E-05	kg/kg UF_6
Sulphate (Inorganic emissions to fresh water)	4.18E-01	kg/kg UF_6
Water (river water) (Water)	3863	kg/kg UF_6
Radioactive tailings (Radioactive waste)	9.40	kg/kg UF_6

B.1.3.4 Gas Centrifuge Enrichment Facility Operation

This gas centrifuge enrichment process is used to increase the concentration of U-235 in UF_6 for effective use of the fuel. Natural concentrations of U-235 are less than one weight percent. For optimal light water nuclear fission in a commercial power plant, the U-235 concentration must be above 3 weight percent.

Gas centrifuge enrichment is the primary enrichment type used in Europe. Centrifuge enrichment achieves significant energy savings over gaseous diffusion enrichment, an older technology which is the only type used in the U.S. However, a license application was submitted in 2005 to the U.S. Nuclear Regulatory Commission (NRC) to construct, operate, and decommission a gas centrifuge uranium enrichment facility near Eunice, New Mexico. The proposed National Enrichment Facility would produce enriched U-235 up to 5 weight percent by the gas centrifuge process with a expected value production of 3 million separative work units per year. The Environmental Impact Statement for the proposed facility (NRC, 2005) is used as the primary source for development of this unit process. The process is used in the LC model of nuclear power to represent centrifuge enrichment in both the U.S. and in Europe.

The centrifuge enrichment process uses a number of large rotating cylinders to separate heavier U-238 isotopes from lighter U-235 isotopes. Heavier isotopes are collected as they move to the outside of the cylinder, then the remaining lighter material continues to another cylinder to repeat the process. The fuel goes through numerous cascades (normally over 100) until it reaches a desired concentration.

Operating parameters for the facility are provided in **Table B-16**. Inputs and outputs to the operation process are given in **Table B-17**. The stack emissions include factors for uranium, helium, argon, nitrogen, hydrogen fluoride, methylene chloride, and ethanol.

Table B-16: Gas Centrifuge Enrichment Operating Parameters

Property	Value	Units	Reference
Natural UF_6 Input	8,600	metric ton/yr.	NRC 2005
SWU Produced	3,000,000	SWU/yr.	NRC 2005
Enriched UF_6 Produced	800	metric ton/yr.	NRC 2005
Tailings (depleted UF_6)	7,800	metric ton/yr.	NRC 2005

Table B-17: **Gas Centrifuge Enrichment Operation Inputs and Outputs**

Flow Name	Value	Units
Inputs		
UF_6 (natural) (Energy carrier)	10.75	kg/kg UF_6
Power (Electric power)	0.15	MWh/kg UF_6
Thermal Energy from Natural Gas Combusted in Industrial Boiler (Valuable substances)	148.57	MJ/kg UF_6
Diesel (Crude oil products)	2.95E-01	L/kg UF_6
Water (surface water) (Water)	1.10E+03	L/kg UF_6
Corrosion Inhibitor	1.00E-02	kg/kg UF_6
Biogrowth Inhibitor	2.25E-03	kg/kg UF_6
Outputs		
UF_6 (enriched) (Energy carrier)	1.00	kg
Tailings - Depleted UF_6 (Stockpile goods)	9.75	kg/kg UF_6
Helium (inorganic emissions to air)	9.82E-05	kg/kg UF_6
Argon (inorganic emissions to air)	4.24E-04	kg/kg UF_6
Nitrogen (N-compounds) (inorganic emissions to air)	8.28E-05	kg/kg UF_6
Hydrogen fluoride (inorganic emissions to air)	1.25E-06	kg/kg UF_6
Dichloromethane (methylene chloride (halogenated organic emissions to air)	7.63E-04	L/kg UF_6
Ethanol (Group NMVOC to air)	5.00E-05	L/kg UF_6
Dust (PM10) (Particles to air)	1.25E-04	kg/kg UF_6
NMVOC (unspecified) (Group NMVOC to air)	3.25E-04	kg/kg UF_6
Nitrogen oxides (Inorganic emissions to air)	1.39E-02	kg/kg UF_6
Carbon dioxide (Inorganic emissions to air)	7.91E-01	kg/kg UF_6
Methane (Organic emissions to air [group VOC])	3.24E-02	kg/kg UF_6
Nitrous oxide (laughing gas) (Inorganic emissions to air)	6.48E-03	kg/kg UF_6
Sulphur dioxide (Inorganic emissions to air)	7.45E-06	kg/kg UF_6
Ammonia (Inorganic emissions to air)	4.26E-01	kg/kg UF_6
Water (river water) (Water)	3.63E+01	L/kg UF_6
Waste (solid) (Waste for disposal)	2.16E-01	kg/kg UF_6
Mixed Waste (Hazardous or Radioactive)	1.11E-01	kg/kg UF_6
Radionuclides (Radioactive emissions to air)	3.16E-01	Bq/kg UF_6

B.1.4 UF_6 Storage and Transport Containment

The scope of this unit process encompasses the materials and weights of those materials necessary to construct a single uranium hexafluoride (UF_6) storage cylinder, to be used for the storage and transportation of both natural and enriched UF_6.

This process is used during LC Stage #1 to store and transport all different types of UF_6 (natural, enriched, and depleted) from naturally occurring to enriched uranium to depleted UF_6. An adjustable parameter is available in the model to switch between the different types of cylinders. Both 48Y and 48X cylinders can be used to transport natural UF_6, while only the 48Y can store depleted UF_6. 30B is the only cylinder which is approved to carry the enriched uranium to the fuel fabrication facilities. The number of and sizes of the cylinders used is determined by the amount of uranium in each step.

The construction of the UF_6 cylinder is based on information provided in the environmental impact statement for the proposed enrichment facility in Lea County, New Mexico (NRC 2005). The different types of cylinders are designed slightly differently based on the materials they will contain and the function they perform. It is assumed that there is no leakage from any of the cylinders to cause any additional emissions during transport or storage.

The total weight of a UF_6 storage cylinder was readily available but reliable data for the material breakdown of storage cylinder subcomponents were not. Diagrams and cylinder measurements were used to calculate the quantity of steel plate (Steel plate, BF (85 percent Recovery Rate) [Metals]).

Properties of each type of storage cylinder are available in **Table B-18**.

Table B-18: UF_6 Storage Cylinder Properties by Cylinder Type

Property	Unit	Type 48X	Type 48Y	Type 30B
Diameter	Meters	1.2	1.2	0.76
Length	Meters	3	3.8	2.06
Wall Thickness	Millimeters	16	16	12.7
Empty Weight	kg	2041	2359	635
UF_6 Capacity	kg	9540	12500	2277

B.1.5 Uranium Fuel Fabrication Facility

Fuel fabrication begins with receipt of uranium hexafluoride (UF_6) from an enrichment plant. The UF_6 is transported in solid form to the fuel fabrication facility, where it is heated to a gas and chemically processed to form uranium dioxide (UO_2) powder. The UO_2 powder is then pelletized, sintered into ceramic form, loaded into tubes, and constructed into fuel assemblies.

The constructed fuel assembly has differing dimensions and contains different quantities of fuel rods depending on the reactor in which it is used. This diversity is not captured in the modeled fuel assembly process. Rather, operation of a generic fuel assembly plant is based on inputs and outputs provided in the "Energy Technology Characterizations Handbook" (DOE, 1983). These data include energy demands during operation of the facility, chemical inputs and emissions from the use of the energy and the chemical transformations.

Inputs and outputs for the fuel fabrication facility operation process are available in **Table B-19**.

Table B-19: Fuel Fabrication Facility Operation Inputs and Outputs

Flow Name	Value	Units
Inputs		
Natural gas USA (Natural gas (resource))	2.89E+00	m^3/kg UO_2
Power (Electric power)	4.89E-02	MWh/kg UO_2
UF_6 (enriched) (Intermediate products)	3.42E+00	kg/kg UO_2
Water (ground water) (Water)	5.67E+02	L/kg UO_2
Outputs		
UO_2 (fuel assembly) (Intermediate products)	1.00E+00	kg/kg UO_2
Ammonia (Inorganic emissions to fresh water)	2.89E-01	kg/kg UO_2
Calcium Fluoride (Emissions to industrial soil)	7.49E-01	kg/kg UO_2
Carbon monoxide (Inorganic emissions to air)	6.22E-03	kg/kg UO_2
Fluoride (Inorganic emissions to fresh water)	1.22E-01	kg/kg UO_2
Nitrate (Inorganic emissions to fresh water)	6.87E-01	kg/kg UO_2
Nitrogen oxides (Inorganic emissions to air)	1.78E-01	kg/kg UO_2
Sulphur dioxide (Inorganic emissions to air)	6.87E-01	kg/kg UO_2
Thorium (Th_{234}) (Radioactive emissions to fresh water)	1.07E-08	Bq/kg UO_2
Uranium (Radioactive emissions to fresh water)	2.10E-08	Bq/kg UO_2
Uranium (Radioactive emissions to industrial soil)	2.43E-07	Bq/kg UO_2
Uranium (U-235) (Radioactive emissions to air)	2.10E-10	Bq/kg UO_2

Construction of the fuel fabrication facility is based on material list provided in the "Energy Technology Characterizations Handbook" (DOE, 1983). Masses for a selection of materials were quantified for construction: concrete, copper, aluminum, cast iron, and steel. While it is known that other materials would likely be used in construction of the facility, the completeness of this data is considered sufficient, given that this unit process has a low level of significance in the LC emissions of nuclear power (as determined by LC screening of relative GHG emissions, for all unit processes). Material inputs for construction of the fuel fabrication facility are provided in **Table B-20.**

Table B-20: Material Inputs for Fuel Fabrication Facility Construction

Flow Name	Value	Units
Aluminum (Metals)	4.44E-02	kg/kg UO_2
Cast iron (Metals)	2.83E-02	kg/kg UO_2
Concrete, ready mix, R-5-0 (Concrete_Cement)	1.39E+01	kg/kg UO_2
Copper (Non renewable elements)	1.62E-01	kg/kg UO_2
Steel cold rolled (St) (Metals)	1.41E-03	kg/kg UO_2

B.2 Raw Materials Transport

Raw materials transport includes transport via both ocean freighter and train. Data and modeling procedure for these modes of transport are discussed in the following text.

B.2.1 Ocean Freighter Transport

Operational data for the ocean freighter is compiled from many sources, to create an emissions profile for criteria air pollutants and other pollutants of interest. The unit process is designed such that the type of cargo being transported and location of transport are irrelevant. This unit process assumes that the unspecified type of cargo is loaded into the ocean freighter during a previous unit process. This unit process transports the unspecified cargo from one location to another.

The user has the ability to vary certain parameters to tailor the dataset to fit the diesel production profile used. The parameters listed in the Adjustable Process Parameter section are the primary differentiators between diesel analyses. Three of the four adjustable parameters help to determine the amount of diesel needed for transportation. These include the energy content of the diesel, the power demand of the ocean freighter, and the roundtrip transport distance. The default values for these parameters are, respectively, 36,641 Btu/liter, 10,099,939 Btu/kg-km, and 1 nautical mile. The fourth adjustable parameter is the sulfur content of the diesel fuel, with a default value of 0.000015 kg S/kg diesel. The sulfur content of the fuel is important due to the effect on the resulting air emissions. These parameters may be varied based on updated information, or the specific values needed for a given investigation.

Table B-21: Emission Factors for Ocean Freighter Transport

Emission	Value (kg/kg-nautical mile cargo transported)	Reference
Carbon Dioxide	5.37E-05	DOE 2006
Methane	1.92E-06	DOE 2006
Nitrous Oxide	6.24E-07	DOE 2006
Sulphur Oxide	1.12E-09	NETL Engineering Calculation
Nitrogen Oxides	3.12E-06	U.S. Federal Register 2008
Particulate Matter, unspecified	2.16E-07	U.S. Federal Register 2008,
VOCs, unspecified	3.36E-07	U.S. Federal Register 2008
Carbon Monoxide	8.88E-06	U.S. Federal Register 2008
Mercury (+II)	3.16E-22	Conaway et al. 2005
Ammonia	2.64E-10	Battye et al. 1994

All emission factors for diesel combustion are provided in **Table B-21**. It is assumed that the ocean freighter will be operating around or after the year 2014, and will therefore be in compliance with the U.S. EPA Tier 4 emissions standards, which will become effective in 2015. The Tier 4 standards include regulations for NO_X, PM, VOCs, and CO (U.S. Federal Register, 2008). Emission factors for CO_2, CH_4, and N_2O were taken from the documentation for the Energy Information Administration's (EIA) form for the voluntary reporting of GHGs (DOE, 2006). Stoichiometric conversions determined the SO_2 emissions from diesel combustion. It was assumed that all sulfur contained in the diesel fuel would be converted to SO_2.

Diesel consumption of the ocean freighter using the default diesel energy content, power demand, and transport distance is 2.39E-06 L/kg-nautical mile cargo transported.

B.2.2 Train Transport

Operational data for the train is compiled from many sources, to create an emissions profile for criteria air pollutants and other pollutants of interest. The unit process is designed such that the type of cargo being transported and location of transport (inside the U.S.) are irrelevant. This unit process assumes that the unspecified type of cargo is loaded into the train during a previous unit process. This unit process transports the unspecified type of cargo from one point to another. Upstream emissions associated with the production diesel fuel and processed cargo are accounted for outside of the boundary of this unit process.

The user has the ability to vary certain parameters to tailor the dataset to fit the diesel production profile used. The parameters listed in the Adjustable Process Parameter section are the primary differentiators between diesel analyses. Three of the four adjustable parameters help to determine the amount of diesel needed for transportation. These include the energy content of the diesel, the power demand of the train, and the roundtrip transport distance. The default values for these parameters are, respectively, 36,641 Btu/liter, 225 Btu/kg-km, and 100 km. The fourth adjustable parameter is the sulfur content of the diesel fuel, with a default value of 0.000015 kg S/kg diesel. The sulfur content of the fuel is important due to the effect on the resulting air emissions. These parameters may be varied based on updated information, or the specific values needed for a given investigation.

Table B-22: Emission Factors for Train Transport

Emission	Value (kg/kg cargo transported 100 km)	Reference
Carbon Dioxide	1.37E-02	DOE 2006
Methane	4.9E-04	DOE 2006
Nitrous Oxide	1.59E-04	DOE 2006
Sulphur Oxide	2.87E-07	NETL Engineering Calculation
Nitrogen Oxides	7.97E-04	U.S. Federal Register 2008
Particulate Matter, unspecified	1.84E-05	U.S. Federal Register 2008
VOCs, unspecified	8.58E-05	U.S. Federal Register 2008
Carbon Monoxide	9.20E-04	U.S. Federal Register 2008
Mercury (+II)	8.08E-20	Conaway et al. 2005
Ammonia	6.74E-08	Battye et al. 1994

All emission factors for diesel combustion are provided in **Table B-22**. It is assumed that the train will be operating around or after the year 2015, and will therefore be in compliance with the U.S. EPA Tier 4 emissions standards, which will become effective in 2015. The Tier 4 standards include regulations for NO_X, PM, VOCs, and CO (U.S. Federal Register 2008). Emission factors for CO_2, CH_4, and N_2O were taken from the documentation for the EIA form for the voluntary reporting of GHGs (DOE 2006). Stoichiometric conversions determined the SO_2 emissions from diesel combustion. It was assumed that all sulfur contained in the diesel fuel would be converted to SO_2.

Diesel consumption of the train using the default diesel energy content, train power demand, and 100 km transport distance is 6.13E-04 L/kg cargo transported.

B.3 Energy Conversion Facility

The two modeled power production pathways are distinguished by power production facility generation. The existing and Gen III+ plant construction, installation, and operation processes are outlined in this section. Power plant decommissioning and spent fuel handling processes are assumed to be common between the two power plant generations.

B.3.1 Existing Power Plant

This unit process accounts for the operating activities of the U.S. average existing nuclear power plant. The process is based on the reference flow of 1 MWh of electricity. The tracked input to the process is the uranium (UO_2) fuel assembly. Water is used for cooling and other process-related utilities; water is assumed to enter the boundaries of this unit process having no upstream resource consumption or environmental emissions. The outputs of this unit process are produced electricity, spent fuel, discarded water, air emissions, water emissions, and solid waste. The output electricity is transmitted to the grid for transportation in LC Stage #4.

The model of existing nuclear power plant operation seeks to represent the industry average of existing nuclear reactors over a forty year period from 1969 to 2009. Data for establishing this average comes partially from the Energy Information Administration's historical operating data on nuclear power plants. From this data, electricity output and proportion of installed Pressurized Water Reactors (PWR) to Boiling Water Reactors (BWR) was calculated. This ratio allows applying a weighted average to inputs and emissions inventoried separately for the two plant types. For example, fuel input data was reported by the Energy Technology Characterizations Handbook (DOE, 1983) according to plant type. The fuel input from each of PWR and PWR plants was then weighted according to the relative power output of all plants of that type to the power output of the total existing fleet.

Water use and withdrawal data came from the Generic Environmental Impact Statement for License Renewal of Nuclear Plants (NUREG-1437 Vol. 1). Because of high variability in water use between cooling water system types, this data was reported separately for once-through and closed-loop systems. Similarly to reactor type, the average water system type in the United was used to appropriately weight water withdrawal and discharge information to produce a national average. Data from Sandia National Laboratory provided the ratio of existing closed-loop to once-through cooling systems (35:60).

Air emissions data for the existing nuclear power plant fleet is taken from U.S. EPA nuclear industry emission factors categorized under the North American Industry Classification System (NAICS) code 221113 (EPA, 2009a). A list of criteria air emissions and hazardous air emissions inventoried by NAICS is available on the 'Average Operations' worksheet of the DS sheet. GHG Emissions produced during normal reactor operation are assumed to be negligible.

Water emissions were collected from the U.S. EPA's *Enforcement & Compliance History Online* report. Reported emissions are separated by cooling type used at the proposed plant: closed-loop and once-through (EPA, 2009b).

Data for radioactive emissions to air and water for several existing U.S. power plants was available from the Westinghouse AP 1000 (Gen III+ PWR) environmental report (Westinghouse, 2009). These values were provided as a comparison for advanced reactor emissions reductions.

A number of important parameters used in the model of the existing nuclear power plant operations are provided in **Table B-23**. **Table B-24** provides a summary of modeled input and output flows for the existing nuclear plant.

Table B-23: Existing Nuclear Power Plant Operating Parameters

Parameter	Value	Source
Average Thermal Efficiency of Existing Reactors (%)	31.6	WNA 2010
Average Annual Capacity Factor, 1969-2009 (%) (Used for scaling reactor construction impacts)	70.7	EIA 2010
Average Annual Electric Output of a Single Reactor, 1969-2009 (MWh/year)	4.93E+06	EIA 2010
Uranium Fuel Input per Electricity Output (kg/MWh)	4.33E-03	DOE 1983
Number of Operating Nuclear Reactors in 2009	104	EIA 2010
Number of Operating PWR Reactors in 2009	69	EIA 2010
Number of Operating BWR Reactors in 2009	35	EIA 2010

Table B-24: Existing Nuclear Power Plant Operation Inputs and Outputs

Flow Name	Value	Units
Inputs		
Uranium Fuel Assemblies (UO_2) (Intermediate product)	4.33E-03	kg/MWh
Water (surface water) (Water)	103.67	kg/MWh
Outputs		
Electricity (Operation)	1.00E+00	MWh
Spent fuel (UO_2)	4.34E-03	kg/MWh
Radionuclides (Radioactive emissions to air)	3.01E+06	Bq/MWh
Carbon dioxide (Inorganic emissions to air)	0.00E+00	kg/MWh
Methane (Organic emissions to air [group VOC])	0.00E+00	kg/MWh
Nitrous oxide (laughing gas) (Inorganic emissions to air)	0.00E+00	kg/MWh
Nitrogen oxides (Inorganic emissions to air)	6.08E-04	kg/MWh
Sulphur dioxide (Inorganic emissions to air)	9.34E-05	kg/MWh
Carbon monoxide (Inorganic emissions to air)	1.17E-04	kg/MWh
NMVOC (unspecified) (Group NMVOC to air)	4.94E-05	kg/MWh
Dust (PM10) (Particles to air)	2.38E-04	kg/MWh
Dust (PM2.5) (Particles to air)	1.52E-04	kg/MWh
Lead (+II) (Heavy metals to air)	4.39E-09	kg/MWh
Mercury (+II) (Heavy metals to air)	6.55E-11	kg/MWh
Ammonia (Inorganic emissions to air)	8.00E-06	kg/MWh
Selenium (Heavy metals to air)	3.02E-10	kg/MWh
Chromium (unspecified) (Heavy metals to air)	6.05E-11	kg/MWh
Manganese (+II) (Heavy metals to air)	1.22E-10	kg/MWh
Nickel (+II) (Heavy metals to air)	6.46E-11	kg/MWh
Arsenic (+V) (Heavy metals to air)	2.71E-11	kg/MWh

Flow Name	Value	Units
Cadmium (+II) (Heavy metals to air)	6.05E-11	kg/MWh
Aluminum (+III) (Inorganic emissions to fresh water)	1.22E-03	kg/MWh
Chlorine (dissolved) (Inorganic emissions to fresh water)	1.19E-02	kg/MWh
Iron (Heavy metals to fresh water)	8.05E-02	kg/MWh
Nitrogen (Inorganic emissions to fresh water)	2.51E-03	kg/MWh
Arsenic (+V) (Heavy metals to fresh water)	4.92E-03	kg/MWh
Chromium (unspecified) (Heavy metals to fresh water)	3.47E-03	kg/MWh
Copper (+II) (Heavy metals to fresh water)	5.83E-03	kg/MWh
Mercury (+II) (Heavy metals to fresh water)	8.15E-09	kg/MWh
Zinc (+II) (Heavy metals to fresh water)	6.07E-02	kg/MWh
Biochemical oxygen demand (Organic emissions to fresh water)	1.29E+00	kg/MWh
Oxidants (unspecified) (Inorganic emissions to fresh water)	1.37E-02	kg/MWh
Oil (unspecified) (Hydrocarbons to fresh water)	7.99E-01	kg/MWh
Phosphorus (Inorganic emissions to fresh water)	1.10E-03	kg/MWh
Solids (suspended) (Particles to fresh water)	1.12E+00	kg/MWh
Water (river water) (Water)	1.01E+05	L/MWh
Waste (solid) (Waste for disposal)	5.71E-05	kg/MWh
Mixed Waste (Hazardous or Radioactive)	2.70E-06	m^3/MWh

The construction of the existing nuclear power plant is based on a study conducted at Oak Ridge National Laboratory in 1974. Estimated quantities of the materials and their constituents are presented in detail for each portion of the power plant. Scott White at the University of Wisconsin used this data to compare construction material quantities required by multiple types of power plants normalized to 1000 MW(e) (White, 1998). The power plant is constructed of concrete ready-mix, stainless steel, steel plate, aluminum, copper sheeting, polyurethane, lead, manganese ore, nickel, silver, and diesel. Other materials are assumed to be negligible. In inventorying these materials, an assumption was made that PWR and BWR require similar quantities of aluminum. It was also assumed that insulation consists primarily of polyurethane foam. The average reactor capacity factor from 1969 to 2009 of 70.7 percent was used to scale the reactor construction impacts to the functional unit of one MWh.

Diesel combusted in heavy equipment accounts for majority of fuel combusted during installation of the power plant. No primary data was available to determine the amount of diesel needed for the installation of the power plant: a significant data limitation. This quantity was estimated from the cost of diesel fuel relative to total plant construction cost. Plant construction cost ranges from 1100 to 6000 $/kWe, depending on the referenced source. The midpoint between these costs is used as the default value for this analysis with each extreme suggested for adjustment in sensitivity analysis. The cost of diesel is assumed to range between 2 and 4 dollars per gallon. The default value of the cost of diesel is 3 dollars per gallon. The cost ratio between the cost of the power plant and the cost of the diesel is assumed to be between 1 and 5 percent. The default value is assumed to be 3 percent.

Table B-25 shows the material inputs for existing plant construction as provided in White 1998 and the estimated installation energy inputs.

Table B-25: Material Inputs for Existing Plant Construction and Installation (White 1998)

Flow Name	Value	Units
Inputs		
Diesel (Crude oil products)	1.14E+08	kg/1000 MW Plant
Aluminum (Metals)	1.80E+04	kg/1000 MW Plant
Concrete, ready mix, R-5-0 (Concrete_Cement)	1.80E+08	kg/1000 MW Plant
Coppersheet (Metals)	7.29E+05	kg/1000 MW Plant
Polyurethane flexible foam (PU) (Plastics)	9.22E+05	kg/1000 MW Plant
Lead (Metals)	4.60E+04	kg/1000 MW Plant
Manganese ore (Non renewable resources)	4.34E+05	kg/1000 MW Plant
Nickel (99.95%; electrolyte nickel) (Metals)	1.25E+05	kg/1000 MW Plant
Silver (Metals)	5.00E+02	kg/1000 MW Plant
Steel plate, BF (85% Recovery Rate) (Metals)	3.40E+07	kg/1000 MW Plant
Stainless Steel Cold Roll, 431 (Metals)	2.08E+06	kg/1000 MW Plant
Outputs		
Carbon dioxide (Inorganic emissions to air)	3.61E+08	kg/1000 MW Plant
Carbon monoxide (Inorganic emissions to air)	2.09E+06	kg/1000 MW Plant
Dust (PM10) (Particles to air)	6.82E+05	kg/1000 MW Plant
Nitrogen dioxide (Inorganic emissions to air)	9.70E+06	kg/1000 MW Plant
Sulphur dioxide (Inorganic emissions to air)	6.38E+05	kg/1000 MW Plant
VOC (unspecified) (Organic emissions to air [group VOC])	7.92E+05	kg/1000 MW Plant

B.3.2 Generation III+ Power Plant

The model of Generation III+ nuclear power plant operation seeks to represent the industry average of proposed advanced nuclear reactors. Data for establishing this average comes from submitted Environmental Impact Statements (EIS) to the Nuclear Regulatory Commission for all of the proposed plants. The proportion of Pressurized Water Reactors (PWR) to Boiling Water Reactors (BWR) in this average is 67:33. In the calculated operating parameters and plant emissions, the contribution from each proposed plant is weighted according to the relative power output of that plant to the power output of the total proposed fleet. The industry average values for plant parameters for each of the types of reactors and the overall Gen III+ value are provided in **Table B-26**.

Table B-26: Proposed Industry Average Gen III+ Nuclear Power Plant Operating Parameters

Parameter	PWR Reactors Average Proposed Plant	BWR Reactors Average Proposed Plant	Overall Gen III+ Average
Single Reactor Output (MW)	1251	1508	1336
Capacity Factor	93.4	95	94.0
Thermal Efficiency	33.9	34.7	34.2
Effective Electric Output (MW)	1174	1438	1261
Plant Lifetime (years)	60	60	60
Calculated Net Electrical Generation (MWh/ year)	1.71E+07	1.68E+07	1.70E+07
Fuel Burn-up (kg uranium fuel/MWh electricity produced)	8.41E-04	9.06E-04	8.63E-04
Average Water Withdrawal (L/kWh)	4,420	3,330	4,060
Water Discharge (L/MWh)	1,450	1,210	1,370
Mixed Waste (m^3/MWh)	1.60E-07	3.96E-08	1.20E-07

The proposed plant EIS's provide plant operating parameters, fuel burnup, water withdrawal and discharge, and mixed waste (mixed hazardous and radioactive waste). For the important parameters of fuel use and water withdrawal, the variability between maximum and minimum of all reported values is recorded with adjustable parameters. GHG Emissions produced during normal reactor operation are assumed to be negligible.

A data limitation exists for Generation III+ nuclear power plant air and water emissions. Therefore, existing nuclear fleet operational data is used as a surrogate. Air and water emissions are representative of emissions from the U.S. average nuclear power industry for one year, and as such, an adjustment is made to the emissions to account for increased thermal efficiency of Gen III+ reactors over existing reactors. Emissions are then normalized by electricity output of Gen III+ plants, thus incorporating the increased capacity factor of Gen III+ plants over existing plants.

Emissions are directly adjusted to account for the increased thermal efficiency of Gen III+ plant as described on the 'Average Operations' worksheet. Air emissions data for the existing plant average is taken from U.S. EPA nuclear industry emission factors categorized under the North American Industry Classification System (NAICS) code 221113 (EPA, 2009a). A list of criteria air emissions and hazardous air emissions inventoried by NAICS is available on the 'Average Operations' worksheet of the DS sheet.

Water emissions were collected from the U.S. EPA's *Enforcement & Compliance History Online* report. Reported emissions are separated by cooling type used at the proposed plant: closed-loop and once-through (EPA, 2009b).

Radioactive emissions to air were compared from two sources: the Westinghouse AP 1000 (PWR) environmental report (Westinghouse, 2009) and the Generic Environmental Impact Statement for License Renewal of Nuclear Plants (NUREG-1437 Vol. 1). The higher of the two values was reported by Westinghouse 2009, thus this value was used as the more conservative estimate. Radioactive water emissions were also taken from Westinghouse.

Table B-27 provides a summary of modeled input and output flows for the Gen III+ nuclear reactor.

Table B-27: Generation III+ Nuclear Power Plant Operation Inputs and Outputs

Flow Name	Value	Units
Inputs		
Uranium Fuel Assemblies (UO_2) (Intermediate product)	2.53E-03	kg/MWh
Water (surface water) (Water)	2.79E-06	kg/MWh
Outputs		
Electricity (Operation)	1.00E+00	MWh
Spent fuel (UO_2)	2.53E-03	kg/MWh
Radionuclides (Radioactive emissions to air)	6.02E+05	Bq/MWh
Radionuclides (Radioactive emissions to water)	2.05E+06	Bq/MWh
Carbon dioxide (Inorganic emissions to air)	0.00E+00	kg/MWh
Methane (Organic emissions to air [group VOC])	0.00E+00	kg/MWh
Nitrous oxide (laughing gas) (Inorganic emissions to air)	0.00E+00	kg/MWh
Nitrogen oxides (Inorganic emissions to air)	5.09E-04	kg/MWh
Sulphur dioxide (Inorganic emissions to air)	7.83E-05	kg/MWh
Carbon monoxide (Inorganic emissions to air)	9.78E-05	kg/MWh
NMVOC (unspecified) (Group NMVOC to air)	4.14E-05	kg/MWh
Dust (PM10) (Particles to air)	2.00E-04	kg/MWh
Dust (PM2.5) (Particles to air)	1.27E-04	kg/MWh
Lead (+II) (Heavy metals to air)	3.68E-09	kg/MWh
Mercury (+II) (Heavy metals to air)	5.49E-11	kg/MWh
Ammonia (Inorganic emissions to air)	6.70E-06	kg/MWh
Selenium (Heavy metals to air)	2.53E-10	kg/MWh
Chromium (unspecified) (Heavy metals to air)	5.07E-11	kg/MWh
Manganese (+II) (Heavy metals to air)	1.02E-10	kg/MWh
Nickel (+II) (Heavy metals to air)	5.41E-11	kg/MWh
Arsenic (+V) (Heavy metals to air)	6.76E-11	kg/MWh
Cadmium (+II) (Heavy metals to air)	5.07E-11	kg/MWh
Aluminum (+III) (Inorganic emissions to fresh water)	8.21E-04	kg/MWh
Chlorine (dissolved) (Inorganic emissions to fresh water)	1.39E-04	kg/MWh
Iron (Heavy metals to fresh water)	5.99E-04	kg/MWh
Oil (unspecified) (Hydrocarbons to fresh water)	6.63E-03	kg/MWh
Phosphorus (Inorganic emissions to fresh water)	7.41E-04	kg/MWh
Solids (suspended) (Particles to fresh water)	1.46E-02	kg/MWh
Ammonia (NH_3)	3.58E-04	kg/MWh
Total Nitrogen (N)	1.69E-03	kg/MWh
Oxidants	9.25E-05	kg/MWh

Flow Name	Value	Units
Barium	9.58E-05	kg/MWh
Boron	4.09E-04	kg/MWh
Fluoride	4.63E-04	kg/MWh
Chromium, Total	2.62E-06	kg/MWh
Copper, total recoverable	3.96E-05	kg/MWh
Mercury, total	5.49E-09	kg/MWh
Zinc	1.92E-04	kg/MWh
Water (river water) (Water)	1.37E+03	L/MWh
Waste (solid) (Waste for disposal)	4.26E-05	kg/MWh
Mixed Waste (Hazardous or Radioactive)	1.20E-07	m^3/MWh

The construction of the Generation III+ nuclear power plant is based on the "DOE NP2010 Nuclear Power Plant Construction Infrastructure Assessment" report (DOE, 2005). The document assesses the adequacy of current infrastructure to construct a new fleet of nuclear power plants in the U.S. between 2010 and 2017. Included in the assessment are material resource requirements: reinforced steel and embedded parts, structural steel, large- and small-bore pipe, cable, and concrete. From these part lists and estimates of raw material requirements for each of the components, a raw material input list was calculated. It was assumed that reinforcing and embedded parts are 50 percent carbon steel, 50 percent stainless steel. It was also assumed that structural steel, miscellaneous steel, and decking are 75 percent carbon steel and 25 percent stainless steel. Pipe weights and raw material requirements came from ANSI Schedule 40 (The Engineering Toolbox, 2005).

Diesel combusted in heavy equipment accounts for majority of fuel combusted during construction of the power plant. No primary data was available to determine the amount of diesel needed for the installation of the power plant: a significant data limitation. This quantity was estimated from the cost of diesel fuel relative to total plant construction cost. Plant construction cost ranges from 1100 to 6000 $/kWe, depending on the referenced source. The midpoint between these costs is used as the default value for this analysis with each extreme suggested for adjustment in sensitivity analysis. The cost of diesel is assumed to range between 2 and 4 dollars per gallon. The default value of the cost of diesel is 3 dollars per gallon. The cost ratio between the cost of the power plant and the cost of the diesel is assumed to be between 1 and 5 percent. The default value is assumed to be 3 percent.

Table B-28 provides a summary of modeled input and output flows for construction and installation of the Gen III+ power plant.

Table B-28: Material Inputs for Generation III+ Plant Construction and Installation

Flow Name	Value	Units
Inputs		
Diesel (Crude oil products)	1.14E+08	kg/1000 MW Plant
Steel plate, BF (85% Recovery Rate) (Metals)	3.84E+07	kg/1000 MW Plant
Steel, pipe welded, BF (85% Recovery Rate) (Metals)	1.01E+07	kg/1000 MW Plant
Steel, Stainless, 316 2B (80% Recycled) (Metals)	2.99E+07	kg/1000 MW Plant
Concrete, ready mix, R-5-0 (Concrete_Cement)	7.58E+08	kg/1000 MW Plant
Outputs		
Nitrogen oxides (Inorganic emissions to air)	9.70E+06	kg/1000 MW Plant
Carbon monoxide (Inorganic emissions to air)	2.09E+06	kg/1000 MW Plant
Sulphur oxides (Inorganic emissions to air)	6.38E+05	kg/1000 MW Plant
Dust (PM10) (Particles to air)	6.82E+05	kg/1000 MW Plant
Carbon dioxide (Inorganic emissions to air)	3.61E+08	kg/1000 MW Plant
NMVOC (unspecified) (Group NMVOC to air)	7.92E+05	kg/1000 MW Plant

B.3.3 Nuclear Power Plant Decommissioning

The decommissioning of a nuclear power plant is based on the 1997 decommissioning of the Yankee Rowe reactor, when it was shipped to a low-level waste disposal facility (YAEC, 1997). Decommissioning materials for each reactor includes 90 tons of steel for shipping containers, 20 tons of steel rope for manipulation of the containers, and 80 tons of concrete for sealing of radioactive contaminated material in the containers.

Power plant decommissioning energy (diesel use by construction vehicles) was assumed to be 10 percent of installation energy. Air emissions from combustion of this diesel are included in the decommissioning unit process, as well as fugitive road dust from operation of the vehicles.

Table B-29 shows the material inputs for nuclear power plant decommissioning.

Table B-29: Material Inputs for Nuclear Power Plant Decommissioning

Flow Name	Value	Units
Inputs		
Steel plate, BF (85% Recovery Rate) (Metals)	3.024E-03	kg/MWh
Concrete, ready mix, R-5-0 (Concrete_Cement)	2.199E-03	kg/MWh
Locomotive Transport	1.776E+01	kg-km/MWh
Diesel (Crude oil product)	3.453E-01	kg/MWh
Outputs		
Mixed Waste (Hazardous or Radioactive)	1.00E-02	kg/MWh
Dust (PM10) (Particles to air)	6.02E-03	kg/MWh
Nitrogen dioxide (Inorganic emissions to air)	2.94E-02	kg/MWh
Carbon monoxide (Inorganic emissions to air)	6.33E-03	kg/MWh
Sulphur dioxide (Inorganic emissions to air)	1.93E-03	kg/MWh
Carbon dioxide (Inorganic emissions to air)	1.09E+00	kg/MWh
Volatile Organic Carbons (Organic emissions to air)	2.40E-03	kg/MWh

B.3.4 Spent Fuel Cask Construction

Terminal end-of-life for nuclear spent fuel is undetermined at this time, therefore, no transport or permanent storage preparation/ construction is included in the study. The constructed spent fuel cask is used to store spent fuel rods after they have been cooled in a storage pool for several years. Construction of the spent fuel cask is based on manufacturer specifications for a MAGNASTOR storage system produced by NAC International (NAC International, 2010). It is assumed there is no leakage of spent fuel or produced residues for the indefinite period of storage.

The total weight of a spent fuel storage cask was readily available but reliable data for the material breakdown of storage cask subcomponents were not. Diagrams and cask measurements were used to calculate the quantity of materials needed for both the concrete and steel portions (Concrete, ready mix, R-5-0 and Stainless steel, 316 2B, 80 percent Recycled). The mass of the spent fuel which could be stored in the cask was calculated by subtracting the mass of the materials from the maximum weight which a crane can lift.

Several assumptions were made in interpreting the available specifications for storage casks:

- It is assumed that the internal cavity dimensions provided by NAC International are descriptive of the interior space within the steel wall. Thus the described canister shell thickness is the thickness of the steel wall.
- It is assumed that the canister has a cap and bottom made of steel.
- It is assumed that two-thirds of the empty space in the canister is concrete (one-third above and one-third below the fuel rods) and one-third is void of material for fuel rod storage.
- It is assumed that the maximum weight will not exceed 114 tons which is the combined weight of the cask and PWR fuel assembles to be moved by a crane.

Total weight for one spent fuel cask is estimated to be approximately 81,330 kg (179,301 lb.) (NAC International, 2010). Based on the volume of the materials needed, 80,663 kg (177,830 lb.) is assumed

to be stainless steel and 666 kg (1,468 lb.) is assumed to be concrete. **Table B-30** provides a summary of modeled input flows.

Table B-30: Material Inputs for Spent Fuel Cask Construction

Flow Name	Value	Units
Concrete, ready mix, R-5-0 (Concrete_Cement)	80,663	kg/cask
Stainless steel, 316 2B, 80% Recycled (Metals)	666	kg/cask
Spent fuel (Energy carrier)	22,090	kg/cask

B.4 Nuclear Waste Management

This analysis of nuclear power includes a screening life cycle assessment (LCA) of nuclear waste management options. This screening required the development of the following four unit processes:

- Low Level Waste (LLW) Disposition
- High Level Waste (HLW) Disposition
- Truck Transport of Nuclear Waste
- Spent Fuel Reprocessing

The data and assumptions for these unit processes are described below, followed by a discussion of how they relate to the other processes of the nuclear LC.

B.4.1 Low Level Waste Disposition

This unit process accounts for the energy and material requirements for constructing a long-term disposal facility for LLW from the nuclear fuel cycle. LLW includes contaminated minerals and metals from steady-state nuclear operations as well as from the decommissioning of nuclear power plants. Key inputs to this unit process include the construction materials and installation energy requirements for a LLW disposition facility. The reference flow of this unit process is the disposition of one kilogram of LLW.

The key materials for constructing a (LLW repository include stainless steel, concrete, and cement (Lenzen, 2008). The construction of an LLW facility requires 500 tonnes of stainless steel, 24,100 tonnes of concrete, and 8,300 tonnes of cement (Lenzen, 2008). These construction requirements are representative of a LLW facility with a capacity of 43.1 thousand tonnes of waste.

The energy requirements for the construction of an LLW facility include thermal energy and electricity. Thermal energy is assumed to be comprised mostly of diesel combusted in heavy equipment; the construction of the facility requires 47 GWh of thermal energy. Electricity requirements for the construction of an LLW facility are 1,051 GWh. These energy requirements are representative of a LLW facility with a capacity of 43.1 million kilograms of waste.

The volume of LLW from spent fuel is 1,300 m^3/year for a 1,000 MW reactor; this is 52,000 m^3 during the 40-year life of a reactor. The volume of LLW from plant decommissioning is 17,900 m^3.

To translate all flows to the reference flow of one kilogram of disposed LLW, the material and energy requirements are divided by the lifetime capacity of the LLW facility. The above material and energy requirements are representative of a LLW facility with a capacity of 43.1 million kilograms of waste (Lenzen, 2008).

Table B-31 shows the energy and material requirements for the construction of a LLW facility. All flows are scaled to the basis of the reference flow (one kilogram of waste).

Table B-31: Inputs and Outputs for Construction of a LLW Facility

Inputs	Value	Units
Low Level Waste	1	kg
Stainless Steel Cold Roll, 431 (Metals)	1.161E-02	kg
Concrete, Ready Mix, R-5-0 (Concrete_Cement)	7.524E-01	kg
Power (Electric Power)	8.640E+01	MJ
Diesel (Crude Oil Products)	9.492E-02	kg
Outputs	**Value**	**Units**
Carbon Dioxide (Inorganic Emissions to Air)	2.538E-01	kg
Nitrogen Oxides (Inorganic Emissions to Air)	6.826E-03	kg
Sulphur Dioxide (Inorganic Emissions to Air)	4.488E-04	kg
Carbon Monoxide (Inorganic Emissions to Air)	1.470E-03	kg
NMVOC (Unspecified) (Group NMVOC to Air)	5.572E-04	kg
Dust (PM10) (Particles to Air)	4.798E-04	kg

B.4.2 High Level Waste Disposition

This unit process accounts for the energy and material requirements for constructing a long-term disposal facility for HLW from the nuclear fuel cycle. HLW includes spent fuel from the operation of a nuclear power plant, including spent fuel that has been stockpiled in temporary storage. Key inputs to this unit process include the construction materials and installation energy requirements for a HLW disposition facility.

The key materials for constructing a HLW repository include reinforced steel, concrete, and copper (Lenzen, 2008). The construction of an HLW facility requires 5,200 tonnes of reinforced steel, 372,600 tonnes of concrete, and 3,200 tonnes of copper (Lenzen, 2008).

The energy requirements for the construction of an HLW facility include thermal energy and electricity. Thermal energy is assumed to be provided by diesel that is combusted in heavy equipment; the construction of the facility requires 119 GWh of thermal energy. Electricity requirements for the construction of an HLW facility are 1,184 GWh.

To translate all flows to the reference flow of one kilogram of disposed HLW, the material and energy requirements are divided by the lifetime capacity of the HLW facility. The above material and energy requirements are representative of a HLW facility with a capacity of 3.19 million kilograms of waste (Lenzen, 2008).

Table B-32 shows the energy and material requirements for the construction of a HLW facility. All flows are scaled to the basis of the reference flow (one kilogram of waste).

Table B-32: Inputs and Outputs for Construction of an HLW Facility

Inputs	Value	Units
High Level Waste	1	kg
Steel Plate, BF (85% Recovery Rate) (Metals)	1.629E+00	kg
Concrete, Ready Mix, R-5-0 (Concrete_Cement)	1.167E+02	kg
Coppersheet (Metals)	1.003E+00	kg
Power (Electric Power)	1.184E+03	MJ
Diesel (Crude Oil Products)	1.130E+01	kg
Outputs	**Value**	**Units**
Carbon Dioxide (Inorganic Emissions to Air)	3.021E+01	kg
Nitrogen Oxides (Inorganic Emissions to Air)	8.122E-01	kg
Sulphur Dioxide (Inorganic Emissions to Air)	5.341E-02	kg
Carbon Monoxide (Inorganic Emissions to Air)	1.750E-01	kg
NMVOC (Unspecified) (Group NMVOC to Air)	6.631E-02	kg
Dust (PM10) (Particles to Air)	5.710E-02	kg

B.4.3 Truck Transport of Nuclear Waste

This unit process accounts for the transport of spent uranium fuel from a nuclear power plant to long-term waste disposition. All spent nuclear fuel is assumed to be transported by a combination truck. The key input is diesel fuel, and key outputs include diesel combustion emissions. The elevated security and safety requirements related to the transport of nuclear waste are not accounted for by this unit process. The reference flow of this unit process is the transport of one kilogram of nuclear waste (either LLW or HLW).

The default transport distance for the transport of spent uranium is 1,000 miles (one way). The truck has a fuel efficiency of 5.1 miles/gallon when fully loaded (Wang, 2006). The truck makes an empty return trip with a fuel efficiency of 9.4 miles/gallon (Franklin Associates, 2004). The total round-trip distance is 2,000 miles. The payload (which is the maximum mass of cargo that can be transported by a single trip) of the combination truck is 20,000 kilogram.

The air emissions from diesel combustion in combination trucks are based on emission factors from GREET version 1.7, an LC model for transportation (Wang, 2006). These emission factors include GHGs and criteria air pollutants. The combustion of one MMBtu of diesel in a combination truck produces 77.8 kilogram of CO_2 emissions. The lower heating value of diesel is 0.128 MMBtu per gallon (Wang, 2006), and the density of diesel is 3.21 kilogram per gallon (ORNL, 2007). Applying the lower heating value and density of diesel to the above CO_2 emission factor gives an emission factor of 3.11 kilogram CO_2 per kilogram of diesel. This same conversion was also applied to the emission factors for other GHG emissions and criteria air pollutants.

Table B-33 shows the energy and emission for the truck transport of spent uranium fuel. All flows are scaled to the basis of the reference flow (the transport of one kilogram of waste).

Table B-33: Inputs and Outputs for Spent UO_2 Transport

Inputs	Value	Units
Diesel (Crude Oil)	4.855E-02	kg
Outputs	**Value**	**Units**
Spent Uranium Fuel (UO_2)	1	kg
VOC (Unspecified) (Organic Emissions to Air [group VOC])	6.541E-05	kg
Carbon Dioxide (Inorganic Emissions to Air)	1.511E-01	kg
Methane (Organic Emissions to Air [group VOC])	3.025E-06	kg
Nitrous Oxide (Laughing Gas) (Inorganic Emissions to Air)	3.887E-06	kg
Sulphur Oxide (Inorganic Emissions to Air)	1.067E-06	kg
Particulate Matter, Unspecified (Other Emissions to Air)	1.465E-05	kg
Nitrogen Oxides (Inorganic Emissions to Air)	7.133E-04	kg
Carbon Monoxide (Inorganic Emissions to Air)	3.472E-04	kg

B.4.4 Spent Fuel Reprocessing

This unit process accounts for the energy and material requirements for operating a facility that reprocesses spent nuclear fuel. The reference flow of this unit process is one kilogram of reprocessed uranium fuel. This unit process is representative of the plutonium and uranium recovery by extraction (PUREX) process for the reprocessing of spent uranium fuel. The feedstock input to the PUREX process is spent uranium fuel from U.S. Gen II reactors. The product output of the PUREX process is mixed oxide fuel (MOX), which is a composite of uranium and plutonium that can be used by Gen II light water reactors. Energy for the PUREX process is provided by electricity and natural gas. There are also ancillary inputs of nitric acid and water.

The annual electricity output of an average Gen II nuclear power plant is 6.19 million MWh. In the same time frame, the average Gen II plant produces 2,870 kilogram of spent fuel. Dividing the spent fuel rate by the electricity rate translates to 0.00464 kilogram of spent fuel per MWh of electricity.

A solution of concentrated nitric acid is used as a reagent for extracting uranium oxide and plutonium from spent fuel. This acid treatment is followed by chemical separation and filtration processes that purify the uranium and plutonium (Boullis & Devezeaux de Lavergne, 2006). It is necessary to feed the recovered uranium through the front end of the nuclear fuel cycle, including the conversion of uranium oxide to uranium hexafluoride (UF_6), followed by enrichment (by centrifuge) and fuel fabrication (WNA, 2011).

On the basis of 1 MWh of electricity production and using a 70.7 percent capacity factor for the power plant (which is representative of the average historical capacity for Gen II power plants), the energy requirements are 0.024 MWh of thermal energy per MWh of electricity and 4.84E-06 MWh of electricity per MWh of electricity. On the basis of one kilogram of spent fuel, the energy requirements are 5.57 MWh of thermal energy and 1.11 MWh of electricity. Finally, converting the thermal energy to a basis of natural gas consumption, 5.57 MWh of thermal energy is 18,520 scf natural gas per kilogram of spent fuel (with natural gas having a heating value of 1,027 Btu/scf).

The amount of nitric acid required for the PUREX process was calculated from the reaction chemistry between nitric acid and uranium oxide. One molecule of uranium reacts with three molecules of HNO_3 to produce a mix of nitrates (Boullis & Devezeaux de Lavergne, 2006). There is a similar reaction between nitric acid in plutonium, in which one molecule of plutonium reacts with four molecules of nitric acid; however, since uranium comprises 95 percent by mass of the spent fuel, the nitric acid requirements are driven mostly by the reaction stoichiometry for uranium nitrates. The molar mass of

uranium oxide and nitric acid are 270 and 63 kg/kgmol, respectively. Thus, at a 1:3 molar ratio between uranium oxide and nitric acid, 0.70 kilogram of nitric acid are required for the reprocessing of 1 kilogram of uranium oxide.

Water is required for process cooling. Based on a draft environmental impact statement of nuclear fuel cycle alternatives (DOE, 2008), spent fuel reprocessing increases the water demand for the nuclear fuel cycle by 24 billion L/yr. for each gigawatt of nuclear power. A gigawatt-year of electricity is equivalent to 8,760,000 MWh, which translates to a water demand of 2,740 L/MWh. On the basis of spent fuel, 2,740 L/MWh is 631,000 L/kg of spent fuel. Ninety-nine percent of this water is returned to the source, and thus water consumption (the difference between withdrawal and discharge) is 6,310 L/kg of spent fuel.

No data are available for the operation of a nuclear fuel reprocessing facility; the U.S. currently does not have any facilities that reprocess spent nuclear fuel. The reprocessing of nuclear fuel uses acid reagents that isolate uranium, followed by a series of separation processes. This process is similar to uranium milling, and thus NETL's unit process for uranium milling is used as a surrogate for nuclear fuel reprocessing. **Table B-34** shows the energy and material flows for the reprocessing of uranium fuel. All flows are scaled to the basis of the reference flow (one kilogram of reprocessed UO_2).

Table B-34: Inputs and Outputs for Spent Fuel Reprocessing

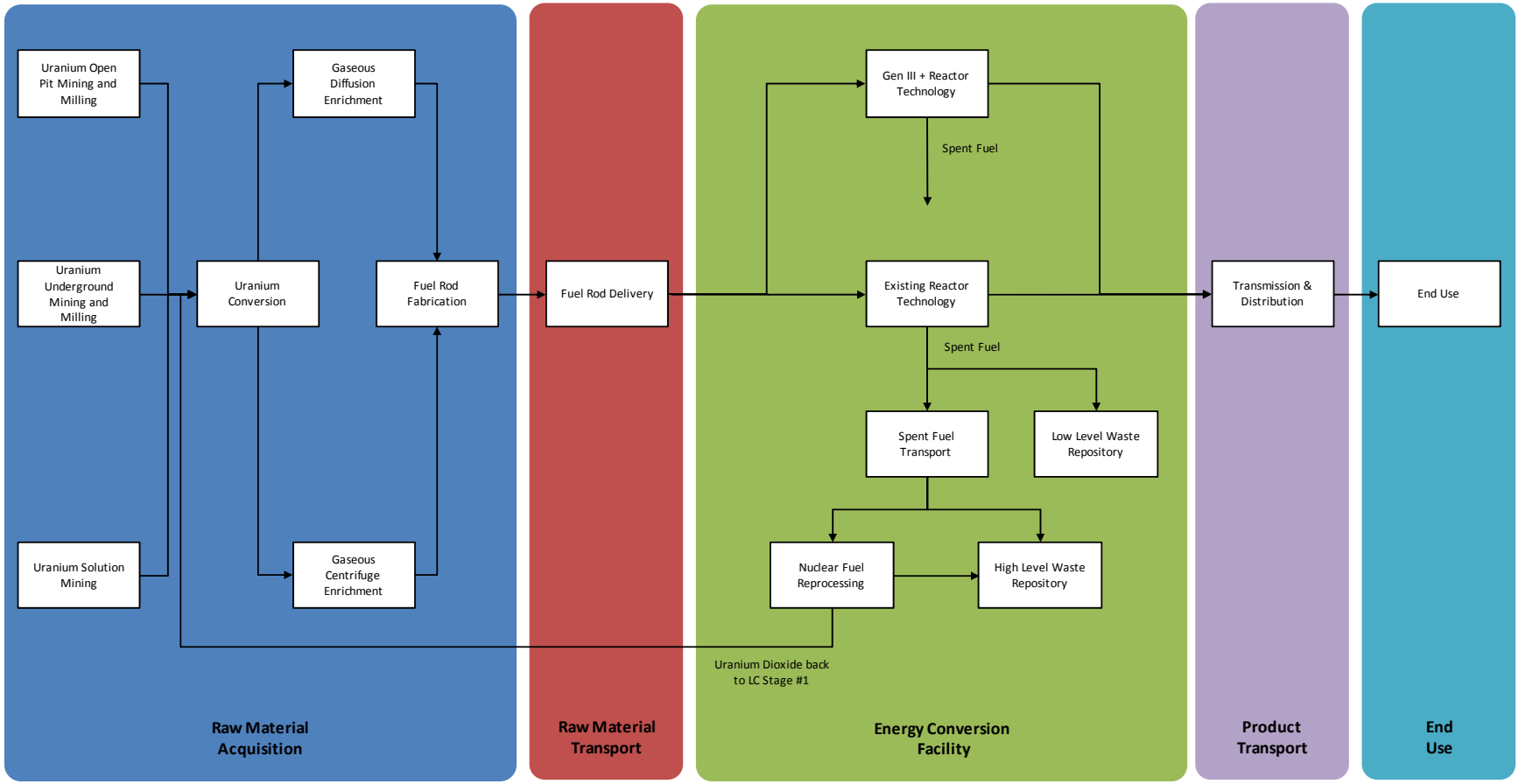
Inputs	Value	Units
Spent Nuclear Fuel	1.047E+00	kg
Nitric Acid	7.176E-01	kg
Water (Ground Water) (Water)	4.364E+05	kg
Water (Surface Water) (Water)	4.364E+05	kg
Power (Electric Power)	2.111E-03	MJ
Natural Gas USA (Natural Gas (Resource))	3.473E-03	kg
Outputs	**Value**	**Units**
Reprocessed Nuclear Fuel	1	kg
Carbon Dioxide (Inorganic Emissions to Air)	9.923E-03	kg
Methane (Organic Emissions to Air [group VOC])	1.902E-07	kg
Nitrous Oxide (Laughing Gas) (Inorganic Emissions to Air)	5.292E-08	kg
Nitrogen Oxides (Inorganic Emissions to Air)	4.134E-06	kg
Sulphur Dioxide (Inorganic Emissions to Air)	4.961E-08	kg
Carbon Monoxide (Inorganic Emissions to Air)	6.946E-06	kg
NMVOC (Unspecified) (Group NMVOC to Air)	4.548E-07	kg
Dust (PM10) (Particles to Air)	6.284E-07	kg
Lead (+II) (Heavy Metals to Air)	4.134E-11	kg
Water (Wastewater) (Water)	8.640E+05	kg
Solid Waste to HLW Disposition	7.642E-01	kg

B.4.5 Modeling Spent Fuel Management in the Nuclear Life Cycle

The following diagram **(Figure B-1**) shows the relationship between the unit processes for spent fuel management and the rest of the nuclear fuel cycle. For this analysis, a Gen II reactor is the chosen nuclear power technology. The spent fuel generated by the Gen II reactor is transported by truck to either an HLW facility that provides long-term disposition of the waste or to a reprocessing facility that recovers uranium that can be returned to the fuel cycle.

Note that an output of the reprocessing facility is waste that is sent to long-term HLW disposition. The reprocessing facility recovers uranium that can be reused by the nuclear fuel cycle, but byproducts of reprocessing, which include heavy metals, cannot be recycled.

Figure B-1: LCA Model Framework for Nuclear Power



B.5 Co-Product Allocation of Uranium Mining and Milling

The UO_2 from the nuclear fuel reprocessing facility is a co-product that is used by the next iteration of the nuclear fuel cycle. It enters the next iteration at the uranium conversion facility and eventually ends up at fuel reprocessing again. This is a closed loop recycling system because all iterations of the cycle are identical and the quality of the recovered uranium does not deteriorate.

The amount of UO_2 recovered from the nuclear fuel cycle depends on the burn rate of the nuclear reactor, the material loss at the reprocessing facility, the concentration of U-235 in recovered UO_2, and the required concentration of U-235 in enriched uranium fuel for use in the Gen II reactor. Based on NETL's unit process for Gen II operations and the new unit processes developed for this analysis (described above), the values for these parameters are as follows:

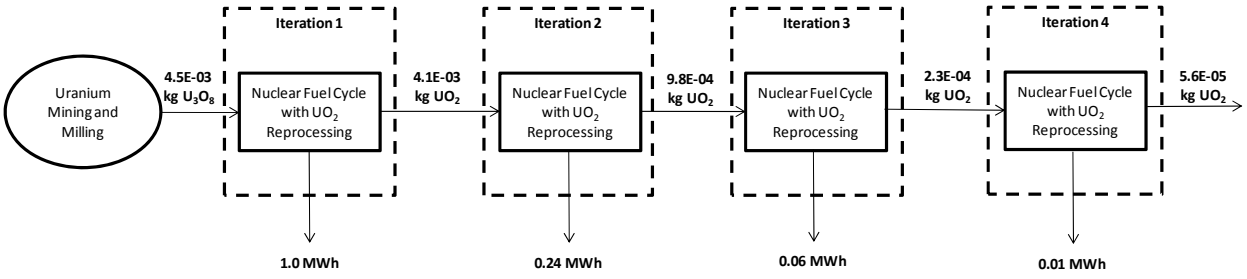
- The burn rate of a Gen II reactor is 4.3E-03 kg UO_2/MWh
- Approximately four percent of UO_2 material is lost during reprocessing
- The concentration of U-235 in reprocessed UO_2 is approximately one percent U-235 by mass
- The concentration of U-235 in enriched UO_2 is approximately four percent U-235 by mass

The above factors indicate that each iteration of the Gen II nuclear fuel cycle results in a 24 percent loss in fissionable uranium, and four iterations of the cycle are necessary before the contribution of recovered UO_2 contributes less than one percent to total environmental burdens. This is shown in **Table B-35** and illustrated in **Figure B-2**.

Table B-35: Uranium and Electricity Flows for Closed Loop Uranium Recycling

Iteration	Uranium Produced by Mining and Milling (kg U_3O_8)	Spent Fuel from Gen II Reactor (kg UO_2)	Uranium Recovered by Reprocessing Facility (kg UO_2)	Electricity Production (MWh)	Share of Uranium Mining and Milling Assigned to Fuel Cycle Iterations
1	4.47E-03	4.30E-03	4.11E-03	1.00	76.4%
2	-	1.03E-03	9.81E-04	0.24	18.2%
3	-	2.45E-04	2.34E-04	0.06	4.4%
4	-	5.85E-05	5.59E-05	0.01	1.0%
Total	**4.47E-03**	**N/A**	**N/A**	**1.31**	**100%**

Figure B-2: Closed Loop Recycling of Uranium Fuel



When UO_2 is recovered by a reprocessing facility, it is returned to the front end of the nuclear cycle, beginning with uranium conversion and proceeding through the remaining steps of the cycle. The mining and milling of uranium are the only activities that occur only once during this LC. Thus, it is necessary to allocate the burdens of the initial mining and milling among all iterations of the reprocessing cycle. There are two methods for accomplishing this allocation:

Method 1: Expand the system boundaries to include all four iterations. The total environmental burdens (the numerator) include all four iterations in addition to the total burdens from mining and milling. The total electricity produced (the denominator) is 1.31 MWh.

Method 2: Restrict the system boundaries to include uranium mining and milling and the first iteration only. Then assign 76 percent of the burdens for uranium mining and milling to the first iteration. The total environmental burdens (the numerator) include the burdens of the first iteration in addition to 76 percent of the burdens from uranium mining and milling. The total electricity produced (the denominator) is 1.00 MWh. The factor of 76 percent is based on the losses calculated in **Table B-35** and illustrated in **Figure B-2**. This factor is consistent with values in literature that state that a nuclear fuel cycle with reprocessing of spent fuel consumes 70 to 80 percent of the uranium consumed by a once-through nuclear fuel cycle (Boullis & Devezeaux de Lavergne, 2006; WNA, 2011)

Both of the above methods give the same result. This analysis uses **Method 2** because of its simplicity. **Method 2** requires a modeling scheme with a single iteration in conjunction with the appropriate scaling of the burdens of uranium mining and milling. **Method 1**, on the other hand, requires a more complicated modeling scheme with four successive cycles.

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Appendix C:
Detailed Results for Nuclear Power Modeling

List of Tables

Table C-1: Existing Nuclear Power with Default Enrichment Mix and No Long Term Waste Management Detailed LCA Results

Category (Units)	Material or Energy Flow	LC Stage #1 (RMA)	LC Stage #2 (RMT)	LC Stage #3 (ECF)	LC Stage #4 (PT)	Total
GHG (kg/MWh)	CO_2	3.07E+01	6.64E-05	2.98E+00	0.00E+00	3.37E+01
	N_2O	4.93E-04	1.45E-09	1.75E-05	0.00E+00	5.11E-04
	CH_4	8.67E-02	2.72E-07	6.14E-03	0.00E+00	9.28E-02
	SF_6	1.83E-07	7.99E-17	1.99E-08	1.43E-04	1.44E-04
	CO_2e (IPCC 2007 100-yr. GWP)	3.31E+01	7.36E-05	3.14E+00	3.27E+00	3.95E+01
Other Air (kg/MWh)	Pb	1.52E-06	9.59E-13	4.98E-07	0.00E+00	2.02E-06
	Hg	3.32E-07	7.96E-14	1.80E-08	0.00E+00	3.50E-07
	NH_3	1.58E-03	5.43E-10	1.52E-05	0.00E+00	1.59E-03
	CO	2.25E-02	9.53E-08	1.43E-02	0.00E+00	3.68E-02
	NO_X	7.36E-02	5.83E-08	2.35E-03	0.00E+00	7.59E-02
	SO_2	1.86E-01	1.12E-07	6.08E-03	0.00E+00	1.92E-01
	VOC	8.19E-03	1.19E-07	1.76E-03	0.00E+00	9.95E-03
	PM	3.91E-03	9.77E-10	3.25E-04	0.00E+00	4.23E-03
Solid Waste (kg/MWh)	Heavy Metals to Industrial Soil	4.70E+01	2.59E-09	6.51E-04	0.00E+00	4.70E+01
	Heavy Metals to Agricultural Soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (L/MWh)	Withdrawal	3.75E+02	1.57E-04	1.12E+05	0.00E+00	1.12E+05
	Discharge	2.96E+02	3.82E-05	1.09E+05	0.00E+00	1.09E+05
	Consumption	7.95E+01	1.19E-04	2.59E+03	0.00E+00	2.67E+03
Water Quality (kg/MWh)	Aluminum	6.77E-06	0.00E+00	2.73E-07	0.00E+00	7.04E-06
	Arsenic (+V)	7.20E-06	8.83E-10	5.30E-03	0.00E+00	5.30E-03
	Copper (+II)	5.64E-06	1.29E-09	6.28E-03	0.00E+00	6.29E-03
	Iron	3.75E-04	6.60E-08	8.73E-02	0.00E+00	8.77E-02
	Lead (+II)	8.06E-06	2.97E-09	3.17E-05	0.00E+00	3.97E-05
	Manganese (+II)	2.70E-04	3.96E-12	2.43E-06	0.00E+00	2.72E-04
	Nickel (+II)	4.98E-01	2.35E-08	2.57E-04	0.00E+00	4.98E-01
	Strontium	5.30E-05	2.17E-11	2.63E-07	0.00E+00	5.33E-05
	Zinc (+II)	1.23E-04	4.09E-08	6.58E-02	0.00E+00	6.59E-02
	Ammonium/Ammonia	1.15E+00	3.35E-07	3.58E-03	0.00E+00	1.15E+00
	Hydrogen Chloride	3.14E-09	8.31E-15	8.98E-11	0.00E+00	3.23E-09
	Nitrogen (as Total N)	1.61E-05	0.00E+00	8.36E-07	0.00E+00	1.69E-05
	Phosphate	5.61E-06	9.82E-13	2.33E-08	0.00E+00	5.64E-06
	Phosphorus	7.65E-05	2.96E-08	1.50E-03	0.00E+00	1.58E-03
Resource Energy (MJ/MWh)	Crude Oil	1.94E+01	2.91E-03	3.15E+01	0.00E+00	5.08E+01
	Hard Coal	2.88E+02	3.90E-05	2.41E+00	0.00E+00	2.91E+02
	Lignite	1.59E+00	2.89E-06	6.29E-02	0.00E+00	1.65E+00
	Natural Gas	1.05E+03	4.11E-04	1.34E+01	0.00E+00	1.07E+03
	Uranium	4.82E+01	1.35E-04	1.07E+04	0.00E+00	1.07E+04
	Total Resource Energy	1.41E+03	3.50E-03	1.07E+04	0.00E+00	1.21E+04
Energy Return on Investment		N/A	N/A	N/A	N/A	0.43:1

Table C-2: Existing Nuclear Power with Default Enrichment Mix and No Long Term Waste Management Detailed LCA Results in Alternate Units

Category (Units)	Material or Energy Flow	LC Stage #1 (RMA)	LC Stage #2 (RMT)	LC Stage #3 (ECF)	LC Stage #4 (PT)	Total
GHG (lb/MWh)	CO_2	6.78E+01	1.46E-04	6.57E+00	0.00E+00	7.43E+01
	N_2O	1.09E-03	3.19E-09	3.86E-05	0.00E+00	1.13E-03
	CH_4	1.91E-01	6.00E-07	1.35E-02	0.00E+00	2.05E-01
	SF_6	4.02E-07	1.76E-16	4.39E-08	3.16E-04	3.16E-04
	CO_2e (IPCC 2007 100-yr. GWP)	7.29E+01	1.62E-04	6.92E+00	7.20E+00	8.70E+01
Other Air (lb/MWh)	Pb	3.35E-06	2.11E-12	1.10E-06	0.00E+00	4.45E-06
	Hg	7.32E-07	1.75E-13	3.98E-08	0.00E+00	7.72E-07
	NH_3	3.48E-03	1.20E-09	3.35E-05	0.00E+00	3.51E-03
	CO	4.97E-02	2.10E-07	3.15E-02	0.00E+00	8.12E-02
	NO_X	1.62E-01	1.29E-07	5.19E-03	0.00E+00	1.67E-01
	SO_2	4.11E-01	2.46E-07	1.34E-02	0.00E+00	4.24E-01
	VOC	1.81E-02	2.63E-07	3.88E-03	0.00E+00	2.19E-02
	PM	8.62E-03	2.15E-09	7.16E-04	0.00E+00	9.33E-03
Solid Waste (lb/MWh)	Heavy Metals to Industrial Soil	1.04E+02	5.71E-09	1.44E-03	0.00E+00	1.04E+02
	Heavy Metals to Agricultural Soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (gal/MWh)	Withdrawal	9.91E+01	4.15E-05	2.95E+04	0.00E+00	2.96E+04
	Discharge	7.81E+01	1.01E-05	2.88E+04	0.00E+00	2.89E+04
	Consumption	2.10E+01	3.14E-05	6.83E+02	0.00E+00	7.04E+02
Water Quality (lb/MWh)	Aluminum	1.49E-05	0.00E+00	6.01E-07	0.00E+00	1.55E-05
	Arsenic (+V)	1.59E-05	1.95E-09	1.17E-02	0.00E+00	1.17E-02
	Copper (+II)	1.24E-05	2.85E-09	1.39E-02	0.00E+00	1.39E-02
	Iron	8.28E-04	1.46E-07	1.92E-01	0.00E+00	1.93E-01
	Lead (+II)	1.78E-05	6.56E-09	6.99E-05	0.00E+00	8.76E-05
	Manganese (+II)	5.95E-04	8.74E-12	5.35E-06	0.00E+00	6.01E-04
	Nickel (+II)	1.10E+00	5.19E-08	5.66E-04	0.00E+00	1.10E+00
	Strontium	1.17E-04	4.78E-11	5.80E-07	0.00E+00	1.17E-04
	Zinc (+II)	2.71E-04	9.01E-08	1.45E-01	0.00E+00	1.45E-01
	Ammonium/Ammonia	2.54E+00	7.39E-07	7.90E-03	0.00E+00	2.54E+00
	Hydrogen Chloride	6.93E-09	1.83E-14	1.98E-10	0.00E+00	7.13E-09
	Nitrogen (as Total N)	3.54E-05	0.00E+00	1.84E-06	0.00E+00	3.72E-05
	Phosphate	1.24E-05	2.16E-12	5.14E-08	0.00E+00	1.24E-05
	Phosphorus	1.69E-04	6.52E-08	3.31E-03	0.00E+00	3.48E-03
Resource Energy (Btu/MWh)	Crude Oil	1.83E+04	2.76E+00	2.98E+04	0.00E+00	4.82E+04
	Hard Coal	2.73E+05	3.69E-02	2.29E+03	0.00E+00	2.76E+05
	Lignite	1.50E+03	2.74E-03	5.96E+01	0.00E+00	1.56E+03
	Natural Gas	9.99E+05	3.90E-01	1.27E+04	0.00E+00	1.01E+06
	Uranium	4.57E+04	1.28E-01	1.01E+07	0.00E+00	1.01E+07
	Total Resource Energy	1.34E+06	3.32E+00	1.01E+07	0.00E+00	1.15E+07
Energy Return on Investment		N/A	N/A	N/A	N/A	0.43:1

Table C-3: Existing Nuclear Power with Centrifuge Enrichment and No Long Term Waste Management Detailed LCA Results

Category (Units)	Material or Energy Flow	LC Stage #1 (RMA)	LC Stage #2 (RMT)	LC Stage #3 (ECF)	LC Stage #4 (PT)	Total
GHG (kg/MWh)	CO_2	4.47E+00	6.64E-05	2.98E+00	0.00E+00	7.45E+00
	N_2O	1.68E-04	1.45E-09	1.75E-05	0.00E+00	1.85E-04
	CH_4	6.96E-02	2.72E-07	6.14E-03	0.00E+00	7.58E-02
	SF_6	2.55E-07	7.99E-17	1.99E-08	1.43E-04	1.44E-04
	CO_2e (IPCC 2007 100-yr. GWP)	6.27E+00	7.36E-05	3.14E+00	3.27E+00	1.27E+01
Other Air (kg/MWh)	Pb	3.30E-07	9.59E-13	4.98E-07	0.00E+00	8.28E-07
	Hg	3.77E-08	7.96E-14	1.80E-08	0.00E+00	5.58E-08
	NH_3	2.80E-03	5.43E-10	1.52E-05	0.00E+00	2.81E-03
	CO	1.22E-02	9.53E-08	1.43E-02	0.00E+00	2.64E-02
	NO_X	2.25E-02	5.83E-08	2.35E-03	0.00E+00	2.49E-02
	SO_2	1.07E-02	1.12E-07	6.08E-03	0.00E+00	1.68E-02
	VOC	7.87E-03	1.19E-07	1.76E-03	0.00E+00	9.63E-03
	PM	6.04E-04	9.77E-10	3.25E-04	0.00E+00	9.28E-04
Solid Waste (kg/MWh)	Heavy Metals to Industrial Soil	4.75E+01	2.59E-09	6.51E-04	0.00E+00	4.75E+01
	Heavy Metals to Agricultural Soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (L/MWh)	Withdrawal	8.01E+01	1.57E-04	1.12E+05	0.00E+00	1.12E+05
	Discharge	7.23E+01	3.82E-05	1.09E+05	0.00E+00	1.09E+05
	Consumption	7.85E+00	1.19E-04	2.59E+03	0.00E+00	2.59E+03
Water Quality (kg/MWh)	Aluminum	7.17E-06	0.00E+00	2.73E-07	0.00E+00	7.44E-06
	Arsenic (+V)	6.84E-06	8.83E-10	5.30E-03	0.00E+00	5.30E-03
	Copper (+II)	5.68E-06	1.29E-09	6.28E-03	0.00E+00	6.29E-03
	Iron	3.07E-04	6.60E-08	8.73E-02	0.00E+00	8.76E-02
	Lead (+II)	8.00E-06	2.97E-09	3.17E-05	0.00E+00	3.97E-05
	Manganese (+II)	2.68E-04	3.96E-12	2.43E-06	0.00E+00	2.71E-04
	Nickel (+II)	5.03E-01	2.35E-08	2.57E-04	0.00E+00	5.03E-01
	Strontium	1.83E-06	2.17E-11	2.63E-07	0.00E+00	2.09E-06
	Zinc (+II)	1.28E-04	4.09E-08	6.58E-02	0.00E+00	6.59E-02
	Ammonium/Ammonia	1.16E+00	3.35E-07	3.58E-03	0.00E+00	1.17E+00
	Hydrogen Chloride	2.93E-09	8.31E-15	8.98E-11	0.00E+00	3.02E-09
	Nitrogen (as Total N)	1.91E-05	0.00E+00	8.36E-07	0.00E+00	2.00E-05
	Phosphate	5.25E-06	9.82E-13	2.33E-08	0.00E+00	5.28E-06
	Phosphorus	7.72E-05	2.96E-08	1.50E-03	0.00E+00	1.58E-03
Resource Energy (MJ/MWh)	Crude Oil	1.47E+01	2.91E-03	3.15E+01	0.00E+00	4.61E+01
	Hard Coal	1.38E+01	3.90E-05	2.41E+00	0.00E+00	1.62E+01
	Lignite	1.36E+00	2.89E-06	6.29E-02	0.00E+00	1.42E+00
	Natural Gas	1.09E+03	4.11E-04	1.34E+01	0.00E+00	1.10E+03
	Uranium	4.55E+01	7.90E-05	1.07E+04	0.00E+00	1.07E+04
	Total Resource Energy	1.16E+03	3.44E-03	1.07E+04	0.00E+00	1.18E+04
Energy Return on Investment		N/A	N/A	N/A	N/A	0.44:1

Table C-4: Existing Nuclear Power with Centrifuge Enrichment and No Long Term Waste Management Detailed LCA Results in Alternate Units

Category (Units)	Material or Energy Flow	LC Stage #1 (RMA)	LC Stage #2 (RMT)	LC Stage #3 (ECF)	LC Stage #4 (PT)	Total
GHG (lb/MWh)	CO_2	9.86E+00	1.46E-04	6.57E+00	0.00E+00	1.64E+01
	N_2O	3.70E-04	3.19E-09	3.86E-05	0.00E+00	4.08E-04
	CH_4	1.54E-01	6.00E-07	1.35E-02	0.00E+00	1.67E-01
	SF_6	5.63E-07	1.76E-16	4.39E-08	3.16E-04	3.17E-04
	CO_2e (IPCC 2007 100-yr. GWP)	1.38E+01	1.62E-04	6.92E+00	7.20E+00	2.79E+01
Other Air (lb/MWh)	Pb	7.27E-07	2.11E-12	1.10E-06	0.00E+00	1.82E-06
	Hg	8.32E-08	1.75E-13	3.98E-08	0.00E+00	1.23E-07
	NH_3	6.16E-03	1.20E-09	3.35E-05	0.00E+00	6.20E-03
	CO	2.68E-02	2.10E-07	3.15E-02	0.00E+00	5.83E-02
	NO_X	4.97E-02	1.29E-07	5.19E-03	0.00E+00	5.49E-02
	SO_2	2.35E-02	2.46E-07	1.34E-02	0.00E+00	3.69E-02
	VOC	1.73E-02	2.63E-07	3.88E-03	0.00E+00	2.12E-02
	PM	1.33E-03	2.15E-09	7.16E-04	0.00E+00	2.05E-03
Solid Waste (lb/MWh)	Heavy Metals to Industrial Soil	1.05E+02	5.71E-09	1.44E-03	0.00E+00	1.05E+02
	Heavy Metals to Agricultural Soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (gal/MWh)	Withdrawal	2.12E+01	4.15E-05	2.95E+04	0.00E+00	2.95E+04
	Discharge	1.91E+01	1.01E-05	2.88E+04	0.00E+00	2.88E+04
	Consumption	2.07E+00	3.14E-05	6.83E+02	0.00E+00	6.85E+02
Water Quality (lb/MWh)	Aluminum	1.58E-05	0.00E+00	6.01E-07	0.00E+00	1.64E-05
	Arsenic (+V)	1.51E-05	1.95E-09	1.17E-02	0.00E+00	1.17E-02
	Copper (+II)	1.25E-05	2.85E-09	1.39E-02	0.00E+00	1.39E-02
	Iron	6.78E-04	1.46E-07	1.92E-01	0.00E+00	1.93E-01
	Lead (+II)	1.76E-05	6.56E-09	6.99E-05	0.00E+00	8.75E-05
	Manganese (+II)	5.92E-04	8.74E-12	5.35E-06	0.00E+00	5.97E-04
	Nickel (+II)	1.11E+00	5.19E-08	5.66E-04	0.00E+00	1.11E+00
	Strontium	4.03E-06	4.78E-11	5.80E-07	0.00E+00	4.61E-06
	Zinc (+II)	2.83E-04	9.01E-08	1.45E-01	0.00E+00	1.45E-01
	Ammonium/Ammonia	2.56E+00	7.39E-07	7.90E-03	0.00E+00	2.57E+00
	Hydrogen Chloride	6.45E-09	1.83E-14	1.98E-10	0.00E+00	6.65E-09
	Nitrogen (as Total N)	4.22E-05	0.00E+00	1.84E-06	0.00E+00	4.40E-05
	Phosphate	1.16E-05	2.16E-12	5.14E-08	0.00E+00	1.16E-05
	Phosphorus	1.70E-04	6.52E-08	3.31E-03	0.00E+00	3.48E-03
Resource Energy (Btu/MWh)	Crude Oil	1.39E+04	2.76E+00	2.98E+04	0.00E+00	4.37E+04
	Hard Coal	1.31E+04	3.69E-02	2.29E+03	0.00E+00	1.54E+04
	Lignite	1.29E+03	2.74E-03	5.96E+01	0.00E+00	1.35E+03
	Natural Gas	1.03E+06	3.90E-01	1.27E+04	0.00E+00	1.04E+06
	Uranium	4.32E+04	7.48E-02	1.01E+07	0.00E+00	1.01E+07
	Total Resource Energy	1.10E+06	3.26E+00	1.01E+07	0.00E+00	1.12E+07
Energy Return on Investment		N/A	N/A	N/A	N/A	0.44:1

Table C-5: Gen III+ Nuclear Power with Default Enrichment Mix and No Long Term Waste Management Detailed LCA Results

Category (Units)	Material or Energy Flow	LC Stage #1 (RMA)	LC Stage #2 (RMT)	LC Stage #3 (ECF)	LC Stage #4 (PT)	Total
GHG (kg/MWh)	CO_2	1.80E+01	3.88E-05	3.01E+00	0.00E+00	2.10E+01
	N_2O	2.88E-04	8.46E-10	1.73E-05	0.00E+00	3.06E-04
	CH_4	5.07E-02	1.59E-07	9.87E-03	0.00E+00	6.05E-02
	SF_6	1.07E-07	4.67E-17	4.87E-08	1.43E-04	1.43E-04
	CO_2e (IPCC 2007 100-yr. GWP)	1.93E+01	4.30E-05	3.26E+00	3.27E+00	2.58E+01
Other Air (kg/MWh)	Pb	8.89E-07	5.60E-13	2.36E-07	0.00E+00	1.12E-06
	Hg	1.94E-07	4.65E-14	1.67E-08	0.00E+00	2.11E-07
	NH_3	9.22E-04	3.17E-10	1.20E-05	0.00E+00	9.34E-04
	CO	1.32E-02	5.57E-08	1.26E-02	0.00E+00	2.57E-02
	NO_X	4.30E-02	3.41E-08	2.05E-02	0.00E+00	6.35E-02
	SO_2	1.09E-01	6.53E-08	6.92E-03	0.00E+00	1.16E-01
	VOC	4.79E-03	6.96E-08	3.51E-03	0.00E+00	8.30E-03
	PM	2.28E-03	5.71E-10	9.73E-04	0.00E+00	3.26E-03
Solid Waste (kg/MWh)	Heavy Metals to Industrial Soil	2.75E+01	1.51E-09	1.54E-03	0.00E+00	2.75E+01
	Heavy Metals to Agricultural Soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (L/MWh)	Withdrawal	2.19E+02	9.17E-05	4.38E+03	0.00E+00	4.60E+03
	Discharge	1.73E+02	2.23E-05	1.48E+03	0.00E+00	1.65E+03
	Consumption	4.64E+01	6.94E-05	2.90E+03	0.00E+00	2.94E+03
Water Quality (kg/MWh)	Aluminum	3.95E-06	0.00E+00	1.66E-06	0.00E+00	5.62E-06
	Arsenic (+V)	4.21E-06	5.16E-10	7.95E-06	0.00E+00	1.22E-05
	Copper (+II)	3.30E-06	7.56E-10	5.41E-05	0.00E+00	5.74E-05
	Iron	2.19E-04	3.86E-08	1.22E-03	0.00E+00	1.44E-03
	Lead (+II)	4.71E-06	1.74E-09	2.57E-05	0.00E+00	3.04E-05
	Manganese (+II)	1.58E-04	2.32E-12	6.13E-06	0.00E+00	1.64E-04
	Nickel (+II)	2.91E-01	1.38E-08	2.19E-04	0.00E+00	2.91E-01
	Strontium	3.10E-05	1.27E-11	1.99E-07	0.00E+00	3.12E-05
	Zinc (+II)	7.20E-05	2.39E-08	5.63E-04	0.00E+00	6.35E-04
	Ammonium/Ammonia	6.72E-01	1.96E-07	3.32E-03	0.00E+00	6.76E-01
	Hydrogen Chloride	1.84E-09	4.86E-15	7.43E-11	0.00E+00	1.91E-09
	Nitrogen (as Total N)	9.38E-06	0.00E+00	1.82E-03	0.00E+00	1.83E-03
	Phosphate	3.28E-06	5.74E-13	9.73E-09	0.00E+00	3.29E-06
	Phosphorus	4.47E-05	1.73E-08	1.05E-03	0.00E+00	1.10E-03
Resource Energy (MJ/MWh)	Crude Oil	1.13E+01	1.70E-03	2.58E+01	0.00E+00	3.71E+01
	Hard Coal	1.69E+02	2.28E-05	3.85E+00	0.00E+00	1.72E+02
	Lignite	9.28E-01	1.69E-06	9.00E-02	0.00E+00	1.02E+00
	Natural Gas	6.16E+02	2.40E-04	2.60E+01	0.00E+00	6.42E+02
	Uranium	2.82E+01	7.86E-05	1.06E+04	0.00E+00	1.06E+04
	Total Resource Energy	8.25E+02	2.05E-03	1.07E+04	0.00E+00	1.15E+04
Energy Return on Investment		N/A	N/A	N/A	N/A	0.46:1

Table C-6: Gen III+ Nuclear Power with Default Enrichment Mix and No Long Term Waste Management Detailed LCA Results in Alternate Units

Category (Units)	Material or Energy Flow	LC Stage #1 (RMA)	LC Stage #2 (RMT)	LC Stage #3 (ECF)	LC Stage #4 (PT)	Total
GHG (lb/MWh)	CO_2	3.96E+01	8.55E-05	6.64E+00	0.00E+00	4.62E+01
	N_2O	6.36E-04	1.87E-09	3.81E-05	0.00E+00	6.74E-04
	CH_4	1.12E-01	3.51E-07	2.17E-02	0.00E+00	1.33E-01
	SF_6	2.35E-07	1.03E-16	1.07E-07	3.16E-04	3.16E-04
	CO_2e (IPCC 2007 100-yr. GWP)	4.26E+01	9.48E-05	7.19E+00	7.20E+00	5.70E+01
Other Air (lb/MWh)	Pb	1.96E-06	1.24E-12	5.20E-07	0.00E+00	2.48E-06
	Hg	4.28E-07	1.03E-13	3.68E-08	0.00E+00	4.64E-07
	NH_3	2.03E-03	6.99E-10	2.66E-05	0.00E+00	2.06E-03
	CO	2.90E-02	1.23E-07	2.77E-02	0.00E+00	5.67E-02
	NO_X	9.48E-02	7.52E-08	4.52E-02	0.00E+00	1.40E-01
	SO_2	2.40E-01	1.44E-07	1.53E-02	0.00E+00	2.55E-01
	VOC	1.06E-02	1.53E-07	7.73E-03	0.00E+00	1.83E-02
	PM	5.04E-03	1.26E-09	2.15E-03	0.00E+00	7.18E-03
Solid Waste (lb/MWh)	Heavy Metals to Industrial Soil	6.06E+01	3.33E-09	3.41E-03	0.00E+00	6.06E+01
	Heavy Metals to Agricultural Soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (gal/MWh)	Withdrawal	5.79E+01	2.42E-05	1.16E+03	0.00E+00	1.21E+03
	Discharge	4.56E+01	5.89E-06	3.91E+02	0.00E+00	4.37E+02
	Consumption	1.23E+01	1.83E-05	7.65E+02	0.00E+00	7.77E+02
Water Quality (lb/MWh)	Aluminum	8.72E-06	0.00E+00	3.67E-06	0.00E+00	1.24E-05
	Arsenic (+V)	9.28E-06	1.14E-09	1.75E-05	0.00E+00	2.68E-05
	Copper (+II)	7.27E-06	1.67E-09	1.19E-04	0.00E+00	1.27E-04
	Iron	4.84E-04	8.50E-08	2.70E-03	0.00E+00	3.18E-03
	Lead (+II)	1.04E-05	3.83E-09	5.66E-05	0.00E+00	6.70E-05
	Manganese (+II)	3.48E-04	5.11E-12	1.35E-05	0.00E+00	3.61E-04
	Nickel (+II)	6.41E-01	3.03E-08	4.82E-04	0.00E+00	6.41E-01
	Strontium	6.83E-05	2.79E-11	4.38E-07	0.00E+00	6.87E-05
	Zinc (+II)	1.59E-04	5.26E-08	1.24E-03	0.00E+00	1.40E-03
	Ammonium/Ammonia	1.48E+00	4.32E-07	7.31E-03	0.00E+00	1.49E+00
	Hydrogen Chloride	4.05E-09	1.07E-14	1.64E-10	0.00E+00	4.21E-09
	Nitrogen (as Total N)	2.07E-05	0.00E+00	4.01E-03	0.00E+00	4.03E-03
	Phosphate	7.23E-06	1.26E-12	2.15E-08	0.00E+00	7.25E-06
	Phosphorus	9.86E-05	3.81E-08	2.32E-03	0.00E+00	2.42E-03
Resource Energy (Btu/MWh)	Crude Oil	1.07E+04	1.61E+00	2.45E+04	0.00E+00	3.52E+04
	Hard Coal	1.60E+05	2.16E-02	3.65E+03	0.00E+00	1.63E+05
	Lignite	8.79E+02	1.60E-03	8.53E+01	0.00E+00	9.65E+02
	Natural Gas	5.84E+05	2.28E-01	2.46E+04	0.00E+00	6.08E+05
	Uranium	2.67E+04	7.45E-02	1.01E+07	0.00E+00	1.01E+07
	Total Resource Energy	7.82E+05	1.94E+00	1.01E+07	0.00E+00	1.09E+07
Energy Return on Investment		N/A	N/A	N/A	N/A	0.46:1

Table C-7: Gen III+ Nuclear Power with Centrifuge Enrichment and No Long Term Waste Management Detailed LCA Results

Category (Units)	Material or Energy Flow	LC Stage #1 (RMA)	LC Stage #2 (RMT)	LC Stage #3 (ECF)	LC Stage #4 (PT)	Total
GHG (kg/MWh)	CO_2	2.61E+00	3.88E-05	3.01E+00	0.00E+00	5.62E+00
	N_2O	9.80E-05	8.46E-10	1.73E-05	0.00E+00	1.15E-04
	CH_4	4.07E-02	1.59E-07	9.87E-03	0.00E+00	5.06E-02
	SF_6	1.49E-07	4.67E-17	4.87E-08	1.43E-04	1.44E-04
	CO_2e (IPCC 2007 100-yr. GWP)	3.66E+00	4.30E-05	3.26E+00	3.27E+00	1.02E+01
Other Air (kg/MWh)	Pb	1.93E-07	5.60E-13	2.36E-07	0.00E+00	4.29E-07
	Hg	2.20E-08	4.65E-14	1.67E-08	0.00E+00	3.87E-08
	NH_3	1.63E-03	3.17E-10	1.20E-05	0.00E+00	1.65E-03
	CO	7.10E-03	5.57E-08	1.26E-02	0.00E+00	1.97E-02
	NO_X	1.32E-02	3.41E-08	2.05E-02	0.00E+00	3.37E-02
	SO_2	6.24E-03	6.53E-08	6.92E-03	0.00E+00	1.32E-02
	VOC	4.60E-03	6.96E-08	3.51E-03	0.00E+00	8.10E-03
	PM	3.53E-04	5.71E-10	9.73E-04	0.00E+00	1.33E-03
Solid Waste (kg/MWh)	Heavy Metals to Industrial Soil	2.78E+01	1.51E-09	1.54E-03	0.00E+00	2.78E+01
	Heavy Metals to Agricultural Soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (L/MWh)	Withdrawal	4.68E+01	9.17E-05	4.38E+03	0.00E+00	4.42E+03
	Discharge	4.22E+01	2.23E-05	1.48E+03	0.00E+00	1.52E+03
	Consumption	4.59E+00	6.94E-05	2.90E+03	0.00E+00	2.90E+03
Water Quality (kg/MWh)	Aluminum	4.19E-06	0.00E+00	1.66E-06	0.00E+00	5.85E-06
	Arsenic (+V)	4.00E-06	5.16E-10	7.95E-06	0.00E+00	1.20E-05
	Copper (+II)	3.32E-06	7.56E-10	5.41E-05	0.00E+00	5.75E-05
	Iron	1.80E-04	3.86E-08	1.22E-03	0.00E+00	1.40E-03
	Lead (+II)	4.67E-06	1.74E-09	2.57E-05	0.00E+00	3.04E-05
	Manganese (+II)	1.57E-04	2.32E-12	6.13E-06	0.00E+00	1.63E-04
	Nickel (+II)	2.94E-01	1.38E-08	2.19E-04	0.00E+00	2.94E-01
	Strontium	1.07E-06	1.27E-11	1.99E-07	0.00E+00	1.27E-06
	Zinc (+II)	7.50E-05	2.39E-08	5.63E-04	0.00E+00	6.38E-04
	Ammonium/Ammonia	6.80E-01	1.96E-07	3.32E-03	0.00E+00	6.83E-01
	Hydrogen Chloride	1.71E-09	4.86E-15	7.43E-11	0.00E+00	1.78E-09
	Nitrogen (as Total N)	1.12E-05	0.00E+00	1.82E-03	0.00E+00	1.83E-03
	Phosphate	3.07E-06	5.74E-13	9.73E-09	0.00E+00	3.08E-06
	Phosphorus	4.51E-05	1.73E-08	1.05E-03	0.00E+00	1.10E-03
Resource Energy (MJ/MWh)	Crude Oil	8.56E+00	1.70E-03	2.58E+01	0.00E+00	3.44E+01
	Hard Coal	8.06E+00	2.28E-05	3.85E+00	0.00E+00	1.19E+01
	Lignite	7.93E-01	1.69E-06	9.00E-02	0.00E+00	8.83E-01
	Natural Gas	6.35E+02	2.40E-04	2.60E+01	0.00E+00	6.61E+02
	Uranium	2.66E+01	7.86E-05	1.06E+04	0.00E+00	1.06E+04
	Total Resource Energy	6.79E+02	2.05E-03	1.07E+04	0.00E+00	1.13E+04
Energy Return on Investment		N/A	N/A	N/A	N/A	0.47:1

Table C-8: Gen III+ Nuclear Power with Centrifuge Enrichment and No Long Term Waste Management Detailed LCA Results in Alternate Units

Category (Units)	Material or Energy Flow	LC Stage #1 (RMA)	LC Stage #2 (RMT)	LC Stage #3 (ECF)	LC Stage #4 (PT)	Total
GHG (lb/MWh)	CO_2	5.76E+00	8.55E-05	6.64E+00	0.00E+00	1.24E+01
	N_2O	2.16E-04	1.87E-09	3.81E-05	0.00E+00	2.54E-04
	CH_4	8.97E-02	3.51E-07	2.17E-02	0.00E+00	1.11E-01
	SF_6	3.29E-07	1.03E-16	1.07E-07	3.16E-04	3.16E-04
	CO_2e (IPCC 2007 100-yr. GWP)	8.07E+00	9.48E-05	7.19E+00	7.20E+00	2.25E+01
Other Air (lb/MWh)	Pb	4.25E-07	1.24E-12	5.20E-07	0.00E+00	9.45E-07
	Hg	4.86E-08	1.03E-13	3.68E-08	0.00E+00	8.54E-08
	NH_3	3.60E-03	6.99E-10	2.66E-05	0.00E+00	3.63E-03
	CO	1.57E-02	1.23E-07	2.77E-02	0.00E+00	4.34E-02
	NO_X	2.90E-02	7.52E-08	4.52E-02	0.00E+00	7.43E-02
	SO_2	1.38E-02	1.44E-07	1.53E-02	0.00E+00	2.90E-02
	VOC	1.01E-02	1.53E-07	7.73E-03	0.00E+00	1.79E-02
	PM	7.78E-04	1.26E-09	2.15E-03	0.00E+00	2.92E-03
Solid Waste (lb/MWh)	Heavy Metals to Industrial Soil	6.12E+01	3.33E-09	3.41E-03	0.00E+00	6.12E+01
	Heavy Metals to Agricultural Soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (gal/MWh)	Withdrawal	1.24E+01	2.42E-05	1.16E+03	0.00E+00	1.17E+03
	Discharge	1.12E+01	5.89E-06	3.91E+02	0.00E+00	4.02E+02
	Consumption	1.21E+00	1.83E-05	7.65E+02	0.00E+00	7.66E+02
Water Quality (lb/MWh)	Aluminum	9.24E-06	0.00E+00	3.67E-06	0.00E+00	1.29E-05
	Arsenic (+V)	8.81E-06	1.14E-09	1.75E-05	0.00E+00	2.63E-05
	Copper (+II)	7.32E-06	1.67E-09	1.19E-04	0.00E+00	1.27E-04
	Iron	3.96E-04	8.50E-08	2.70E-03	0.00E+00	3.09E-03
	Lead (+II)	1.03E-05	3.83E-09	5.66E-05	0.00E+00	6.70E-05
	Manganese (+II)	3.46E-04	5.11E-12	1.35E-05	0.00E+00	3.59E-04
	Nickel (+II)	6.48E-01	3.03E-08	4.82E-04	0.00E+00	6.49E-01
	Strontium	2.35E-06	2.79E-11	4.38E-07	0.00E+00	2.79E-06
	Zinc (+II)	1.65E-04	5.26E-08	1.24E-03	0.00E+00	1.41E-03
	Ammonium/Ammonia	1.50E+00	4.32E-07	7.31E-03	0.00E+00	1.51E+00
	Hydrogen Chloride	3.77E-09	1.07E-14	1.64E-10	0.00E+00	3.93E-09
	Nitrogen (as Total N)	2.47E-05	0.00E+00	4.01E-03	0.00E+00	4.04E-03
	Phosphate	6.77E-06	1.26E-12	2.15E-08	0.00E+00	6.79E-06
	Phosphorus	9.95E-05	3.81E-08	2.32E-03	0.00E+00	2.42E-03
Resource Energy (Btu/MWh)	Crude Oil	8.12E+03	1.61E+00	2.45E+04	0.00E+00	3.26E+04
	Hard Coal	7.64E+03	2.16E-02	3.65E+03	0.00E+00	1.13E+04
	Lignite	7.51E+02	1.60E-03	8.53E+01	0.00E+00	8.37E+02
	Natural Gas	6.02E+05	2.28E-01	2.46E+04	0.00E+00	6.26E+05
	Uranium	2.52E+04	7.45E-02	1.01E+07	0.00E+00	1.01E+07
	Total Resource Energy	6.43E+05	1.94E+00	1.01E+07	0.00E+00	1.08E+07
Energy Return on Investment		N/A	N/A	N/A	N/A	0.47:1

Table C-9: Existing Nuclear Power with Default Enrichment Mix and Long Term Waste Management Detailed LCA Results

Category (Units)	Material or Energy Flow	LC Stage #1 (RMA)	LC Stage #2 (RMT)	LC Stage #3 (ECF)	LC Stage #4 (PT)	Total
GHG (kg/MWh)	CO_2	3.07E+01	6.64E-05	4.65E+00	0.00E+00	3.54E+01
	N_2O	4.93E-04	1.45E-09	4.32E-05	0.00E+00	5.37E-04
	CH_4	8.67E-02	2.72E-07	4.34E-02	0.00E+00	1.30E-01
	SF_6	1.83E-07	7.99E-17	2.63E-07	1.43E-04	1.44E-04
	CO_2e (IPCC 2007 100-yr. GWP)	3.31E+01	7.36E-05	5.75E+00	3.27E+00	4.21E+01
Other Air (kg/MWh)	Pb	1.52E-06	9.59E-13	1.08E-06	0.00E+00	2.60E-06
	Hg	3.32E-07	7.96E-14	4.12E-08	0.00E+00	3.73E-07
	NH_3	1.58E-03	5.43E-10	1.65E-05	0.00E+00	1.59E-03
	CO	2.25E-02	9.53E-08	1.60E-02	0.00E+00	3.85E-02
	NO_X	7.36E-02	5.83E-08	1.34E-02	0.00E+00	8.70E-02
	SO_2	1.86E-01	1.12E-07	1.04E-02	0.00E+00	1.97E-01
	VOC	8.19E-03	1.19E-07	7.48E-03	0.00E+00	1.57E-02
	PM	3.91E-03	9.77E-10	6.15E-04	0.00E+00	4.53E-03
Solid Waste (kg/MWh)	Heavy Metals to Industrial Soil	4.70E+01	2.59E-09	8.25E-03	0.00E+00	4.70E+01
	Heavy Metals to Agricultural Soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (L/MWh)	Withdrawal	3.75E+02	1.57E-04	1.12E+05	0.00E+00	1.12E+05
	Discharge	2.96E+02	3.82E-05	1.09E+05	0.00E+00	1.09E+05
	Consumption	7.95E+01	1.19E-04	2.59E+03	0.00E+00	2.67E+03
Water Quality (kg/MWh)	Aluminum	6.77E-06	0.00E+00	3.05E-05	0.00E+00	3.72E-05
	Arsenic (+V)	7.20E-06	8.83E-10	5.30E-03	0.00E+00	5.31E-03
	Copper (+II)	5.64E-06	1.29E-09	6.29E-03	0.00E+00	6.29E-03
	Iron	3.75E-04	6.60E-08	8.74E-02	0.00E+00	8.78E-02
	Lead (+II)	8.06E-06	2.97E-09	3.47E-05	0.00E+00	4.28E-05
	Manganese (+II)	2.70E-04	3.96E-12	3.09E-05	0.00E+00	3.01E-04
	Nickel (+II)	4.98E-01	2.35E-08	3.60E-04	0.00E+00	4.98E-01
	Strontium	5.30E-05	2.17E-11	3.86E-07	0.00E+00	5.34E-05
	Zinc (+II)	1.23E-04	4.09E-08	6.58E-02	0.00E+00	6.59E-02
	Ammonium/Ammonia	1.15E+00	3.35E-07	4.10E-03	0.00E+00	1.15E+00
	Hydrogen Chloride	3.14E-09	8.31E-15	1.06E-10	0.00E+00	3.25E-09
	Nitrogen (as Total N)	1.61E-05	0.00E+00	1.10E-05	0.00E+00	2.71E-05
	Phosphate	5.61E-06	9.82E-13	5.07E-08	0.00E+00	5.67E-06
	Phosphorus	7.65E-05	2.96E-08	1.53E-03	0.00E+00	1.61E-03
Resource Energy (MJ/MWh)	Crude Oil	1.94E+01	2.91E-03	3.30E+01	0.00E+00	5.23E+01
	Hard Coal	2.88E+02	3.90E-05	1.07E+01	0.00E+00	2.99E+02
	Lignite	1.59E+00	2.89E-06	9.85E-02	0.00E+00	1.69E+00
	Natural Gas	1.05E+03	4.11E-04	1.21E+02	0.00E+00	1.17E+03
	Uranium	4.82E+01	1.35E-04	1.07E+04	0.00E+00	1.07E+04
	Total Resource Energy	1.41E+03	3.50E-03	1.08E+04	0.00E+00	1.22E+04
Energy Return on Investment		N/A	N/A	N/A	N/A	0.42:1

Table C-10: Existing Nuclear Power with Default Enrichment Mix and Long Term Waste Management Detailed LCA Results in Alternate Units

Category (Units)	Material or Energy Flow	LC Stage #1 (RMA)	LC Stage #2 (RMT)	LC Stage #3 (ECF)	LC Stage #4 (PT)	Total
GHG (lb/MWh)	CO_2	6.78E+01	1.46E-04	1.02E+01	0.00E+00	7.80E+01
	N_2O	1.09E-03	3.19E-09	9.52E-05	0.00E+00	1.18E-03
	CH_4	1.91E-01	6.00E-07	9.57E-02	0.00E+00	2.87E-01
	SF_6	4.02E-07	1.76E-16	5.80E-07	3.16E-04	3.17E-04
	CO_2e (IPCC 2007 100-yr. GWP)	7.29E+01	1.62E-04	1.27E+01	7.20E+00	9.28E+01
Other Air (lb/MWh)	Pb	3.35E-06	2.11E-12	2.39E-06	0.00E+00	5.74E-06
	Hg	7.32E-07	1.75E-13	9.09E-08	0.00E+00	8.23E-07
	NH_3	3.48E-03	1.20E-09	3.64E-05	0.00E+00	3.52E-03
	CO	4.97E-02	2.10E-07	3.52E-02	0.00E+00	8.49E-02
	NO_X	1.62E-01	1.29E-07	2.96E-02	0.00E+00	1.92E-01
	SO_2	4.11E-01	2.46E-07	2.28E-02	0.00E+00	4.34E-01
	VOC	1.81E-02	2.63E-07	1.65E-02	0.00E+00	3.45E-02
	PM	8.62E-03	2.15E-09	1.36E-03	0.00E+00	9.98E-03
Solid Waste (lb/MWh)	Heavy Metals to Industrial Soil	1.04E+02	5.71E-09	1.82E-02	0.00E+00	1.04E+02
	Heavy Metals to Agricultural Soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (gal/MWh)	Withdrawal	9.91E+01	4.15E-05	2.95E+04	0.00E+00	2.96E+04
	Discharge	7.81E+01	1.01E-05	2.88E+04	0.00E+00	2.89E+04
	Consumption	2.10E+01	3.14E-05	6.84E+02	0.00E+00	7.05E+02
Water Quality (lb/MWh)	Aluminum	1.49E-05	0.00E+00	6.72E-05	0.00E+00	8.21E-05
	Arsenic (+V)	1.59E-05	1.95E-09	1.17E-02	0.00E+00	1.17E-02
	Copper (+II)	1.24E-05	2.85E-09	1.39E-02	0.00E+00	1.39E-02
	Iron	8.28E-04	1.46E-07	1.93E-01	0.00E+00	1.93E-01
	Lead (+II)	1.78E-05	6.56E-09	7.65E-05	0.00E+00	9.43E-05
	Manganese (+II)	5.95E-04	8.74E-12	6.80E-05	0.00E+00	6.63E-04
	Nickel (+II)	1.10E+00	5.19E-08	7.94E-04	0.00E+00	1.10E+00
	Strontium	1.17E-04	4.78E-11	8.50E-07	0.00E+00	1.18E-04
	Zinc (+II)	2.71E-04	9.01E-08	1.45E-01	0.00E+00	1.45E-01
	Ammonium/Ammonia	2.54E+00	7.39E-07	9.03E-03	0.00E+00	2.55E+00
	Hydrogen Chloride	6.93E-09	1.83E-14	2.34E-10	0.00E+00	7.16E-09
	Nitrogen (as Total N)	3.54E-05	0.00E+00	2.43E-05	0.00E+00	5.97E-05
	Phosphate	1.24E-05	2.16E-12	1.12E-07	0.00E+00	1.25E-05
	Phosphorus	1.69E-04	6.52E-08	3.37E-03	0.00E+00	3.54E-03
Resource Energy (Btu/MWh)	Crude Oil	1.83E+04	2.76E+00	3.12E+04	0.00E+00	4.96E+04
	Hard Coal	2.73E+05	3.69E-02	1.01E+04	0.00E+00	2.84E+05
	Lignite	1.50E+03	2.74E-03	9.33E+01	0.00E+00	1.60E+03
	Natural Gas	9.99E+05	3.90E-01	1.15E+05	0.00E+00	1.11E+06
	Uranium	4.57E+04	1.28E-01	1.01E+07	0.00E+00	1.01E+07
	Total Resource Energy	1.34E+06	3.32E+00	1.03E+07	0.00E+00	1.16E+07
Energy Return on Investment		N/A	N/A	N/A	N/A	0.42:1

Table C-11: Existing Nuclear Power with Default Enrichment Mix, Long Term Waste Management and Spent Fuel Reprocessing Detailed LCA Results

Category (Units)	Material or Energy Flow	LC Stage #1 (RMA)	LC Stage #2 (RMT)	LC Stage #3 (ECF)	LC Stage #4 (PT)	Total
GHG (kg/MWh)	CO_2	3.05E+01	6.64E-05	4.20E+00	0.00E+00	3.47E+01
	N_2O	4.81E-04	1.45E-09	5.40E-05	0.00E+00	5.35E-04
	CH_4	8.41E-02	2.72E-07	3.33E-02	0.00E+00	1.17E-01
	SF_6	1.70E-07	7.99E-17	1.97E-07	1.43E-04	1.44E-04
	CO_2e (IPCC 2007 100-yr. GWP)	3.28E+01	7.36E-05	5.05E+00	3.27E+00	4.11E+01
Other Air (kg/MWh)	Pb	1.51E-06	9.59E-13	9.25E-07	0.00E+00	2.44E-06
	Hg	3.30E-07	7.96E-14	3.50E-08	0.00E+00	3.65E-07
	NH_3	1.58E-03	5.43E-10	1.61E-05	0.00E+00	1.59E-03
	CO	2.20E-02	9.53E-08	1.55E-02	0.00E+00	3.75E-02
	NO_X	7.27E-02	5.83E-08	1.04E-02	0.00E+00	8.32E-02
	SO_2	1.86E-01	1.12E-07	9.20E-03	0.00E+00	1.95E-01
	VOC	7.86E-03	1.19E-07	5.93E-03	0.00E+00	1.38E-02
	PM	3.86E-03	9.77E-10	5.35E-04	0.00E+00	4.39E-03
Solid Waste (kg/MWh)	Heavy Metals to Industrial Soil	4.34E+01	2.59E-09	6.20E-03	0.00E+00	4.34E+01
	Heavy Metals to Agricultural Soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (L/MWh)	Withdrawal	3.71E+02	1.57E-04	1.15E+05	0.00E+00	1.16E+05
	Discharge	2.92E+02	3.82E-05	1.13E+05	0.00E+00	1.13E+05
	Consumption	7.86E+01	1.19E-04	2.63E+03	0.00E+00	2.71E+03
Water Quality (kg/MWh)	Aluminum	6.61E-06	0.00E+00	2.23E-05	0.00E+00	2.90E-05
	Arsenic (+V)	6.64E-06	8.83E-10	5.30E-03	0.00E+00	5.30E-03
	Copper (+II)	5.47E-06	1.29E-09	6.29E-03	0.00E+00	6.29E-03
	Iron	3.60E-04	6.60E-08	8.74E-02	0.00E+00	8.77E-02
	Lead (+II)	7.92E-06	2.97E-09	3.39E-05	0.00E+00	4.18E-05
	Manganese (+II)	2.63E-04	3.96E-12	2.32E-05	0.00E+00	2.86E-04
	Nickel (+II)	4.59E-01	2.35E-08	3.32E-04	0.00E+00	4.60E-01
	Strontium	5.28E-05	2.17E-11	3.53E-07	0.00E+00	5.32E-05
	Zinc (+II)	1.20E-04	4.09E-08	6.58E-02	0.00E+00	6.59E-02
	Ammonium/Ammonia	1.06E+00	3.35E-07	3.96E-03	0.00E+00	1.07E+00
	Hydrogen Chloride	2.92E-09	8.31E-15	1.02E-10	0.00E+00	3.03E-09
	Nitrogen (as Total N)	1.54E-05	0.00E+00	8.27E-06	0.00E+00	2.37E-05
	Phosphate	4.82E-06	9.82E-13	4.56E-08	0.00E+00	4.86E-06
	Phosphorus	7.52E-05	2.96E-08	1.52E-03	0.00E+00	1.60E-03
Resource Energy (MJ/MWh)	Crude Oil	1.88E+01	2.91E-03	3.25E+01	0.00E+00	5.13E+01
	Hard Coal	2.87E+02	3.90E-05	8.44E+00	0.00E+00	2.96E+02
	Lignite	1.42E+00	2.89E-06	9.30E-02	0.00E+00	1.52E+00
	Natural Gas	1.03E+03	4.11E-04	9.19E+01	0.00E+00	1.12E+03
	Uranium	4.73E+01	1.35E-04	1.07E+04	0.00E+00	1.07E+04
	Total Resource Energy	1.39E+03	3.50E-03	1.08E+04	0.00E+00	1.22E+04
Energy Return on Investment		N/A	N/A	N/A	N/A	0.42:1

Table C-12: Existing Nuclear Power with Default Enrichment Mix, Long Term Waste Management and Spent Fuel Reprocessing Detailed LCA Results in Alternate Units

Category (Units)	Material or Energy Flow	LC Stage #1 (RMA)	LC Stage #2 (RMT)	LC Stage #3 (ECF)	LC Stage #4 (PT)	Total
GHG (lb/MWh)	CO_2	6.73E+01	1.46E-04	9.26E+00	0.00E+00	7.65E+01
	N_2O	1.06E-03	3.19E-09	1.19E-04	0.00E+00	1.18E-03
	CH_4	1.85E-01	6.00E-07	7.35E-02	0.00E+00	2.59E-01
	SF_6	3.76E-07	1.76E-16	4.35E-07	3.16E-04	3.17E-04
	CO_2e (IPCC 2007 100-yr. GWP)	7.22E+01	1.62E-04	1.11E+01	7.20E+00	9.06E+01
Other Air (lb/MWh)	Pb	3.33E-06	2.11E-12	2.04E-06	0.00E+00	5.37E-06
	Hg	7.27E-07	1.75E-13	7.71E-08	0.00E+00	8.04E-07
	NH_3	3.48E-03	1.20E-09	3.56E-05	0.00E+00	3.51E-03
	CO	4.84E-02	2.10E-07	3.42E-02	0.00E+00	8.27E-02
	NO_X	1.60E-01	1.29E-07	2.30E-02	0.00E+00	1.83E-01
	SO_2	4.10E-01	2.46E-07	2.03E-02	0.00E+00	4.30E-01
	VOC	1.73E-02	2.63E-07	1.31E-02	0.00E+00	3.04E-02
	PM	8.50E-03	2.15E-09	1.18E-03	0.00E+00	9.68E-03
Solid Waste (lb/MWh)	Heavy Metals to Industrial Soil	9.57E+01	5.71E-09	1.37E-02	0.00E+00	9.57E+01
	Heavy Metals to Agricultural Soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (gal/MWh)	Withdrawal	9.80E+01	4.15E-05	3.05E+04	0.00E+00	3.06E+04
	Discharge	7.73E+01	1.01E-05	2.98E+04	0.00E+00	2.99E+04
	Consumption	2.08E+01	3.14E-05	6.94E+02	0.00E+00	7.15E+02
Water Quality (lb/MWh)	Aluminum	1.46E-05	0.00E+00	4.93E-05	0.00E+00	6.38E-05
	Arsenic (+V)	1.46E-05	1.95E-09	1.17E-02	0.00E+00	1.17E-02
	Copper (+II)	1.21E-05	2.85E-09	1.39E-02	0.00E+00	1.39E-02
	Iron	7.93E-04	1.46E-07	1.93E-01	0.00E+00	1.93E-01
	Lead (+II)	1.75E-05	6.56E-09	7.47E-05	0.00E+00	9.22E-05
	Manganese (+II)	5.80E-04	8.74E-12	5.11E-05	0.00E+00	6.31E-04
	Nickel (+II)	1.01E+00	5.19E-08	7.32E-04	0.00E+00	1.01E+00
	Strontium	1.17E-04	4.78E-11	7.79E-07	0.00E+00	1.17E-04
	Zinc (+II)	2.65E-04	9.01E-08	1.45E-01	0.00E+00	1.45E-01
	Ammonium/Ammonia	2.34E+00	7.39E-07	8.73E-03	0.00E+00	2.35E+00
	Hydrogen Chloride	6.44E-09	1.83E-14	2.24E-10	0.00E+00	6.67E-09
	Nitrogen (as Total N)	3.40E-05	0.00E+00	1.82E-05	0.00E+00	5.22E-05
	Phosphate	1.06E-05	2.16E-12	1.00E-07	0.00E+00	1.07E-05
	Phosphorus	1.66E-04	6.52E-08	3.36E-03	0.00E+00	3.52E-03
Resource Energy (Btu/MWh)	Crude Oil	1.78E+04	2.76E+00	3.08E+04	0.00E+00	4.86E+04
	Hard Coal	2.72E+05	3.69E-02	8.00E+03	0.00E+00	2.80E+05
	Lignite	1.35E+03	2.74E-03	8.82E+01	0.00E+00	1.44E+03
	Natural Gas	9.78E+05	3.90E-01	8.71E+04	0.00E+00	1.07E+06
	Uranium	4.49E+04	1.28E-01	1.01E+07	0.00E+00	1.01E+07
	Total Resource Energy	1.31E+06	3.32E+00	1.02E+07	0.00E+00	1.15E+07
Energy Return on Investment		N/A	N/A	N/A	N/A	0.42:1