NATIONAL ENERGY TECHNOLOGY LABORATORY

Power Generation Technology Comparison from a Life Cycle Perspective

NETL Office of Strategic Energy Analysis and Planning

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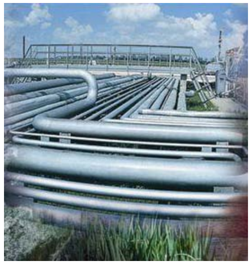
U.S. DEPARTMENT OF ENERGY

Agenda

- Evaluation Criteria
- Technology Description
- Technology Performance Summary
- Resource Base and Growth
- Environmental Analysis
- Cost Analysis
- Barriers to Implementation
- Risks of Implementation
- Expert Opinions
- Summary







Evaluation Criteria

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	Financial, environmental, regulatory, and/or public perception concerns that are obstacles to implementation. Non-technical barriers
Expert Opinion	Opinions of stakeholders in industry, academia, and government

Brief Technology Description
(7 Technology Groups)

1. Natural Gas

Role of Alternative Energy Sources: Natural Gas Technology Assessment (NETL, 2012)
http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=435

- Conventional and unconventional natural gas sources
- Construction and operation of simple and combined cycle power plants (GTSC and NGCC)
- Includes a carbon capture and sequestration (CCS) case
- Operation of fleet average natural gas power plants

2. Co-firing

Role of Alternative Energy Sources: Pulverized Coal and Biomass Co-firing Technology Assessment (NETL, 2012)
http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=453

- Acquisition of coal and biomass (hybrid poplar (HP) and forest residue (FR))
- Existing pulverized coal (PC) boiler
- Includes a coal-only system for comparison

3. Nuclear

Role of Alternative Energy Sources: Nuclear Technology Assessment (NETL, 2012)
http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=441

- Acquisition of uranium, using a mix of enrichment technologies
- Construction and operation of existing and advanced (Generation III+) nuclear power plants
- Includes short-term and long-term nuclear waste management scenarios

Brief Technology Description
(7 Technology Groups)

4. Wind

Role of Alternative Energy Sources: Wind Technology Assessment (NETL, 2012)
http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=451
– Construction and operation of conventional and advanced onshore wind farms
– Construction and operation of offshore wind farms

5. Hydropower

Role of Alternative Energy Sources: Hydropower Technology Assessment (NETL, 2012)
http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=447
– Four conventional dam scenarios: Greenfield, Power Addition, Upgrade, and Existing
– Brief assessment of hydrokinetic hydropower potential

6. Geothermal

Role of Alternative Energy Sources: Geothermal Technology Assessment (NETL, 2012)
http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=445
– Construction and operation of a flash steam, geothermal power facility

7. Solar Thermal

Role of Alternative Energy Sources: Solar Thermal Technology Assessment (NETL, 2012)
http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=449
– Construction and operation of a concentrated solar power plant with parabolic trough reflectors

Technology Performance Summary

Energy Source	Power Plant Technology	Net Plant Power (MW)	Capacity Factor (%)	Heat Rate (MJ/MWh)	Thermal Efficiency (%)	Water (kL/MWh)		Power Plant Greenhouse Gas Emissions (kg/MWh)		
						Withdrawal	Consumption	CO_2	CH_4	N_2O
Natural Gas	NGCC	555	85.0%	7,171	50.2%	0.96	0.75	365	7.4E-06	2.1E-06
	NGCC/ccs	474	85.0%	8,411	42.8%	1.91	1.43	47.1	8.6E-06	2.4E-06
	GTSC	360	85.0%	11,984	30.0%	0	0	560	N/A	N/A
	Fleet Baseload	N/A	N/A	7,643	47.1%	N/A	N/A	368	N/A	N/A
Co-firing (Coal and Biomass)	Coal Only	550	85.0%	10,907	33.0%	2.5	1.9	930	2.0E-06	1.4E-07
	Co-fired Coal and Biomass	550	85.0%	10,983	32.8%	2.5	1.9	943	No data	No data
Nuclear	Existing	796	70.7%	11,392	31.6%	105	2.5	0	0	0
	Gen III+	2,060	94.0%	10,526	34.2%	4.3	2.7	0	0	0
Wind	Onshore Conventional (1.5 MW Turbine)	200	30.0%	N/A	N/A	N/A	N/A	0	0	0
	Onshore Advanced (6.0 MW Turbines)	200	30.0%	N/A	N/A	N/A	N/A	0	0	0
	Offshore (3.6 MW Turbines)	468	39.0%	N/A	N/A	N/A	N/A	0	0	0
Hydro	Conventional Dam	2,080	37.0%	N/A	N/A	6.85	6.83	17	0.233	0
Geothermal	Flash Steam	50	90.0%	21,100	17.1%	38.0	38.0	214	0.4	0
Solar Thermal	Parabolic Trough	250	27.4%	N/A	N/A	0.41	0.35	0	0	0

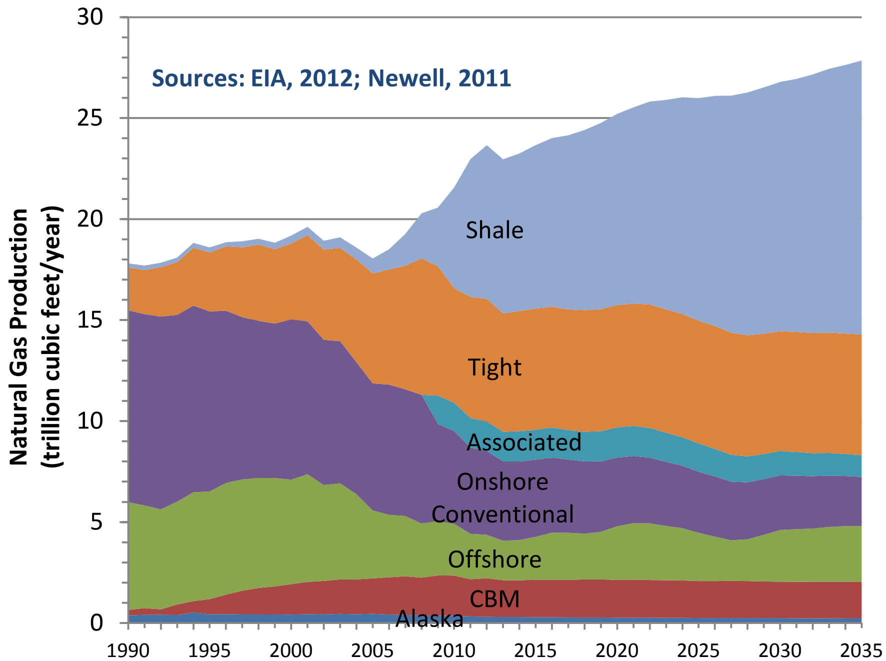
Resource Base and Growth

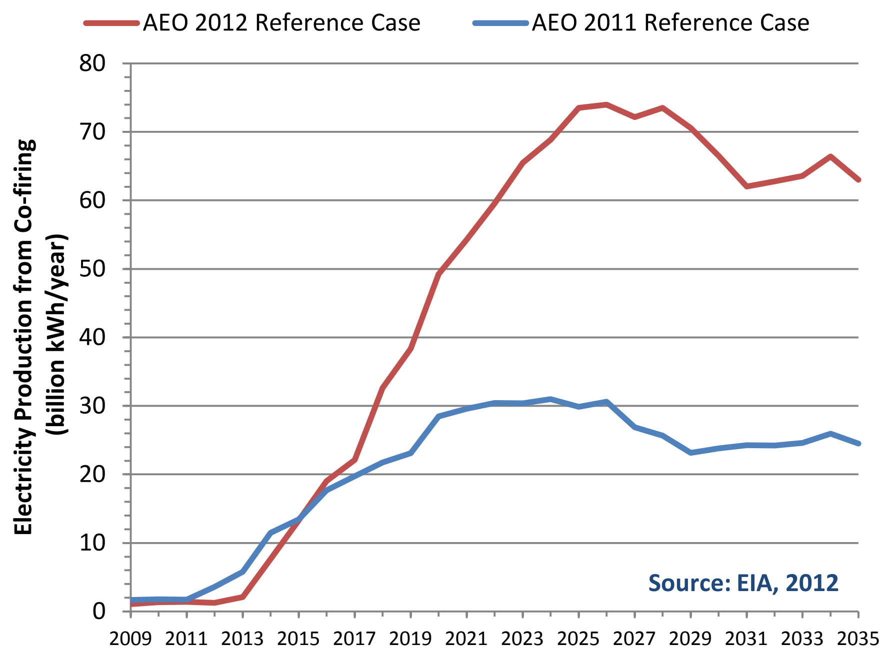
Key Conclusions

- Technology spurs growth for some resources, while policy is necessary for growth of other resources
- Estimates of *technically* recoverable resources should be balanced by an evaluation of *economically* recoverable resources
- Supply and demand proximity a key driver for growth of renewable energy

Resource Base and Growth

Example 1: New Technology vs. Policy





Technology Driven: Projected growth in natural gas production is due to new technology that allows development of shale gas plays.

Policy Driven: Projected growth in coal and biomass co-firing is based on state renewable portfolio standards (RPS) and other policies that encourage the use of renewable fuels.

Other examples

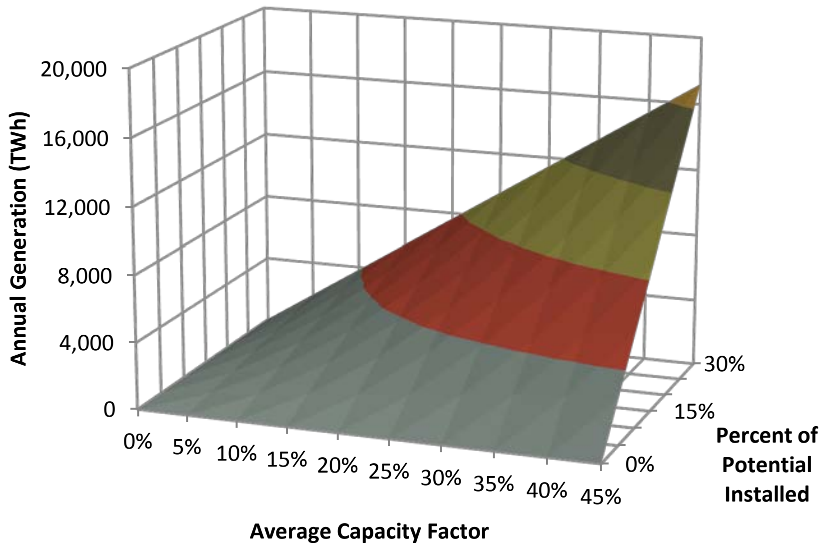
Policy Driven: Wind power grew from 0.1% to 2.3% of U.S. electricity generation between 2000 and 2010. This growth was made possible by electricity production tax credits due to expire in 2012.

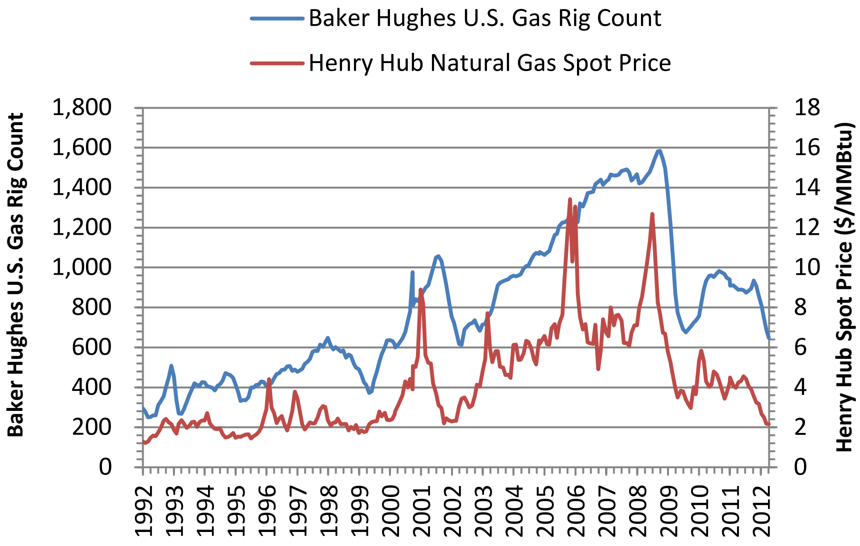
Policy Driven: Growth of nuclear power in the U.S. depends on number of facilities that undergo license renewals and policy decision surrounding long-term waste disposition.

Technology Driven: Torrefaction reduces biomass supply chain uncertainty and could increase the growth rate of co-firing.

Resource Base and Growth

Example 2: Technically vs. Economically Recoverable





Sources: EIA, 2012; Baker Hughes, 2012

Onshore wind power in the U.S. has an estimated capacity of 10.4 terawatts (TW) (AWEA, 2011). At a 30% capacity factor this is equivalent to 27,000 terawatthours (TWh) per year.

Due to economic and other factors, only a fraction of wind resources can be recovered.

Technical advancements caused a large increase in new natural gas well completions, but in 2006 well developers were slow to respond to dropping natural gas prices.

Approximately 60 percent of the technically recoverable shale gas can be produced at a wellhead price of $6/MMBtu or less (MIT, 2010).

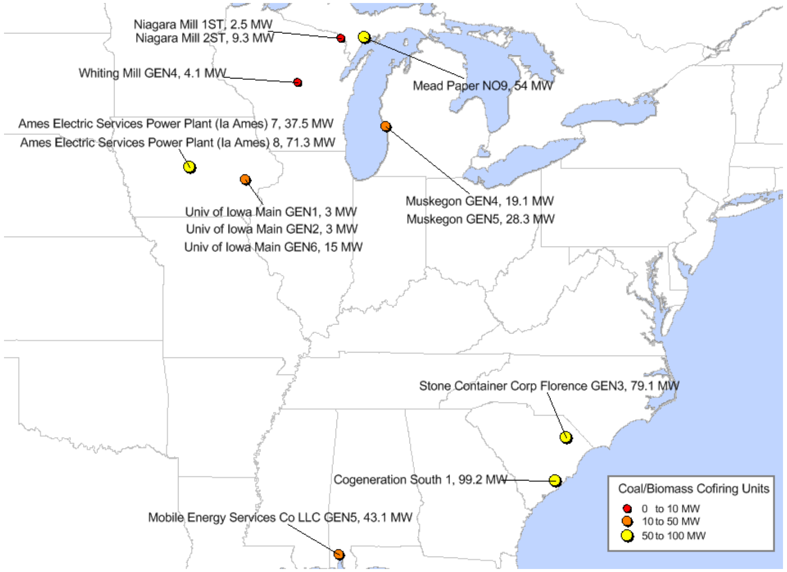
Other examples

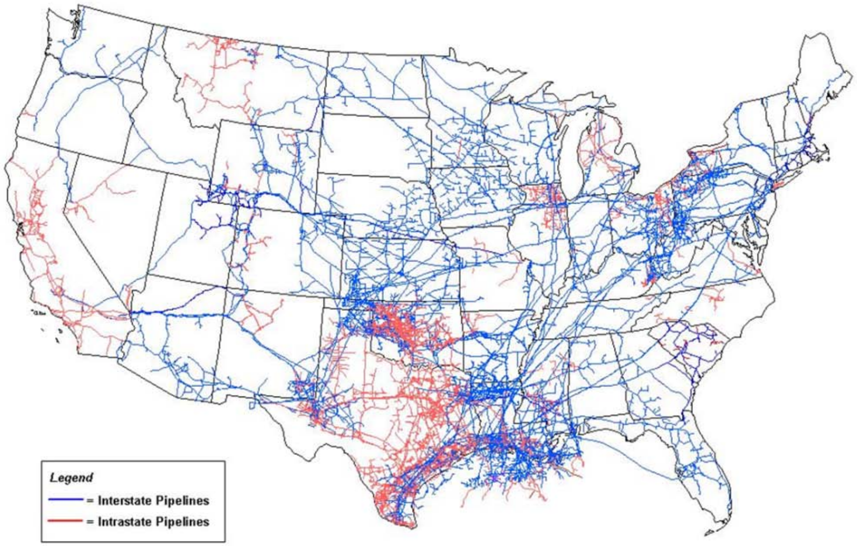
High drilling costs hinder recovery of deep geothermal resources.

In general, renewable energy sources are plentiful, but their development costs are high.

Resource Base and Growth

Example 3: Supply and Demand Proximity





Proximity Matters: The logistical challenges of biomass transport are a barrier to economical acquisition of biomass. Existing co-fired facilities are near woody biomass sources and include power generation at pulp and paper mills.

Proximity Does Not Matter: The U.S. has an extensive natural gas pipeline network that allows economical, long-distance transport between extraction and consumption.

Other examples

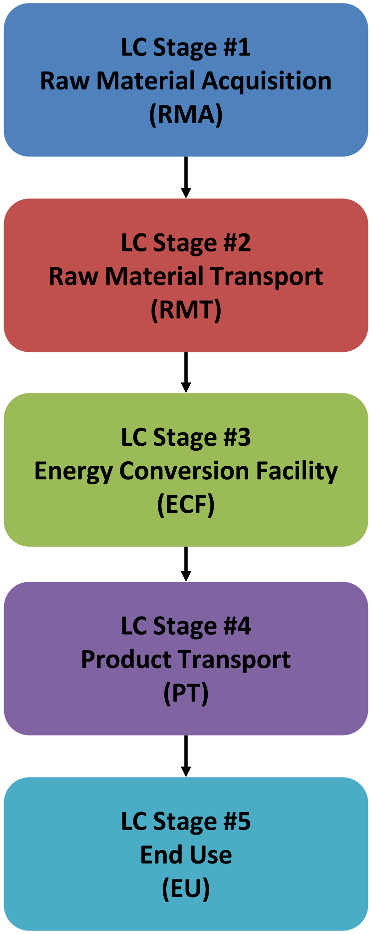
Proximity Matters: Renewable energy sources – including wind, geothermal, and solar thermal – are located in remote areas with limited infrastructure for electricity transmission and distribution.

Proximity Does Not Matter: The high energy density of nuclear fuel allows for economical, long-distance transport of nuclear fuel.

Environmental Analysis (LCA)

Life Cycle (LC) Stages

- **LC Stage #1, Raw Material Acquisition (RMA)**
  - Extraction of primary fuel from ground, field, or forest
  - Wind, hydro, solar, and geothermal energy do not require RMA
- **LC Stage #2, Raw Material Transport (RMT)**
  - Transport of primary energy feedstock from extraction to energy conversion facility
  - Wind, hydro, solar, and geothermal energy do not require RMT
- **LC Stage #3, Energy Conversion Facility (ECF)**
  - Conversion of primary energy source to electricity
- **LC Stage #4, Product Transport (PT)**
  - Transmission and distribution of electricity
- **LC Stage #5, End Use (EU)**
  - Consumption of electricity
  - No energy or material flows when modeling life cycle of electricity



Environmental Metrics

- Greenhouse gas (GHG) and other air emissions of concern
- Water withdrawal, discharge, and consumption
- Water quality
- Energy return on investment (EROI)

Functional Unit = 1 MWh delivered electricity

Natural Gas LCA Boundaries

Raw Material Transport

Surface Water for Hydrofracking (Marcellus Only)
Diesel
Steel
Concrete
Flowback Water Treated by Crystallization (Marcellus Only)
Diesel
Electricity
Venting/Flaring
Venting/Flaring
Venting/Flaring
Venting/Flaring

Transport of Water by Truck (Marcellus Only)
Well Construction
Flowback Water Treated at a WWTP (Marcellus Only)
Water Withdrawal & Discharge During Well Operation
Well Completion
Liquids Unloading
Workovers
Other Point Source Emissions
Other Fugitive Emissions
Valve Fugitive Emissions

Diethanolamine
Acid Gas Removal
Dehydration
Valve Fugitive Emissions
Other Point Source Emissions
Other Fugitive Emissions

Venting/Flaring
Venting/Flaring
Venting/Flaring

Venting/Flaring
Gas Centrifugal Compressor
Reciprocating Compressor
Electricity
Electric Centrifugal Compressor
Venting/Flaring

Electricity
Pipeline Operation (Energy & Combustion Emissions)
Pipeline Operation (Fugitive Methane)
Plant Operation
CCUS Operation
CCUS Construction
Trunkline Operation
Switchyard and Trunkline Construction

Steel
Pipeline Construction
Concrete
Plant Construction
Diesel
Cast Iron
Steel
Concrete
Aluminum

Transmission & Distribution

End Use **(Assume 100%** Efficient)

Raw Material Extraction | **Raw Material Processing** | **Raw Material Acquisition** | **Energy Conversion Facility** | **Product Transport** | **End Use**

Complex network of many unit processes

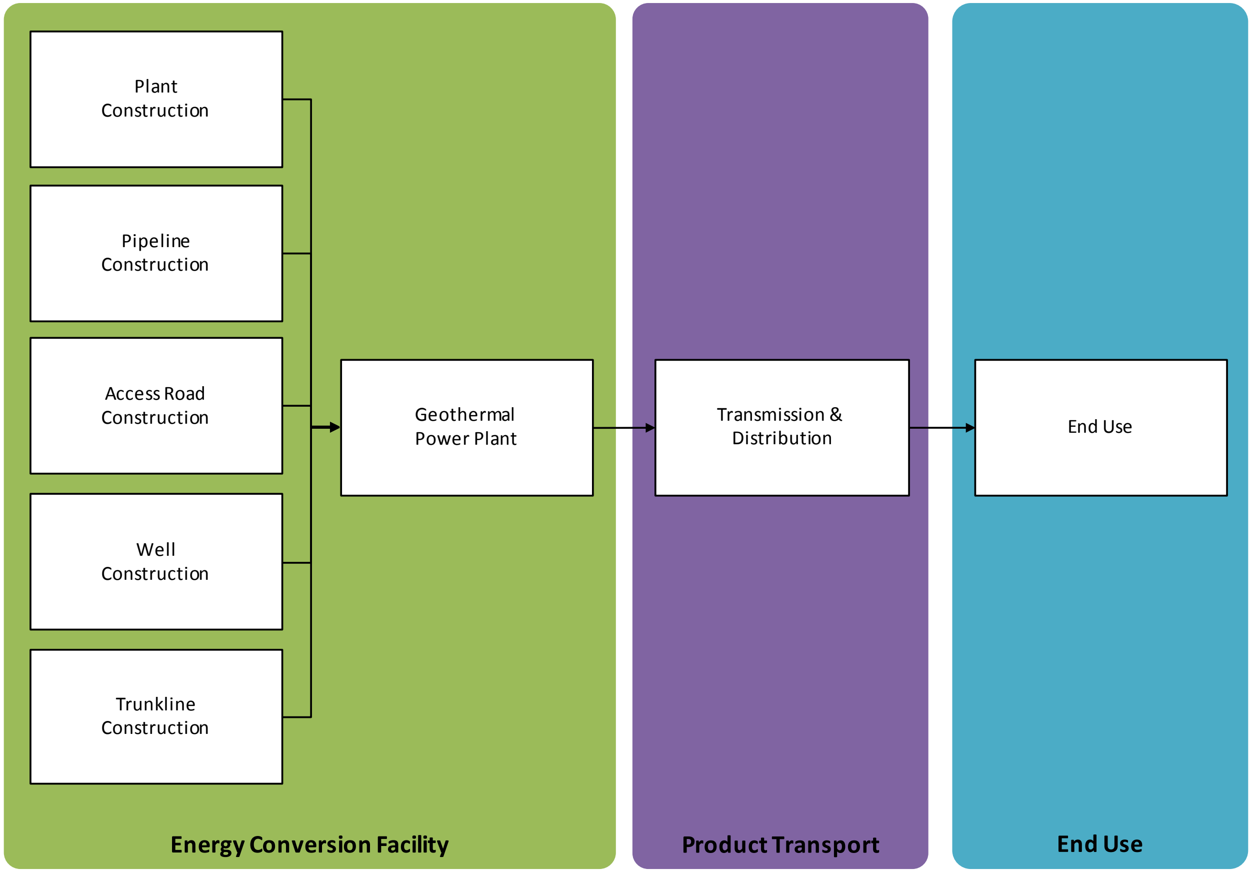
– Requires temporal normalization of steady-state and periodic emissions

– Parameterization of production rates, emission factors, and flaring rates allows modeling of conventional and unconventional natural gas extraction technologies

– Distance of natural gas transport by pipeline is another key parameter

– Various switches within the energy conversion facility

Geothermal LCA Boundaries



Simple network of a few unit processes

– Represents only one scenario (flash steam geothermal power)

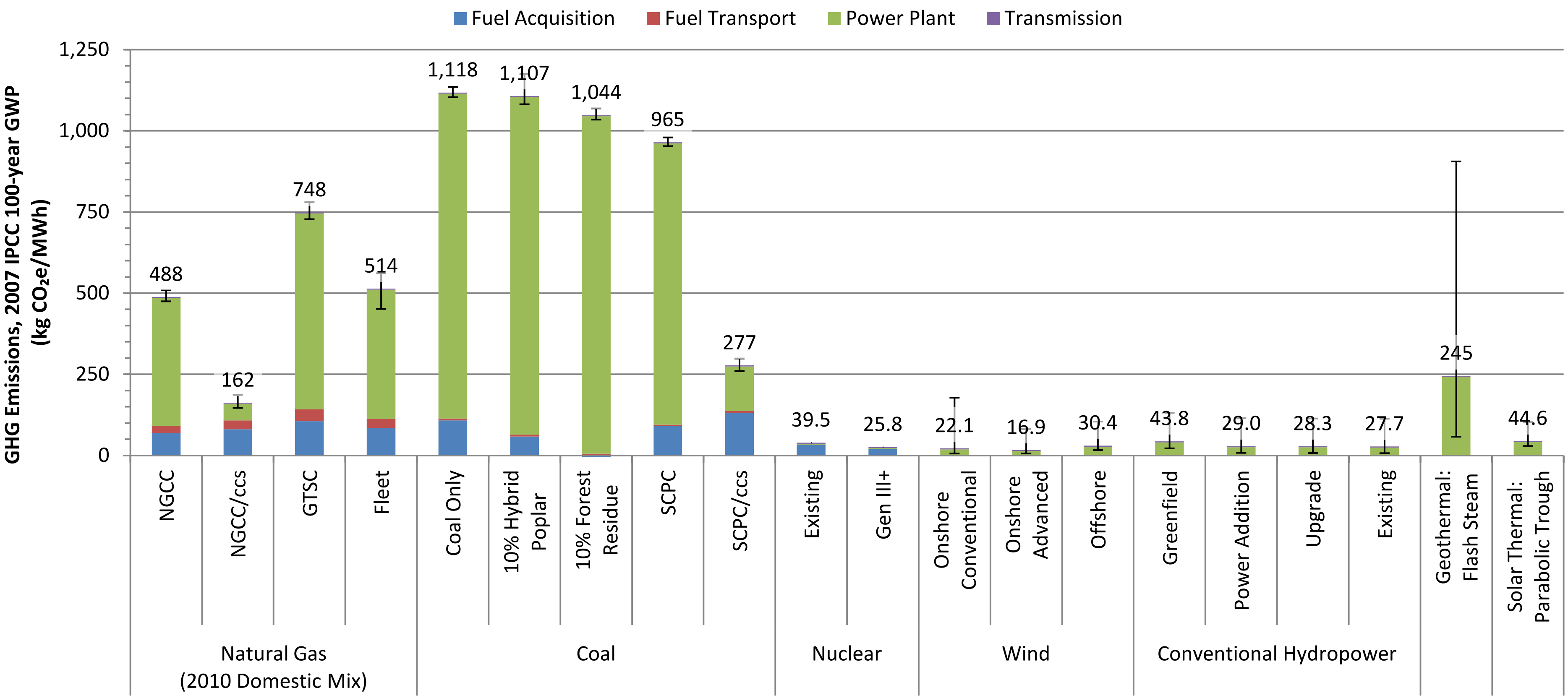
– Most unit processes were adapted from other NETL LCAs

– Key parameters are the composition of geofluid and heat rate of the power plant

Key LCA Data Sources

- **Natural Gas**
  - Background Technical Support Document (Subpart W) (EPA, 2011)
  - Various water use and water quality documents (GWPC & ALL, 2009; ANL, 2004; DOE, 2006)
  - NETL bituminous baseline report (NETL, 2010)
  - eGRID Database (EPA, 2010)
- **Co-firing**
  - Greenhouse Gas Reductions in the Power Industry Using Domestic Coal and Biomass (NETL, 2011)
  - Near-Term Opportunities for Integrating Biomass into the U.S. Electricity Supply (Ortiz, et al., 2011)
- **Nuclear**
  - Environmental Impact Statement for the Moore Ranch ISR Project in Campbell County, Wyoming (NRC, 2009)
  - Environmental Impact Statement for the Proposed National Enrichment Facility in Lea County, New Mexico (NRC, 2005)
  - Net Energy from Nuclear Power (Rotty, Perry, & Reister, 1975)
  - Quarterly Operational and Environmental Compliance Report for Port Hope Conversion Facility (Cameco, 2009)
- **Wind**
  - Wind turbine scaling equations (NREL, 2006)
  - Environmental Impact Statement for Cape Wind Energy Project (MMS, 2009)
  - 2010 Wind Technologies Market Report (Wiser & Bolinger, 2011)
- **Hydropower**
  - Los Vaqueros Reservoir and Watershed (Contra Costa Water District, 2011)
  - California Water Plan Update 2005 (California Department of Water Resources, 2005)
  - Potential Hydroelectric Development at Existing Federal Facilities (U.S. Department of Energy, U.S. Department of the Army, & U.S. Department of the Interior, 2007)
- **Geothermal**
  - Environmental Impact Statement for Geothermal Leasing in the Western United States (BLM, 2008)
  - Geothermal Electrical Production CO_2 Emissions (Bloomfield, 1999)
- **Solar Thermal**
  - Environmental Impact Statement for the Blythe Solar Power Project (BLM, 2010a)
  - Environmental Impact Statement for the Genesis Solar Energy Project (BLM, 2010b)

Life Cycle GHG Emissions



- Super Critical Pulverized Coal (SCPC) with & without carbon capture are not part of this study; included here for comparison
- Natural gas power has high RMA and RMT emissions; high ECF efficiencies yield lower life cycle GHG emissions than other fossil power
- Co-firing with hybrid poplar (at 10% of energy feedstock) does not significantly reduce GHG emissions of coal plants
- Nuclear is only technology where RMA dominates other stages
- Renewables have lower expected GHG emissions, but greater uncertainty due to resource variability
- Backup power should be considered when evaluating wind power: wind with backup power ranges from 416 to 501 kg CO_2e/MWh

Life Cycle Criteria Air Pollutants and Other Air Emissions (kg/MWh)

Energy Source	Technology	Pb	Hg	NH_3	CO	NO_X	SO_2	VOC	PM
Natural Gas (2010 Domestic Mix)	NGCC	4.82E-06	1.02E-07	1.88E-02	4.72E-02	5.13E-01	7.37E-03	3.81E-01	1.46E-03
	NGCC/CCS	5.56E-06	1.25E-07	2.03E-02	5.62E-02	6.00E-01	8.91E-03	4.47E-01	1.82E-03
	GTSC	3.87E-06	1.26E-07	2.90E-02	7.34E-02	7.92E-01	1.11E-02	5.87E-01	2.25E-03
	Fleet	2.59E-06	9.48E-08	3.81E-06	5.47E-02	8.89E-01	1.18E-02	4.69E-01	1.33E-03
Co-firing	Coal Only	1.55E-06	3.79E-05	2.26E-04	1.55E+00	1.10E+00	4.51E-01	5.49E-03	2.79E-01
	10% HP	3.30E-06	3.46E-05	8.67E-03	1.50E+00	9.81E-01	4.53E-01	5.04E+00	3.33E-01
	10% Forest Residue	1.81E-06	3.45E-05	2.24E-04	1.49E+00	9.59E-01	4.39E-01	4.05E-02	3.25E-01
Nuclear	Existing	2.02E-06	3.50E-07	1.59E-03	3.68E-02	7.59E-02	1.92E-01	9.95E-03	4.23E-03
	Gen III+	1.12E-06	2.11E-07	9.34E-04	2.57E-02	6.35E-02	1.16E-01	8.30E-03	3.26E-03
Wind	Onshore Conventional	-9.51E-06	1.45E-07	8.20E-04	5.00E-02	4.47E-02	2.86E-02	8.81E-03	2.72E-02
	Onshore Advanced	7.83E-07	1.68E-07	5.64E-04	3.81E-02	2.68E-02	2.99E-02	7.24E-03	1.68E-02
	Offshore	9.38E-06	6.54E-07	2.90E-04	8.89E-02	1.76E-01	4.33E-02	1.06E-02	9.66E-03
Conventional Hydropower	Greenfield	4.83E-07	5.26E-08	2.55E-06	1.22E-02	1.73E-02	1.12E-02	5.97E-04	5.27E-03
	Power Addition	3.61E-07	1.34E-08	3.55E-07	2.33E-03	1.25E-03	4.36E-04	1.60E-05	1.16E-04
	Upgrade	6.52E-08	7.58E-10	9.77E-08	3.56E-04	1.15E-04	5.42E-05	4.29E-06	1.97E-05
	Existing	0	0	0	0	0	0	0	0
Geothermal	Flash Steam	1.34E-06	3.86E-08	4.53E-01	2.51E-02	1.25E-02	3.11E-03	4.42E-04	1.32E-03
Solarthermal	Parabolic Trough	1.73E-05	1.01E-06	6.64E-05	6.07E-01	9.44E-02	5.92E-02	3.76E-02	3.52E-02

Without impact assessment, these results should be interpreted with care.

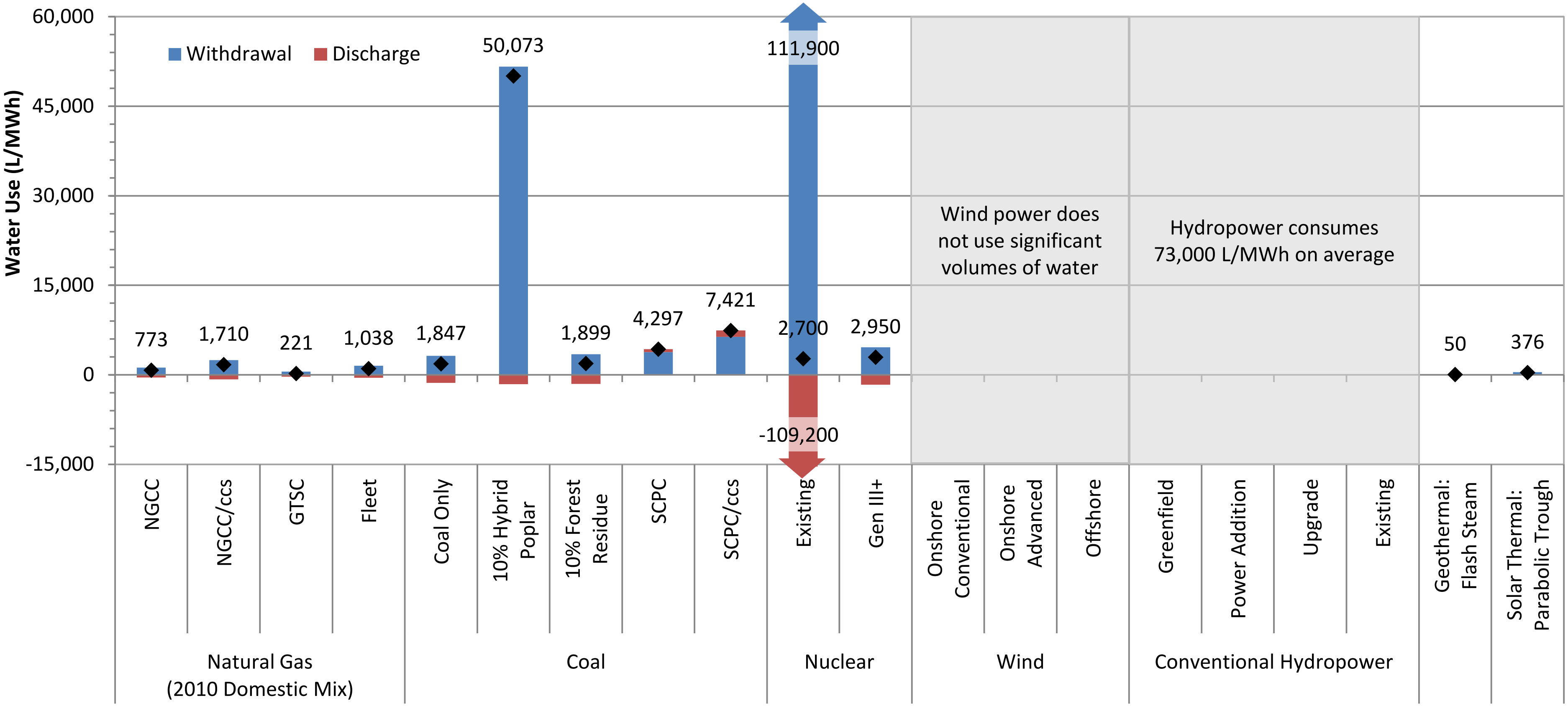
Negative Pb emissions for onshore conventional wind power are due to displacements caused by recycling.

Existing conventional hydropower does not have any construction and installation activities, which are the only sources of CAPs and other non-GHG air emissions in the hydropower model.

High NH_3 emissions from geothermal power are from naturally-occurring NH_3 in geofluid.

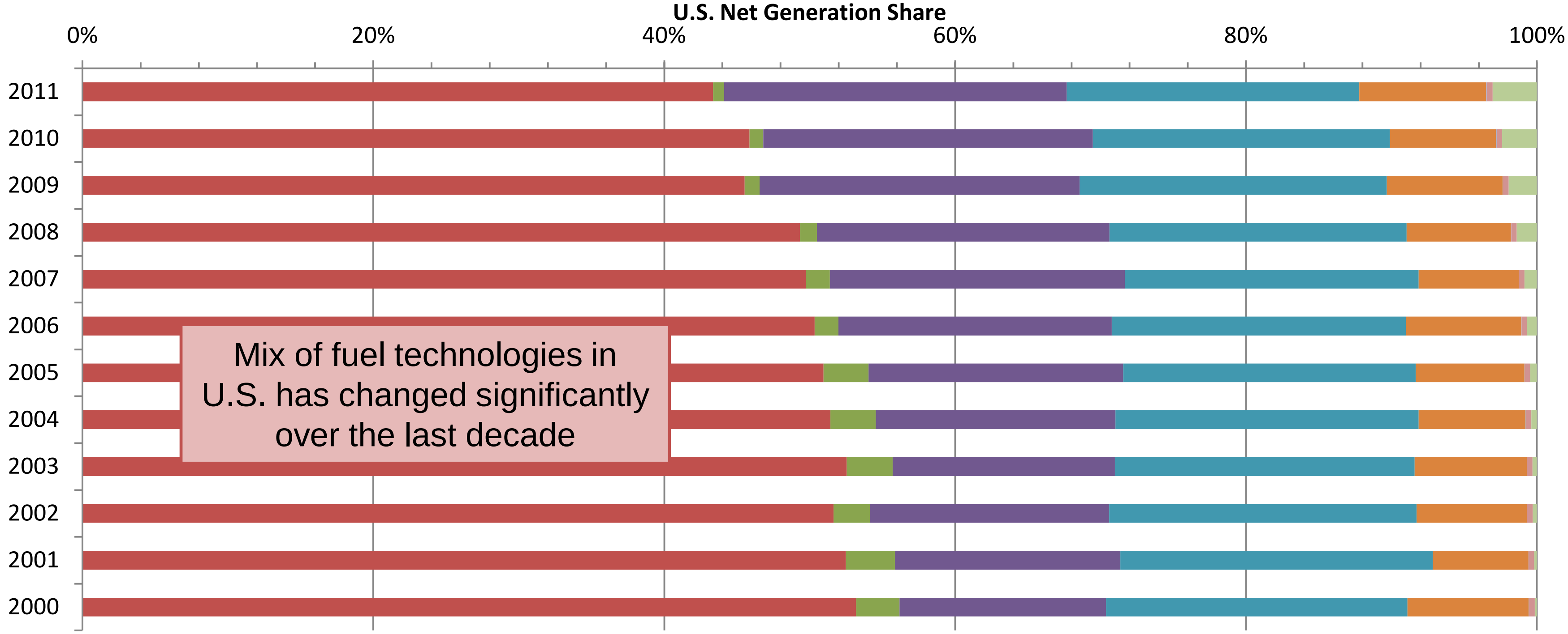
Cofiring with hybrid poplar (HP) has high VOC emissions from fertilizer production and use.

Life Cycle Water Use



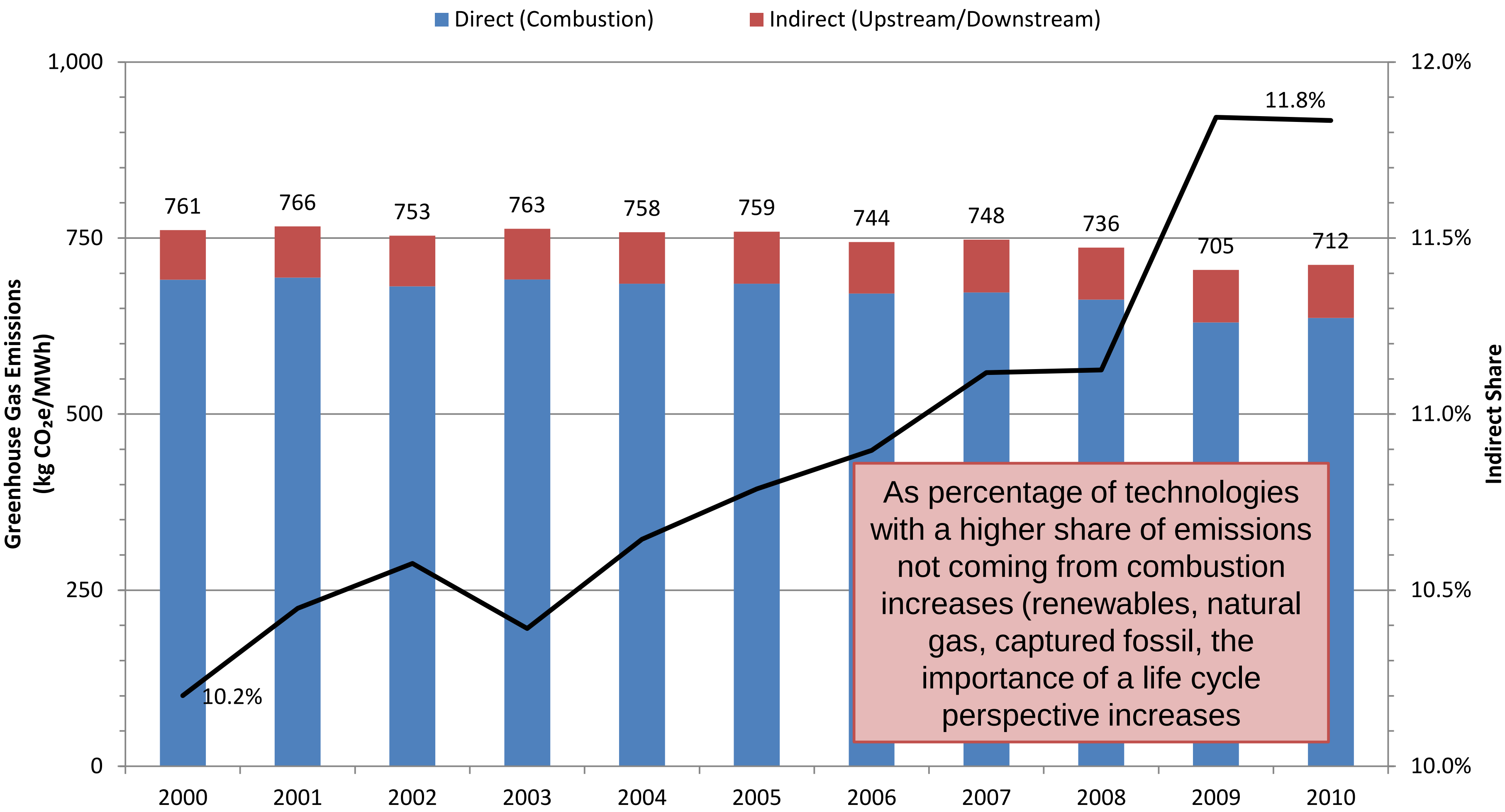
- Super Critical Pulverized Coal (SCPC) with & without carbon capture are not part of this study; included here for comparison
- Withdrawal and discharge rates for once-through cooling can be ~50 times higher than for recirculated cooling
- Acquisition of hybrid poplar or other dedicated energy crops introduces cultivation water to life cycle water balance
- Water consumed by hydropower is due to evaporation from reservoirs and varies according to latitude
- Geothermal water consumption is due to vapor losses during flashing of geofluid
- Solar Thermal water consumption is due to cooling water makeup and reflector cleaning

Combine Technologies into a Mix of Generation



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Coal	53.2%	52.5%	51.6%	52.5%	51.4%	51.0%	50.3%	49.7%	49.3%	45.5%	45.9%	43.4%
Petroleum	3.0%	3.4%	2.5%	3.2%	3.1%	3.1%	1.6%	1.6%	1.2%	1.0%	0.9%	0.7%
Natural Gas	14.2%	15.5%	16.4%	15.3%	16.5%	17.5%	18.8%	20.3%	20.1%	22.0%	22.7%	23.6%
Nuclear	20.7%	21.5%	21.1%	20.6%	20.8%	20.1%	20.2%	20.2%	20.4%	21.1%	20.4%	20.1%
Hydro	8.4%	6.6%	7.6%	7.7%	7.4%	7.5%	7.9%	6.9%	7.2%	8.0%	7.3%	8.7%
Solar	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Geothermal	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
Wind	0.2%	0.2%	0.3%	0.3%	0.4%	0.5%	0.7%	0.9%	1.4%	1.9%	2.4%	3.0%

For Grid Power, Contribution of Indirect Emissions to Full Life Cycle is Increasing



Life Cycle Cost (LCC) Approach

- **Discounted cash flow model that accounts for cash flows over life of power plant**
- **Calculates cost of electricity (COE) using same boundaries as LCA environmental models**
- **Delivered price of fuels to ECF captures all costs of RMA and RMT**
- **Key financial assumptions (excluding nuclear):**
  - Low risk investor owned utilities with 50/50 debt/equity
  - 4.5% interest rate
  - 15-year debt term
  - 20-year accelerated depreciation
  - 38% combined tax rate
  - 3% annual escalation of O&M
  - 3.6% annual escalation of capital during construction
  - Internal Rate of Return on Equity (IRROE) = 12%

Life Cycle Cost (LCC) Approach - Nuclear

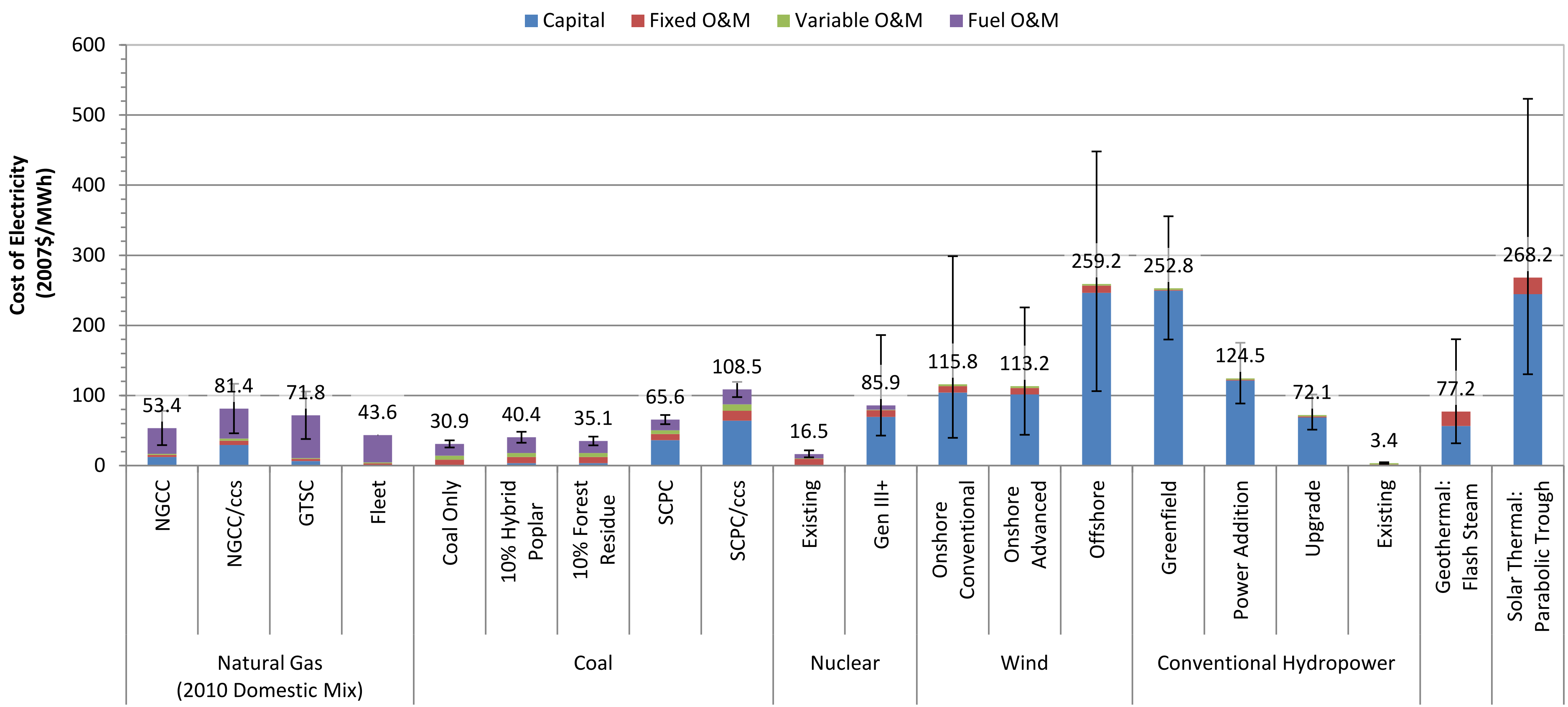
- **Financial parameters for nuclear power are based on a detailed survey of nuclear experts and are slightly different than other technologies (higher IRROE, debt ratio, interest rates, and debt term)**

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%

LCC Cost Parameters

Energy Source	Technology	Capacity Factor (%)	Plant Life (Years)	Capital Cost (Total Overnight Capital) ($/kW)	Variable O&M ($/MWh)	Fixed O&M ($/MW-yr)	Fuel Price ($/GJ)	Fuel Cost ($/MWh)
Natural Gas	NGCC	85.0%	30	$802	$1.32	$22,065	$4.74	$34.2
	NGCC/CCS	85.0%	30	$1,913	$2.68	$44,222	$4.74	$40.1
	GTSC	85.0%	30	$428	$0.96	$22,065	$4.74	$57.1
	Fleet	N/A	N/A	N/A	$1.32	$22,065	$4.74	$36.4
Co-firing	Coal Only	85.0%	30	N/A	$7.65	$86,600	$1.64	$15.8
	10% Hybrid Poplar	85.0%	30	$230	$7.65	$86,600	$1.64 (I-6 Coal) $4.27 (HP)	$21.1
	10% Forest Residue	85.0%	30	$230	$7.65	$86,600	$1.73	$16.1
Nuclear	Existing	90.6%	N/A	N/A	$0.86	$69,100	$0.61	$5.68
	Gen III+	90.6%	49	$4,267	$0.86	$69,100	$0.61	$5.68
Wind	Onshore Conventional	30.0%	20	$1,970	$2.62	$24,050	N/A	N/A
	Onshore Advanced	30.0%	20	$1,920	$2.62	$24,050	N/A	N/A
	Offshore	39.0%	20	$5,470	$2.62	$34,188	N/A	N/A
Hydropower	Greenfield	37.1%	80	$6,300	$1.86	$4,120	N/A	N/A
	Power Addition	37.1%	80	$3,200	$1.86	$4,120	N/A	N/A
	Upgrade	37.1%	80	$1,900	$1.86	$4,120	N/A	N/A
	Existing	37.1%	80	$0	$1.86	$4,120	N/A	N/A
Geothermal	Flash Steam	90.0%	25	$3,000	$0.00	$164,640	N/A	N/A
Solar Thermal	Parabolic Trough	27.4%	30	$4,693	$0.00	$56,780	N/A	N/A

LCC Results



– Super Critical Pulverized Coal (SCPC) with & without carbon capture are not part of this study; included here for comparison

– Capital costs are a significant component of most power systems (except for existing systems)

– Natural gas power has significant capital costs, but fuel costs account for majority of COE for all natural gas cases

– COE of geothermal power is relatively low due to its high capacity factor

– Performance and financing variability are key drivers of COE uncertainty for renewables

Barriers to Implementation

Existing infrastructure will not support growth for:

- **Natural gas** – Limited pipeline capacity near new extraction sites
- **Nuclear** – Long-term storage of waste fuel

Resource is not easily accessible for:

- **Co-firing** – Complicated biomass supply chain logistics
- **Hydro** – Large-scale hydropower has been fully developed
- **Wind, geothermal, & solar thermal** – Resource base is further from electricity grid and demand

Cost uncertainty for:

- **Offshore wind & geothermal** – Construction contingencies
- **Offshore wind & solar thermal** – Learning curves for new technologies

Risks of Implementation

Legislative uncertainty and policy hurdles for:

- **Natural gas** – Policy debates on hydrofracking of Marcellus Shale
- **Co-firing & renewables** – Legislative uncertainty regarding renewable energy incentives
- **Hydropower & offshore wind** – Lengthy environmental review and approval processes

Security and safety concerns for:

- **Nuclear** – Negative perceptions engendered by historic system failures
- **Nuclear** – Long-term storage of waste fuel
- **Geothermal** – Induced seismic activity

Aesthetic and ecological concerns for:

- **Wind** – Bird and bat strikes
- **Wind** – Obstruction of scenery
- **All** – Land use change and habitat loss

Expert Opinions

Resource and growth projections

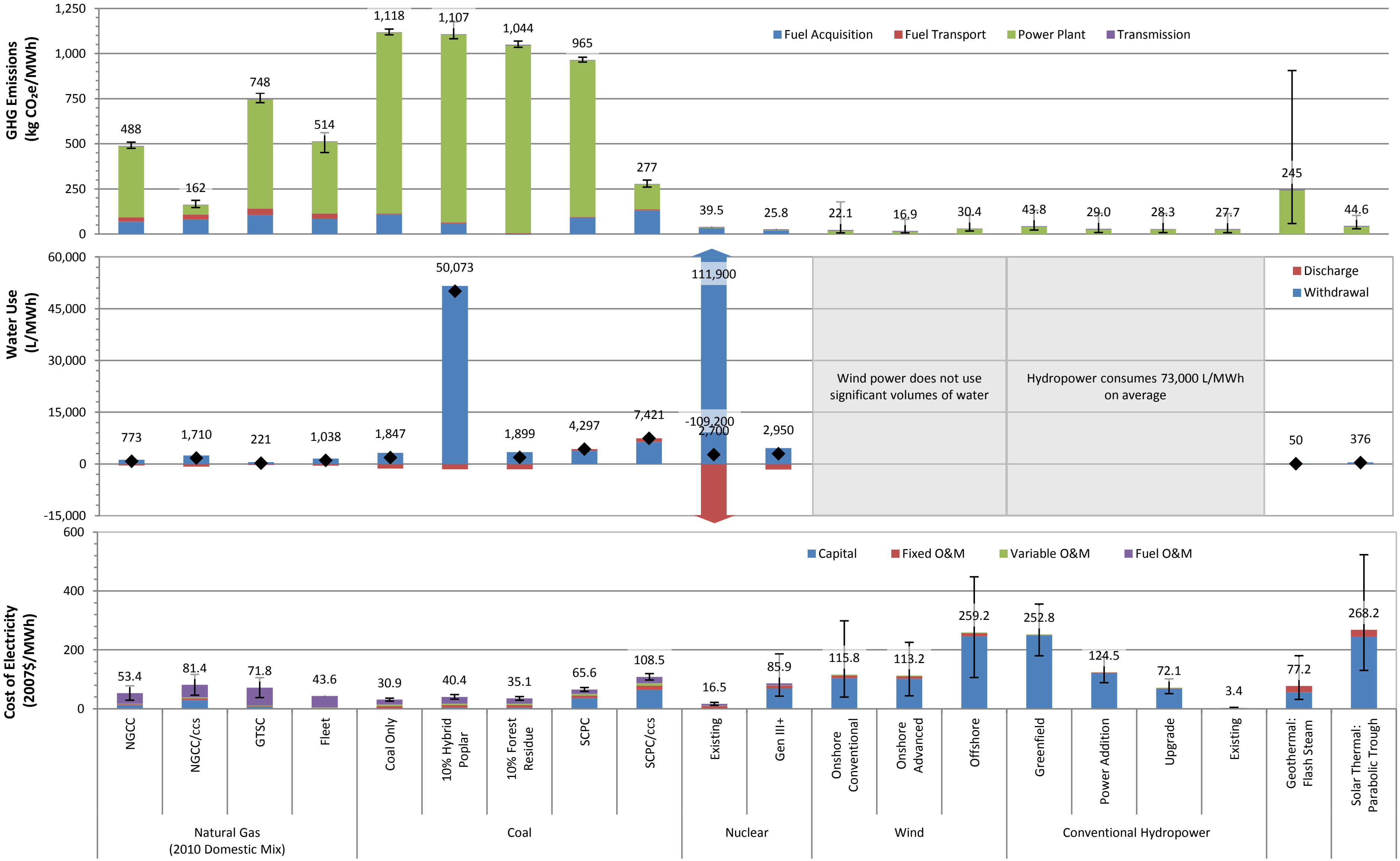
- Technically recoverable natural gas from Marcellus Shale has a resource base of 88 Tcf according to USGS (Pierce, Colman, & Demas, 2011), and up to 489 Tcf according to Pennsylvania State University (Engelder, 2009)
- Long term growth of co-firing, wind, and other renewables are dependent on tax incentives and other policy mechanisms
- Enhanced geothermal systems have high capacity potential, but are at least 15 years from implementation (MIT, 2006)
- Low natural gas prices will prevent growth of nuclear power capacity (Standard & Poor's, 2011)

Infrastructure concerns

- According to El Paso Pipeline Group, natural gas pipeline capacity can be easily increased in Northeast U.S. (Langston, 2011)
- Nuclear capacity growth is hindered by lack of long-term waste repository

Most expert opinions echo NETL's findings for resource base, growth, environmental and cost performance, barriers, and risks

Summary Results: GHG, Water, COE



Summary (continued)

- **Natural Gas**
  - \+ A cleaner alternative to other fossil fuels and a growing resource base
  - – Methane emissions from extraction and transport should be managed
- **Coal and Biomass Co-firing**
  - \+ Existing systems can be easily retrofitted to increase the share of renewable energy for power production
  - – Does not significantly reduce life cycle GHG emissions and biomass delivery has logistical challenges
- **Nuclear**
  - \+ Stable source of baseload power with low GHG emissions
  - – Growth is hindered by high initial capital costs, security and safety concerns, and no long-term waste repository
- **Wind**
  - \+ Low GHG emissions and low water consumption
  - – Future growth depends on tax incentives and backup power is necessary if it will compete with other baseload technologies
- **Hydropower**
  - \+ Conventional hydropower is a proven technology with a 7% share of U.S. electricity supply
  - – Large resources have already been developed and many hydrokinetic installations are necessary to achieve significant capacity
- **Geothermal**
  - \+ A large resource base with a high capacity factor
  - – High drilling costs and high CO_2 emissions from the flash process
- **Solar Thermal**
  - \+ A large resource base
  - – Solar collectors have high capital costs and best solar resources are far from population centers

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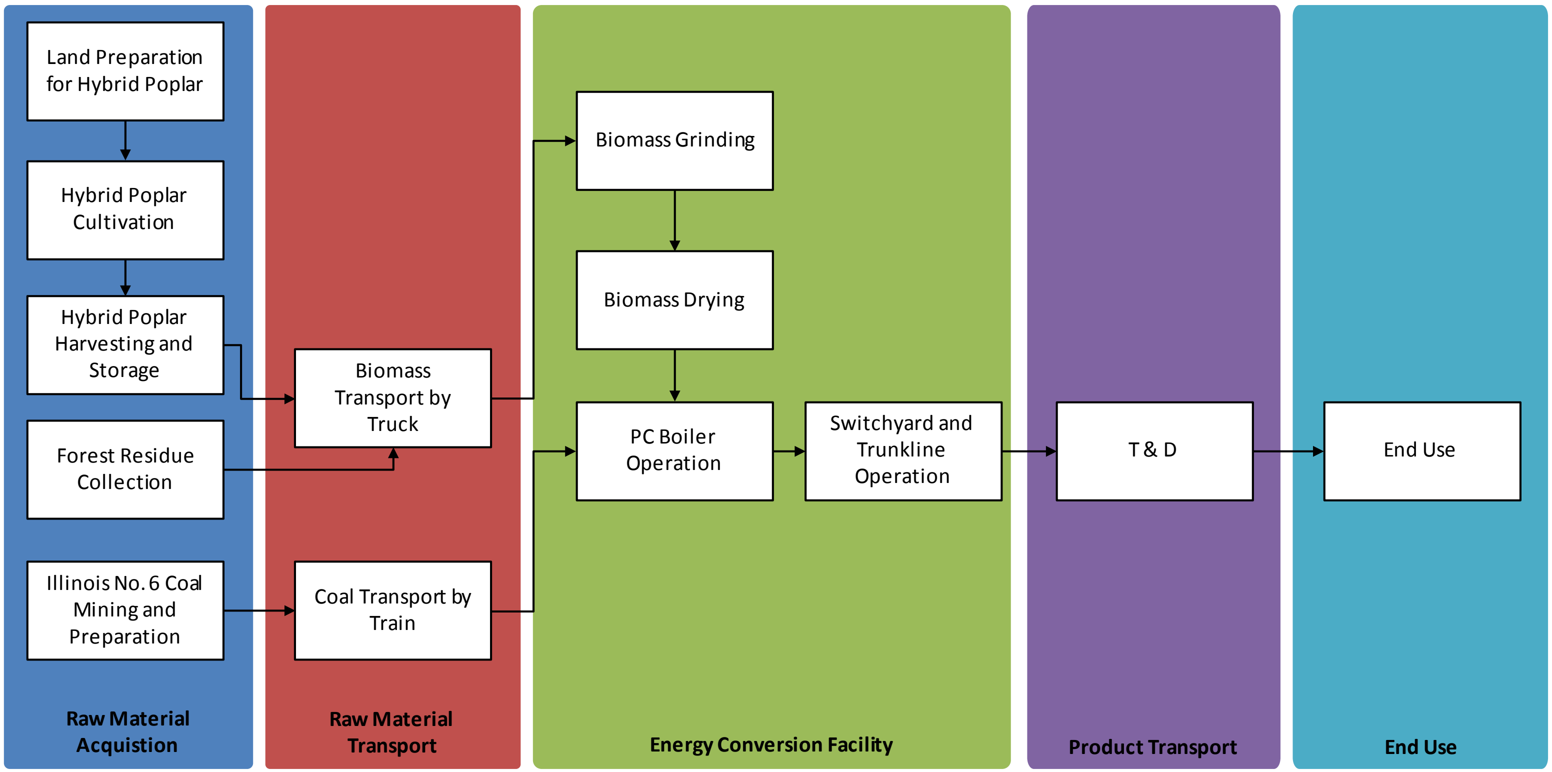
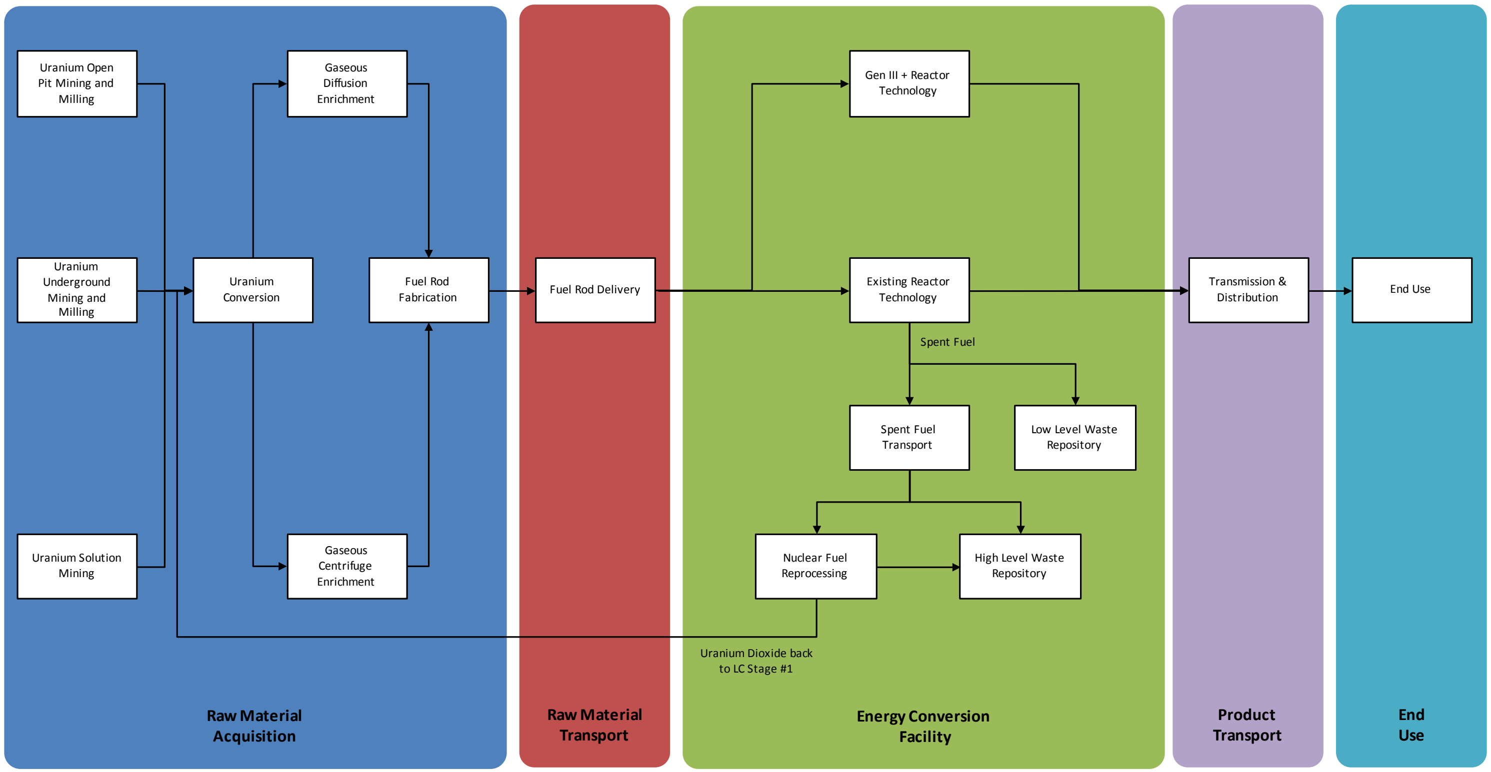
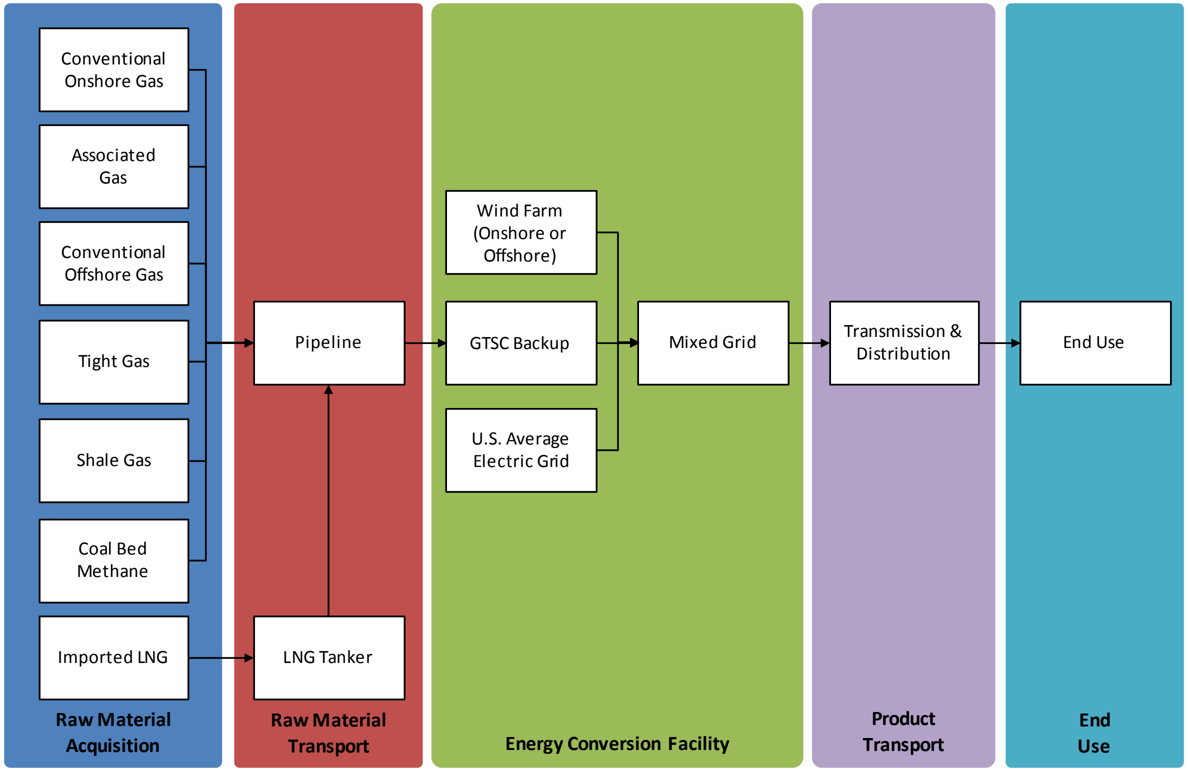
Co-firing LCA Boundaries



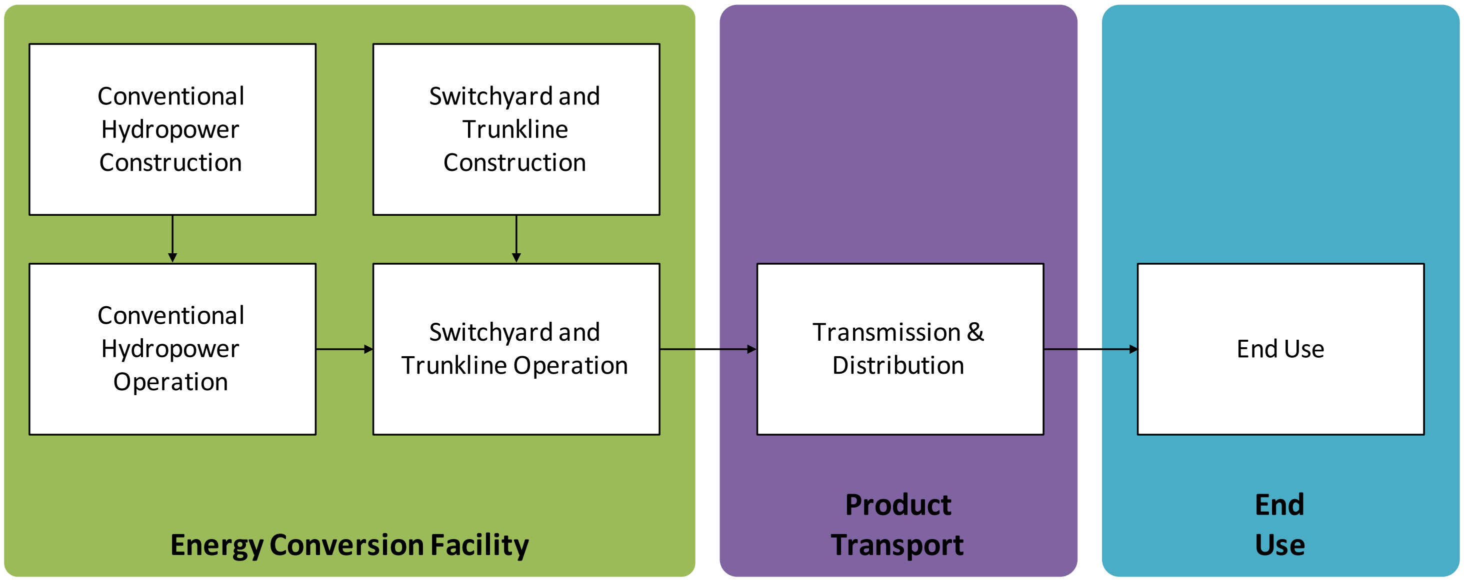
Nuclear LCA Boundaries



Wind LCA Boundaries



Hydropower LCA Boundaries



Solar Thermal LCA Boundaries