NATIONAL ENERGY TECHNOLOGY LABORATORY

Role of Alternative Energy Sources: Nuclear Technology Assessment

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Agenda

- Technology Description
- Resource Base
- Growth of Nuclear Power
- Environmental Analysis
- Cost Analysis
- Barriers to Implementation
- Risks of Implementation
- Expert Opinions

Technology Description: Nuclear

- **Nuclear Power**
  - 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 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
  - The energy produced by nuclear fission is used to produce steam for a Rankine power cycle similar to other thermoelectric power plants.

Beaver Valley Power Station
Source: U.S. Nuclear Regulatory Commission

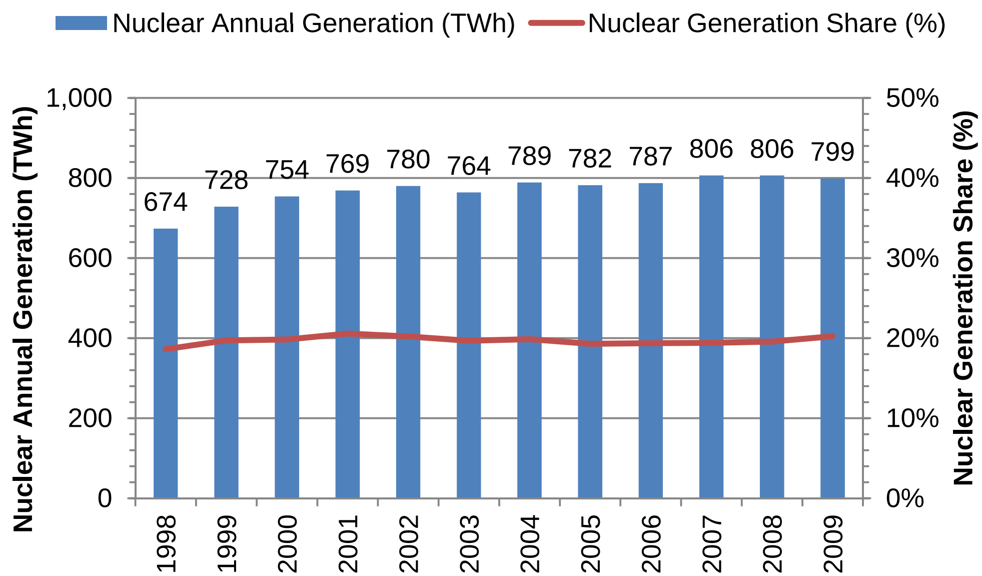
Technology Description: Nuclear Performance Characteristics

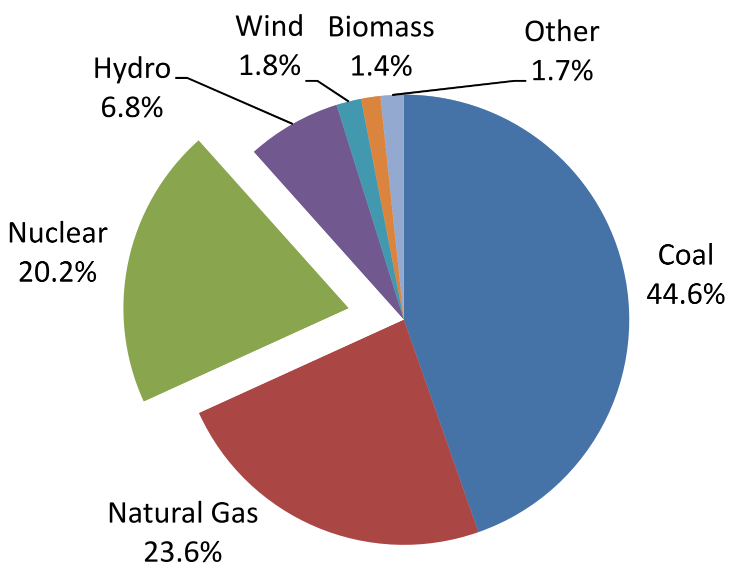
- **Analysis focuses on existing and Gen III+ nuclear power**
  - Nuclear capacity in the U.S. consists of 104 light water reactors, which are a combination of pressurized water reactors (PWRs) and boiling water reactors (BWRs), located on a total of 65 different sites
  - In a BWR, steam produced in 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
  - 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 (Nuclear Regulatory Commission)

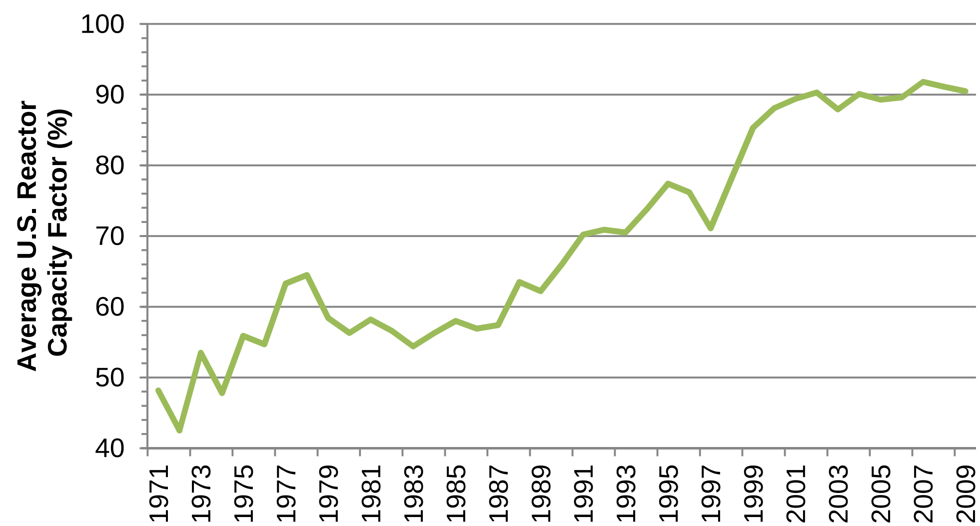
Parameter	Value	Source
Average Thermal Efficiency of Existing Reactors (%)	31.6	WNA, 2010a
Average Capacity Factor of the Existing Nuclear Reactor Fleet, 2009 (%)	90.6	EIA, 2010b
Average Annual Electric Output of a Single Reactor, 1969-2009 (MWh/ year)	4.93E+06	EIA, 2010b
Uranium Fuel Input per Electricity 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

Resource, Capacity, and Growth

Nuclear power has maintained a relatively stable 20% of net electricity generation, despite increasing annual demand for power and no new plant construction







Source: EIA (2010)

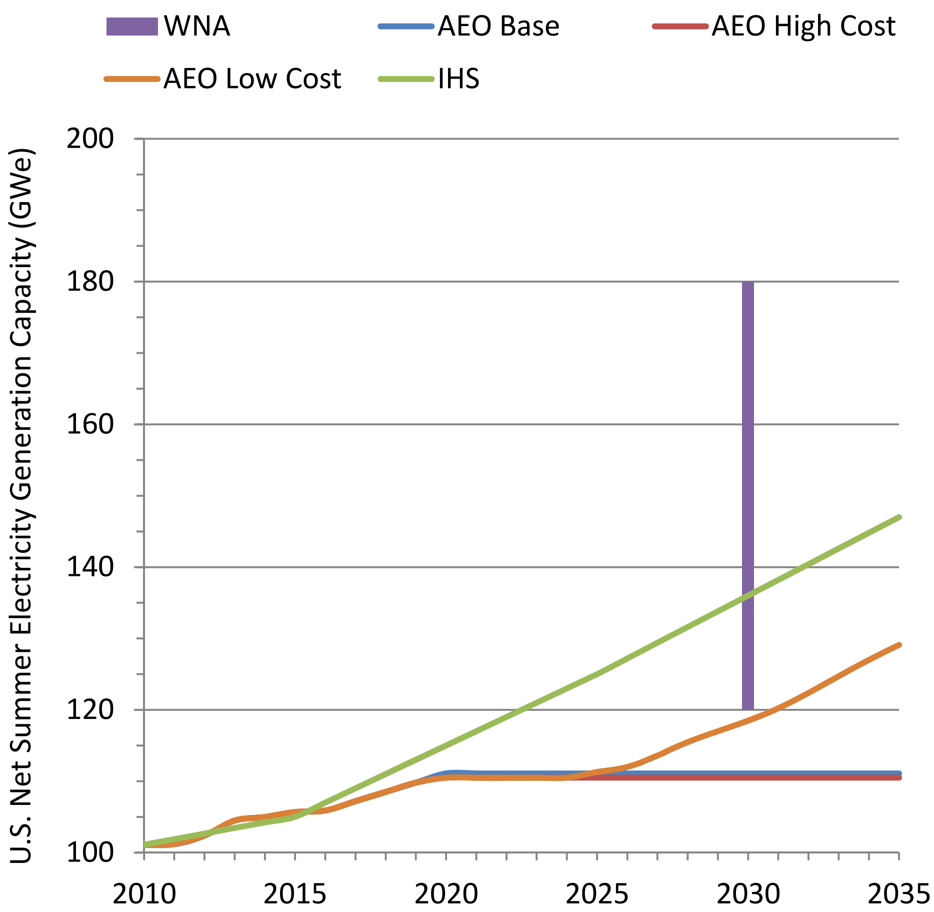
Resource, Capacity, and Growth

Nation	Metric Tonnes Uranium	Percent of World Total	DOE Sensitive Country
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	2%	yes
Mongolia	49,000	1%	no
Other	150,000	3%	n/a
World Total	**5,404,000**	**100%**	

Source: DOE (2011a), WNA (2010b)

- ~70% of recoverable uranium reserves are in "non-sensitive" (low risk) countries
- World uranium demand is 66,000 tonnes annually for a production capacity of 370 GWe (IAEA, 2011)
- 80 year virgin supply of uranium at a recoverable cost of less than $130/kg U
- 40 year virgin supply of uranium at a recoverable cost of less than $130/kg If demand increases to IAEA 2030 forecasted high of 807 GWe
- Doubling the price of uranium ore results in a 10-15% increase in the cost of electricity

Resource, Capacity, and Growth



Source: EIA (2011), IAEA (2010), WNA (2011a)

- U.S. nuclear capacity consists of 104 light water reactors located on a total of 65 different sites
- 20 proposed reactors have active COL (combined operating license) applications at the NRC with proposed startups beginning ranging from 2016 to 2027
- Forecasted nuclear capacity as projected by EIA, IAEA, IHS, and WNA ranges from 110 to 180 GW in 2035 based on a 2010 capacity of approximately 101 GW
- 39 reactors would be shut down by 2035 if the maximum lifetime is constrained to 60 years

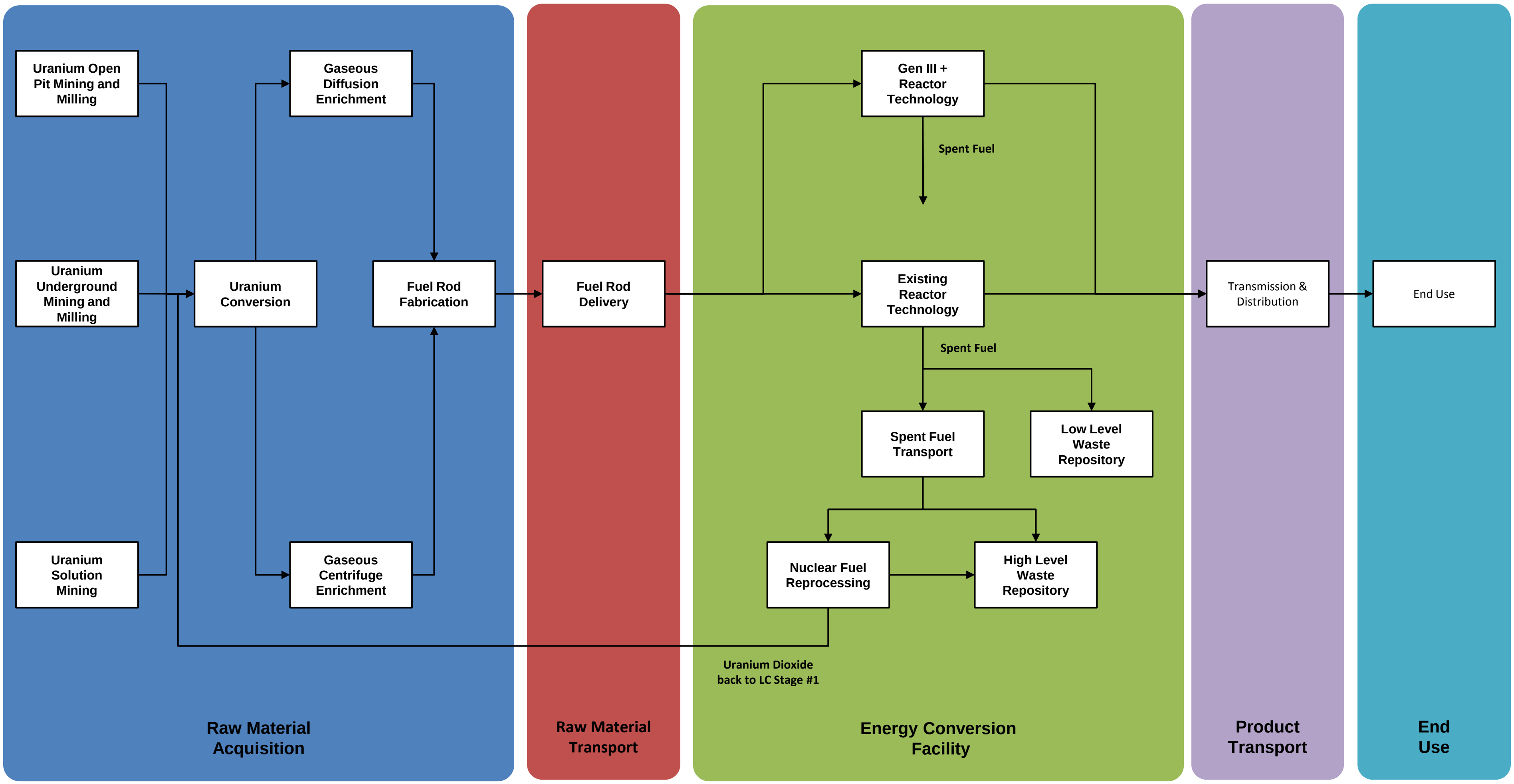
Environmental Analysis of Nuclear

- **Life Cycle Analysis (LCA) completed for Nuclear Power**

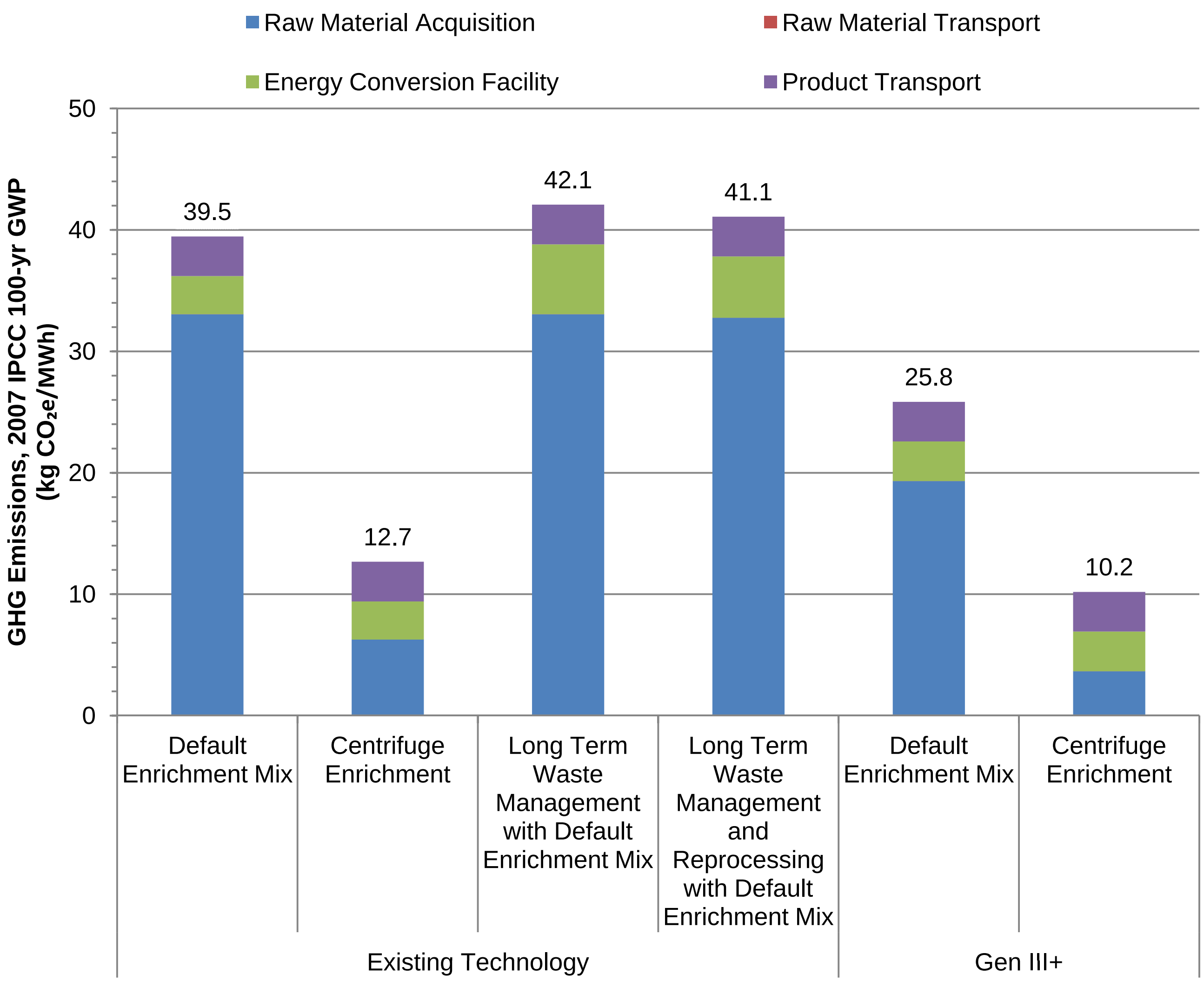
- **Model broken into life cycle stages:**
  - Stage 1: Raw Material Acquisition (RMA) accounts for the raw material acquisition and processing requirements for uranium fuel. The first step in this stage is the extraction of uranium ore from mines. Intermediate steps include the milling of ore to isolate yellow cake (U_3O_8), conversion of yellow cake to uranium hexafluoride (UF_6), and enrichment of UF_6 so it has a higher concentration of U-235, and the manufacturing of fuel assemblies
  - 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.
  - Stage 3: Energy Conversion Facility (ECF) includes all construction, operation, and decommissioning activities at a 1,000 MW net nuclear power plant. This analysis models existing (Gen II/III) 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.
  - Stage 4: Transmission and Distribution – grid transmission and associated loss of 7%
  - Stage 5: Electricity use by consumer – no losses or environmental burdens

- **Model comprised of interconnected network of processes**

Environmental Analysis of Nuclear: LCA Modeling Structure



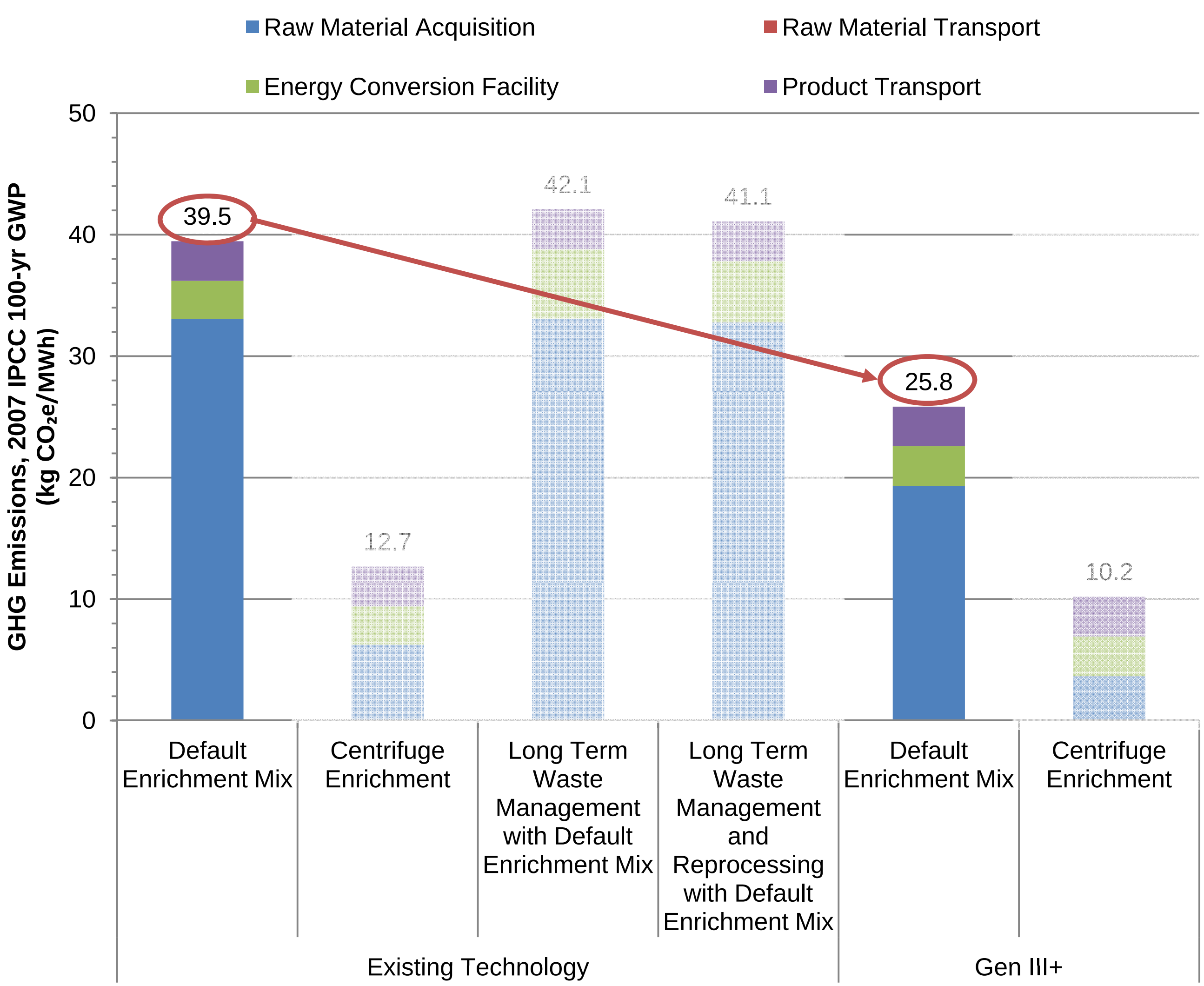
Environmental Analysis: GHG Results



Three important LCA GHG comparisons:

1. Existing vs. Gen III+ Reactor Technology
2. Default Enrichment Mix (52% Diffusion; 48% Centrifuge) vs. 100% Gaseous Centrifuge Enrichment
3. No waste management vs. long term waste management and/or spent fuel reprocessing

Environmental Analysis: GHG Results

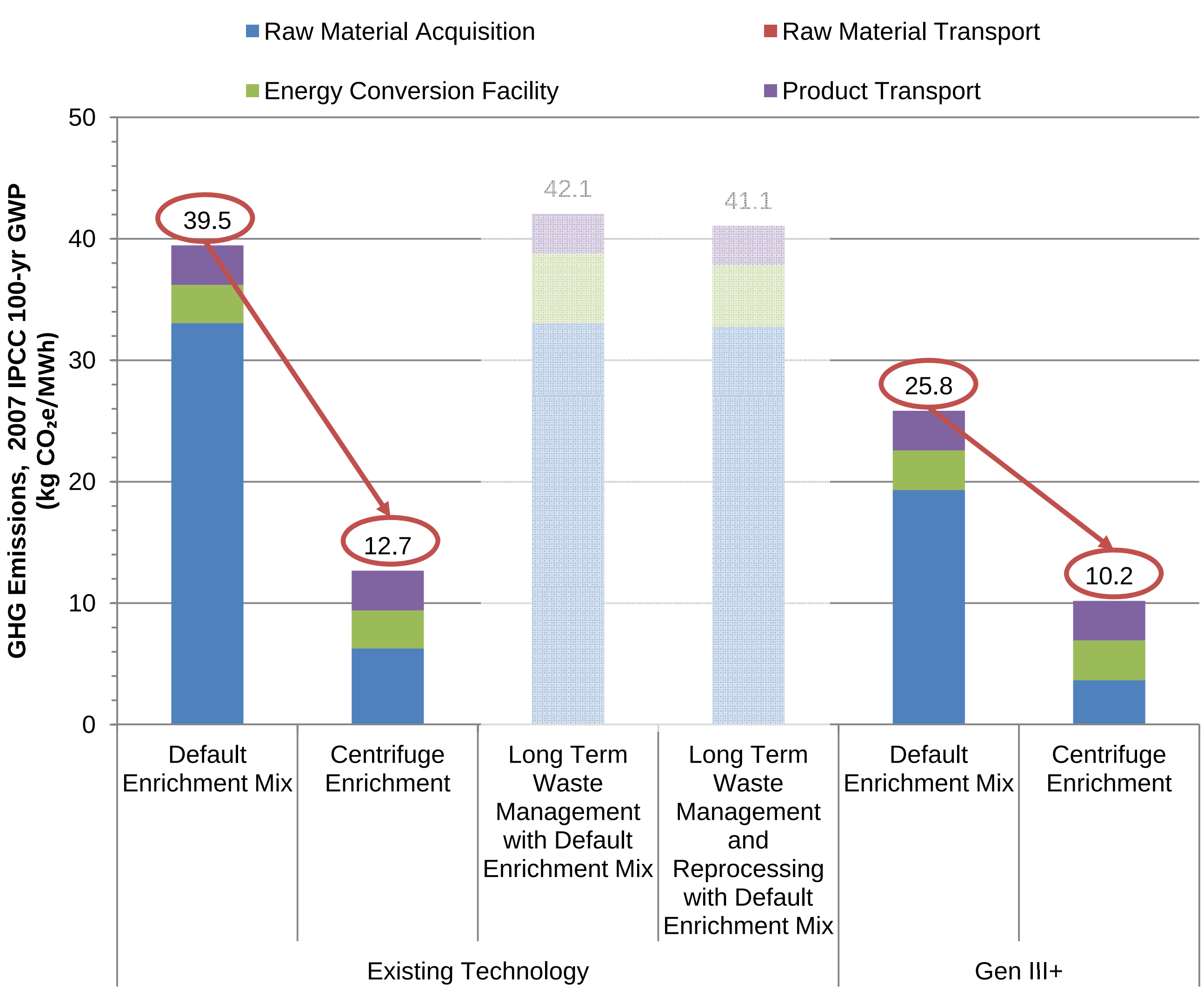


Nuclear power from Gen III+ reactor technology has 35% lower GHG emissions than Existing reactor technology based on the following characteristics:

Higher capacity factor, higher fuel burn up, lower fuel replacement rates, and higher thermal efficiency

5-6% of GHG emissions from mining, 64-71% from enrichment, 5-6% from fuel fabrication, and 7-11% from plant construction and decommissioning

Environmental Analysis: GHG Results

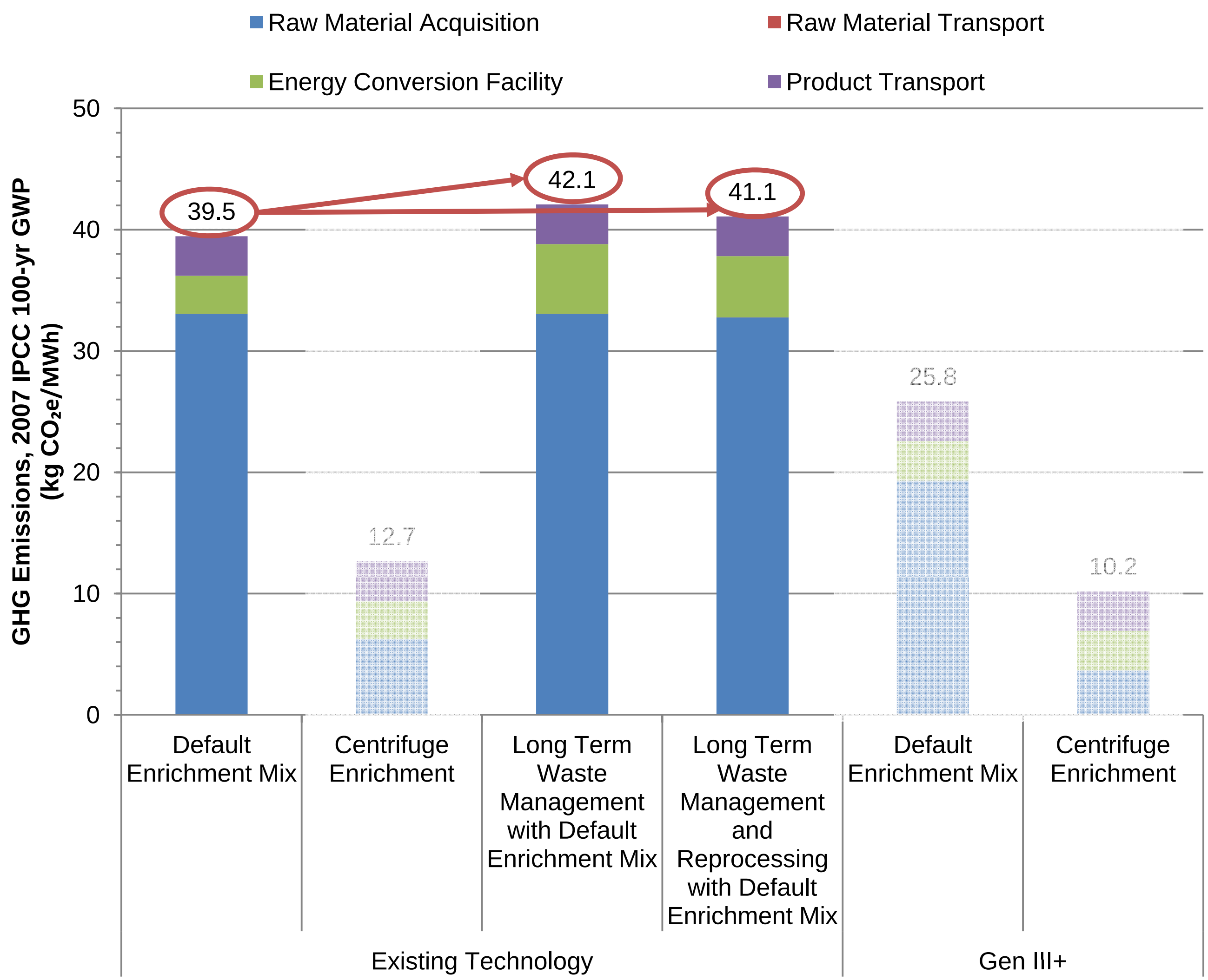


Diffusion enrichment is leading contributor to GHG emissions in nuclear fuel cycle because of electricity requirements of process

Current mix for U.S. enriched uranium is 52% diffusion (enriched domestically) and 48% centrifuge (imported from Europe)

Switching from gaseous diffusion to centrifuge enrichment in the U.S. can lead to 60-70% reduction in GHG emissions from fuel cycle depending on reactor type

Environmental Analysis: GHG Results



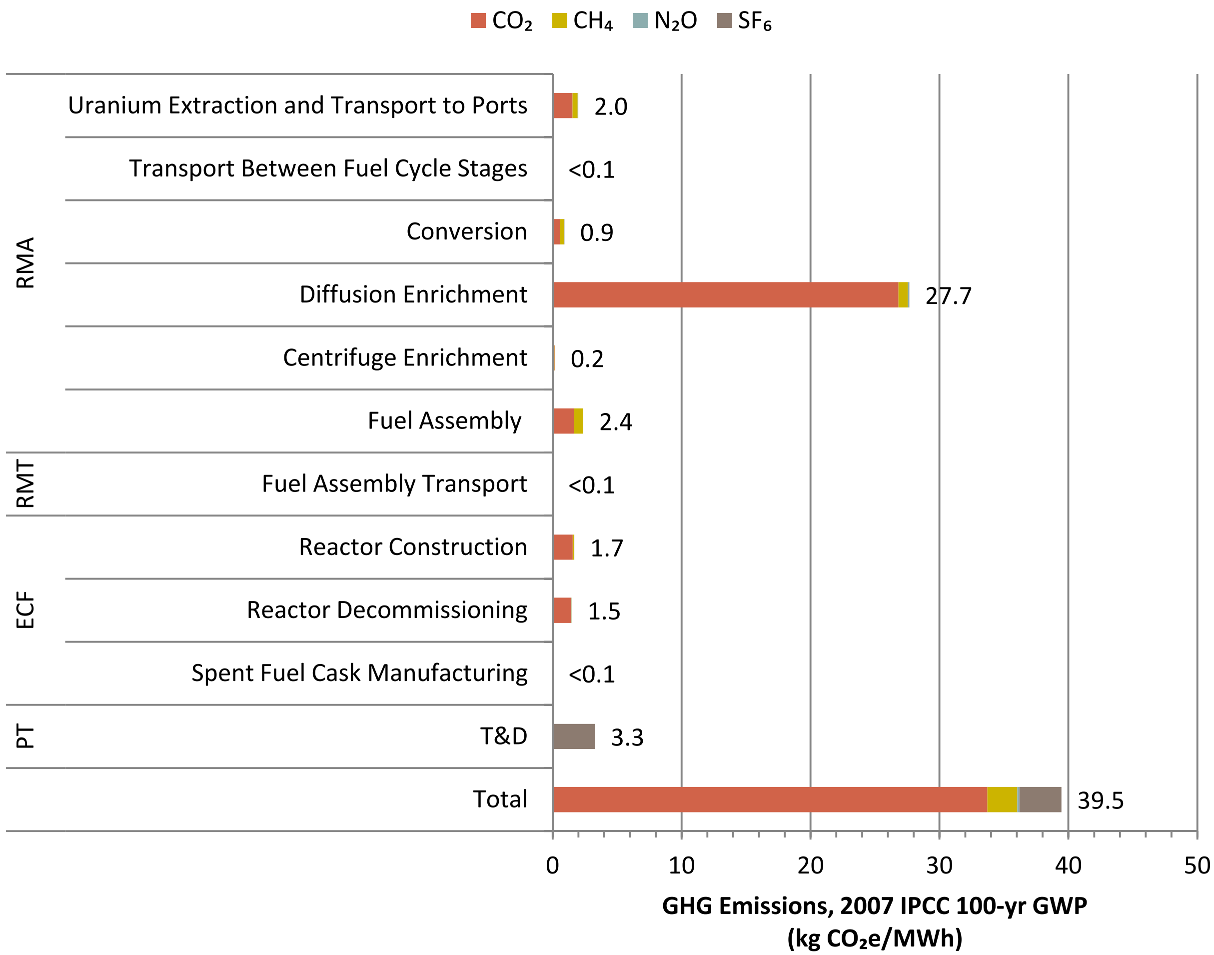
Small increase in GHG emissions from waste management and reprocessing options

Reprocessed UO_2 backs out virgin uranium, yielding a small reduction in GHG emissions in RMA (~1%), but an increase at ECF

4% of GHG emissions from HLW disposal, less than 0.02% from reprocessing

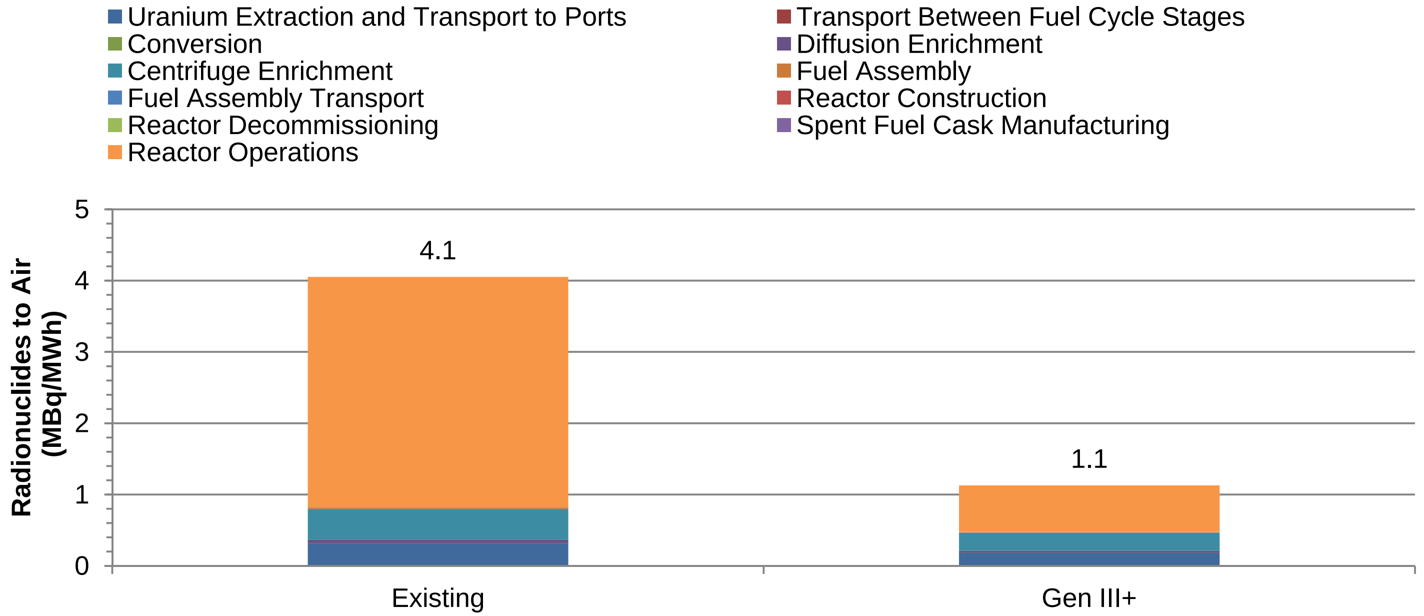
Larger impact on GHG emissions from switch to centrifuge enrichment than reprocessing

Environmental Analysis: GHG Results Existing Nuclear Power



- GHG profile is dominated by carbon dioxide (85%) from combustion of coal, natural gas, and diesel for construction of the power plant and energy for uranium fuel processing
- Gaseous diffusion enrichment process for U.S. enriched fuel is 70% of existing plant life cycle GHG emissions
- Sulfur hexafluoride from T&D accounts for 8% of life cycle GHG emissions
- GHG emissions from construction and decommissioning of the nuclear power plant account for 8%
- Emissions from land use add an additional 0.65 kg CO_2e/MWh

Environmental Analysis: Radionuclide Emissions to Air



- Difference between radionuclide releases (measured in Becquerels) and biological radiation exposure (measured in mrem)
- Dose limit for general public exposure from nuclear power plants is 100 mrem per year exclusive of other sources (10 CFR 20.1301)
- Average value for nuclear power plants is 0.01 mrem/year
- Comparables (ANS, 2011):
  - Cosmic radiation in Pittsburgh: 26 mrem/year; Terrestrial radiation in Colorado: 63 mrem/year
  - Food (C-14 and K-40): 40 mrem/yr; Air (Radon): 228 mrem/year
  - Chest x-ray: 10 mrem/procedure; Dental x-ray: 0.5 mrem/procedure

Environmental Analysis: Other Results

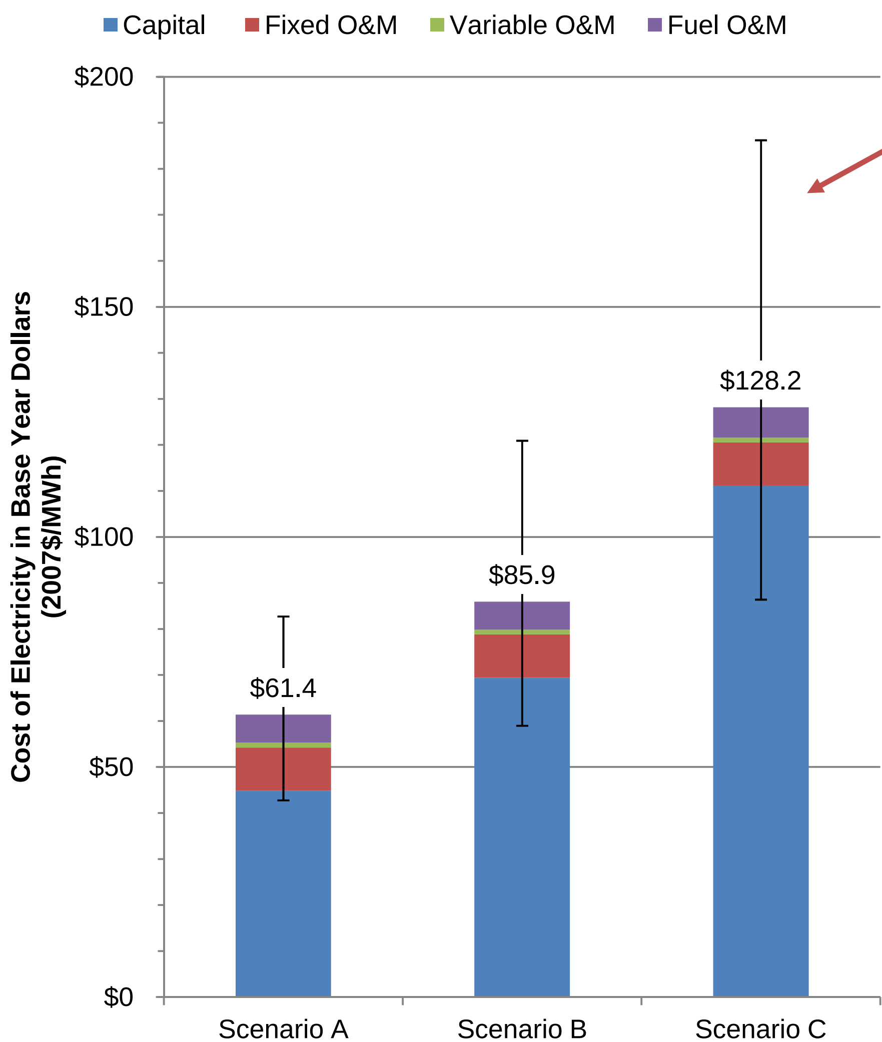
- **Water Use**
  - Nuclear plants consume more water because of thermodynamic constraints relative to the fuel assembly which prevent high temperatures akin to fossil fuel systems (EPRI, 2007)
  - While closed-loop cooling requires significantly less water withdrawal than once-through, the consumption is almost a factor of five higher (NETL, 2011)
- **Land Use**
  - Gen III+ pathway land use GHG emissions are 85 % less than existing pathway (smaller plant footprint)
- **Energy Return on Investment**
  - Values range from 0.43:1 (existing nuclear with default enrichment mix) to 0.47:1 (Gen III+ with centrifuge enrichment)
- **Other Air Emissions**
  - Dominated by gaseous diffusion operation and power plant construction
  - Combustion emissions come from hard coal electricity provided to the diffusion enrichment plant as well as diesel combustion in the construction and decommissioning processes
  - Gen III+ life cycle has lower air emissions than the existing plants

Cost Analysis: Financial and Cost Parameters – New Gen III+ Reactor

Financial Parameter	Scenario A Minimize COE	Scenario B Expected COE	Scenario C Maximize COE
Debt Fraction (1 - Equity)	0.71	0.58	0.44
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%

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

Cost Analysis: LCC Results



Uncertainty bars represent range of COE for a given financial scenario based on range of LCC plant operations parameters (capital costs, plant capacity, fuel costs, operating & maintenance costs, and decommissioning costs)

Financial Parameter	Scenario A Minimize COE	Scenario B Best Estimate COE	Scenario C Maximize COE
Debt Fraction (1 - Equity)	0.71	0.58	0.44
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Tax Rate (%)	36%	39%	41%
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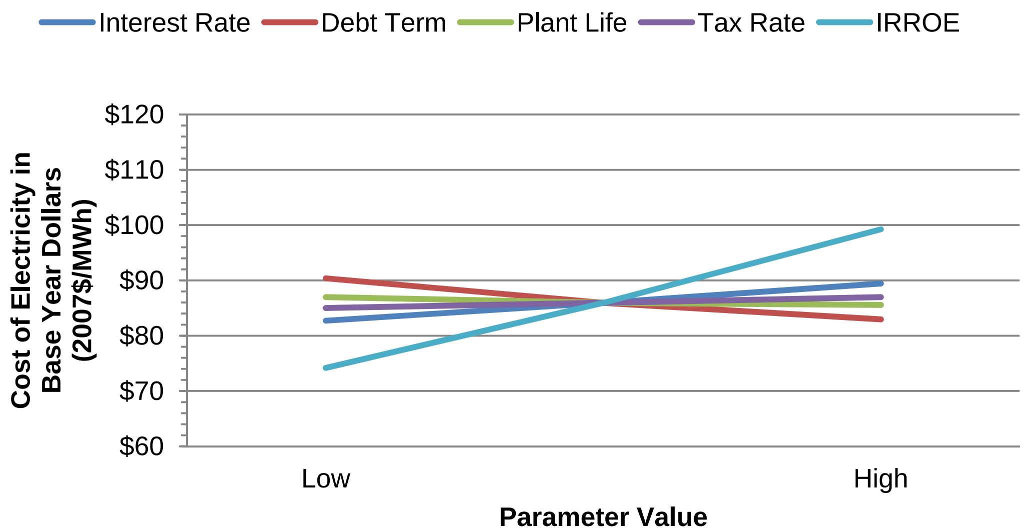
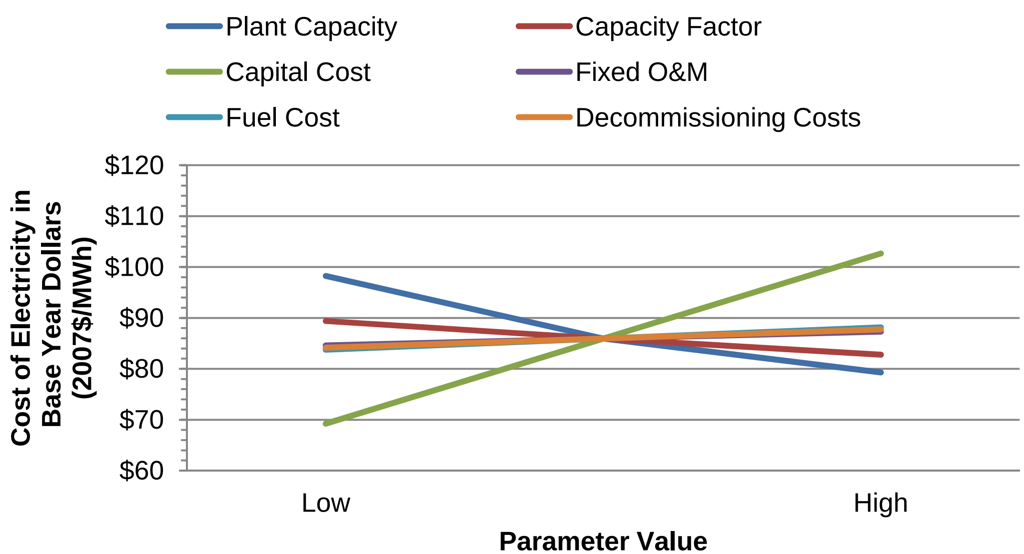
- Expected COE is $85.9/MWh (delivered, 2007$)
- The breakdown of COE cost components:
  - 81% capital
  - 11% fixed O&M
  - 1% variable O&M
  - 7% fuel costs

Cost Analysis: LCC Results Sensitivity





- LCC financial and operations parameters varied one at a time, all others held constant at the expected value
- Financial parameters (top graph) can in some cases have a more significant impact on COE than operations parameters (bottom graph)
- Expected rate of return on investment is the financial parameter with largest impact on COE
- A longer debt payback period and lower interest on the loan have significant benefits
- Installed capital and plant size have the greatest sensitivity and will have the largest impact on the COE of the operations parameters, while fuel costs, O&M costs and decommissioning costs are not as sensitive

Barriers to Implementation

- **Storage of spent nuclear fuel – Yucca Mountain**
  - 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
  - The NWPA limited the capacity of the first repository to 70,000 metric tons of heavy metal
  - In 2008, DOE submitted the license application to the NRC for authorization to construct the repository at Yucca Mountain (NRC, 2012)
  - 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, 2011b)

- **Blue Ribbon Commission on America's Nuclear Future**
  - The BRC was formed in early 2010 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 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)

Risks of Implementation

- **Engineering Failures**
  - Three significant events in history of commercial power are likely drivers for public resistance to technology: Three Mile Island (1979), Chernobyl (1986) and Fukushima (2011)
  - U.S. and Japanese nuclear programs diverged in 1980s when U.S. stopped building new reactor technologies and focused on operational improvements and cost savings, while Japan continued to build and design new reactors
  - Japan did not commit to all of the mandatory modifications that U.S. fleet incorporated during the 1980s

- **Terrorist Attacks**
  - Following 9/11 terrorist attacks, 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, facilities also focused on enhanced training of security forces and added new posts along with restrictions to site entry

- **Release of Radioactive Material**
  - 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 (NRC, 2011a)
  - The National Cancer Institute concluded in 1991 that no increased risk of death resulted in counties adjacent to nuclear facilities (Jablon, Hrubec, & Boice, 1991)

Expert Opinions

- **Reactor Safety Post-Fukushima Event**
  - 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 & Hibbs, 2012)
  - 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 (Acton & Hibbs, 2012)

- **Small Modular Reactors (SMRs)**
  - Cost gap between SMRs and conventional large-scale nuclear reactors has narrowed as cost of new Gen III+ plants has escalated substantially
  - Other advantages include efficiencies in fabrication and transportation and increased operation time between refueling
  - SMRs are also being mentioned as a possible replacement for aging coal facilities (DOE, 2011b); in this replacement scenario, SMRs may utilize some existing site infrastructure, which further reduces costs (Mowry, 2011)

- **Competiveness of Nuclear Power**
  - Cost of natural gas needs to be higher than $6/MMBtu for new nuclear power generation to be economically favorable (S&P, 2010)
  - Estimated construction costs have been increasing at a rate of 15% per year (MIT, 2009); these high costs relative to other power production options have hindered several projects and resulted in temporary setbacks at proposed new nuclear installations

References

Acton, J. M., & Hibbs, M. (2012). *Why Fukushima Was Preventable*. Washington, DC: Carnegie Endowment for International Peace Retrieved June 25, 2012, from http://carnegieendowment.org/2012/03/06/why-fukushima-was-preventable

BRC. (2012). *Blue Ribbon Commission on America's Nuclear Future*. Washington, DC: Retrieved May 9, 2012, from http://brc.gov/sites/default/files/documents/brc_finalreport_jan2012.pdf

DOE. (1983). *The Aerospace Corporation and Mueller Associates, Inc. Energy Technology Characterizations Handbook*. Washington, DC: U.S. Department of Energy.

DOE. (2011a). DOE List of Sensitive Countries Retrieved September 21, 2011, from http://www.ameslab.gov/files/documents/doe_sensitive_countries_list.pdf

DOE. (2011b). *DOE Small Modular Reactor Program Presentation by John E. Kelly*. U.S. Department of Energy Retrieved October 28, 2011, from http://www.nrc.gov/reading-rm/doc-collections/commission/slides/2011/20110329/kelly-20110329.pdf

EIA. (2010a). *Electric Power Annual 2009*. Washington, DC: United States Department of Energy Retrieved from http://www.eia.gov/cneaf/electricity/epa/epa_sum.html.

EIA. (2010b). *Uranium Annual Marketing Report*. Washington, DC: U.S. Energy Information Administration Retrieved from http://www.eia.doe.gov/cneaf/nuclear/umar/umar.html.

EIA. (2011). *Annual Energy Outlook 2011*. (DOE/EIA-0383(2011)). Washington, DC: U.S. Department of Energy, Energy Information Administration Retrieved from http://www.eia.gov/forecasts/aeo/.

EPRI. (2007). *Assessment of Waterpower Potential and Development Needs*. (1014762). Palo Alto, CA: Electric Power Research Institute

IAEA. (2010). *International Status and Prospects of Nuclear Power*. (GOV/INF/2010-12-GC(54)/INF/5). Vienna, Austria: International Atomic Energy Agency Retrieved from http://www.iaea.org/About/Policy/GC/GC54/GC54InfDocuments/English/gc54inf-5_en.pdf.

Jablon, S., Hrubec, Z., & Boice, J. D. (1991). Cancer in Populations Living Near Nuclear Facilities. *Journal of the American Medical Association, 265*.

MIT. (2009). *Updated of the MIT 2003 Future of Nuclear Power: An Interdisciplinary MIT Study*. Cambridge, MA: Massachusetts Institute of Technology, from http://web.mit.edu/nuclearpower/pdf/nuclearpower-update2009.pdf

References

Mowry, C. M. (2011). *Written Testimony of Christofer M. Mowry President Babcock & Wilcox Nuclear Energy Inc. Before the Energy & Water Subcommittee of the Senate Appropriations Committee United States Senate*. The Babcock & Wilcox Company Retrieved October 28, 2011, from http://www.babcock.com/news_and_events/pdf/mowry_testimony.pdf

NETL. (2011). Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements 2011 Update. (DOE/NETL-2011/1523). Pittsburgh, PA: National Energy Technology Laboratory, from http://netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=402

NRC. (2008). Backgrounder - Nuclear Security Retrieved July 26, 2011, from http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/security-enhancements.html

NRC. (2009). Three Mile Island Accident. *U.S. Nuclear Regulatory Commission* Retrieved May 25, 2011, from http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html

NRC. (2011a). Fact Sheet on Biological Effects of Radiation Retrieved September 21, 2011, from http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/bio-effects-radiation.html

NRC. (2011b). High-Level Waste Disposal. U.S. Nuclear Regulatory Commission Retrieved May 9, 2012, from https://www.nrc.gov/waste/hlw-disposal.html

NRC. (2012). DOE's License Application for a High-Level Waste Geologic Repository at Yucca Mountain U.S. Nuclear Regulatory Commission Retrieved May 9, 2012, from http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app.html

Obama, B. (2010). Memorandum for the Secretary of Energy Blue Ribbon Commission on America's Nuclear Future Retrieved May 9, 2012, from http://brc.gov/index.php?q=page/executive-order

Standard & Poor's. (2010, August 16). The Economics of U.S. Nuclear Power: Natural Gas Prices and Loan Guarantees Are Key to Viability Retrieved July, 26, 2011, from http://www.standardandpoors.com/ratings/articles/en/eu/?assetID=1245225877193

WNA. (2010a). Advanced Nuclear Power Reactors. World Nuclear Association Retrieved July 18, 2010, from http://www.world-nuclear.org/info/inf08.html

WNA. (2010b). Supply of Uranium. World Nuclear Association Retrieved June 21, 2011, from http://www.world-nuclear.org/info/inf75.html

WNA. (2011a). Chernobyl Accident 1986. World Nuclear Association Retrieved June 21, 2011, from http://www.world-nuclear.org/info/chernobyl/inf07.html

WNA. (2011b). Nuclear Century Outlook Data. World Nuclear Association Retrieved September 21, 2011, from http://world-nuclear.org/outlook/nuclear_century_outlook.html

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