NATIONAL ENERGY TECHNOLOGY LABORATORY

# Role of Alternative Energy Sources: Technology Assessment Compilation


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U.S. DEPARTMENT OF ENERGY

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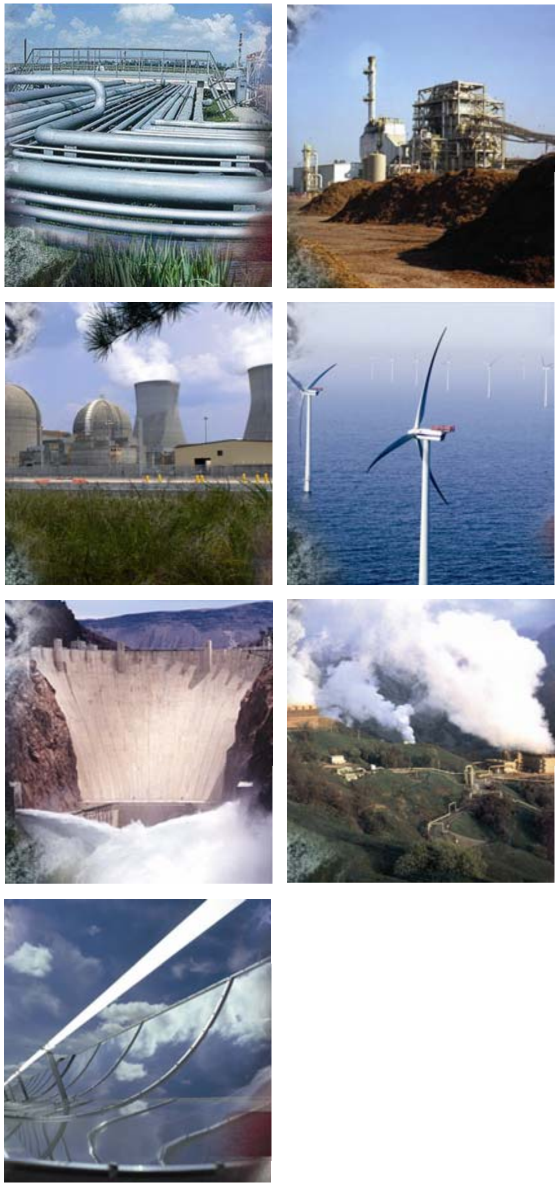


# Purpose of the Study

- **Provide a broad assessment of power technologies**
- **Look at alternate current or near-term technologies**
- **Provide insights into key criteria for technology feasibility**
- **Ability to compare energy platforms on a consistent basis**

# 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 to Implementation | 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 |

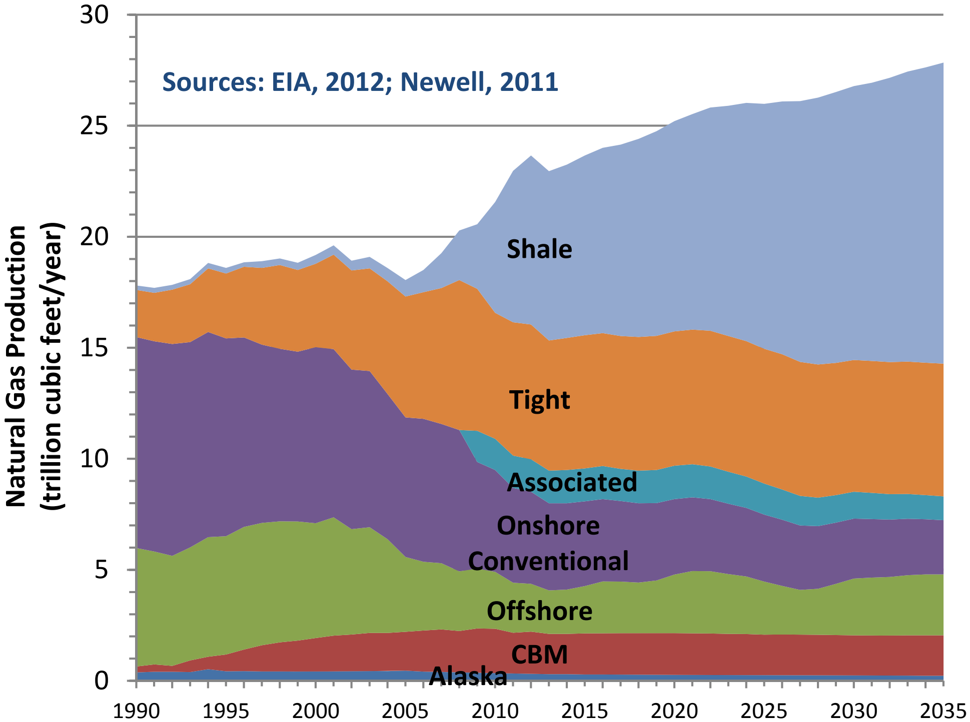
# Technology Description (7 Technology Groups)

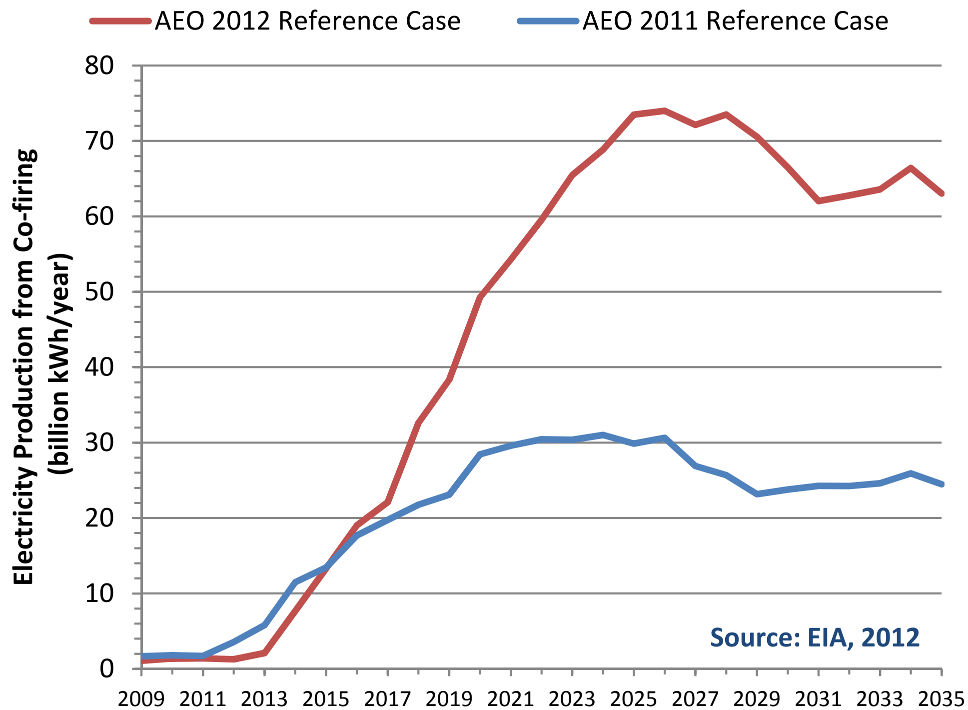
- **Natural Gas**
  - Conventional and unconventional natural gas sources
  - Construction and operation (C&O) of simple and combined cycle power plants (GTSC and NGCC)
  - Includes a carbon capture and sequestration (CCS) case
  - Operation of fleet average natural gas power plants
- **Co-firing of Coal & Biomass**
  - Acquisition of coal and biomass (hybrid poplar (HP) and forest residue (FR))
  - Existing pulverized coal (PC) boiler
  - Includes a coal-only system for comparison
- **Nuclear**
  - Acquisition of uranium, using a mix of enrichment technologies
  - C&O of existing and advanced (Generation III+) nuclear power plants
  - Includes short-term and long-term nuclear waste management scenarios
- **Wind**
  - C&O of conventional and advanced onshore wind farms
  - C&O of offshore wind farms
  - Backup power (GTSC)
- **Hydropower**
  - Four conventional dam scenarios: Greenfield, Power Addition, Upgrade, and Existing
  - Brief assessment of hydrokinetic hydropower potential
- **Geothermal**
  - C&O of a flash steam, geothermal power facility
- **Solar Thermal**
  - C&O of a concentrated solar power plant with parabolic trough reflectors

# Technology Performance Summary

| Energy Source | Power Plant Technology | Net Plant Power (MW) | Capacity Factor (%) | Thermal Efficiency (%) |
|---|---|---|---|---|
| Natural Gas | NGCC | 555 | 85.0% | 50.2% |
| | NGCC/ccs | 474 | 85.0% | 42.8% |
| | GTSC | 360 | 85.0% | 30.0% |
| | Fleet Baseload | N/A | N/A | 47.1% |
| Co-firing (Coal and Biomass) | Coal Only | 550 | 85.0% | 33.0% |
| | Co-fired Coal and Biomass | 550 | 85.0% | 32.8% |
| Nuclear | Existing | 796 | 70.7% | 31.6% |
| | Gen III+ | 2,060 | 94.0% | 34.2% |
| Wind | Onshore Conventional (1.5 MW Turbine) | 200 | 30.0% | N/A |
| | Onshore Advanced (6.0 MW Turbines) | 200 | 30.0% | N/A |
| | Offshore (3.6 MW Turbines) | 468 | 39.0% | N/A |
| Hydro | Conventional Dam | 2,080 | 37.0% | N/A |
| Geothermal | Flash Steam | 50 | 90.0% | 17.1% |
| Solar Thermal | Parabolic Trough | 250 | 27.4% | N/A |

# Resource Base and Growth
## Example 1: New Technology vs. Policy




*Technology Driven:* Projected growth in NG 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**

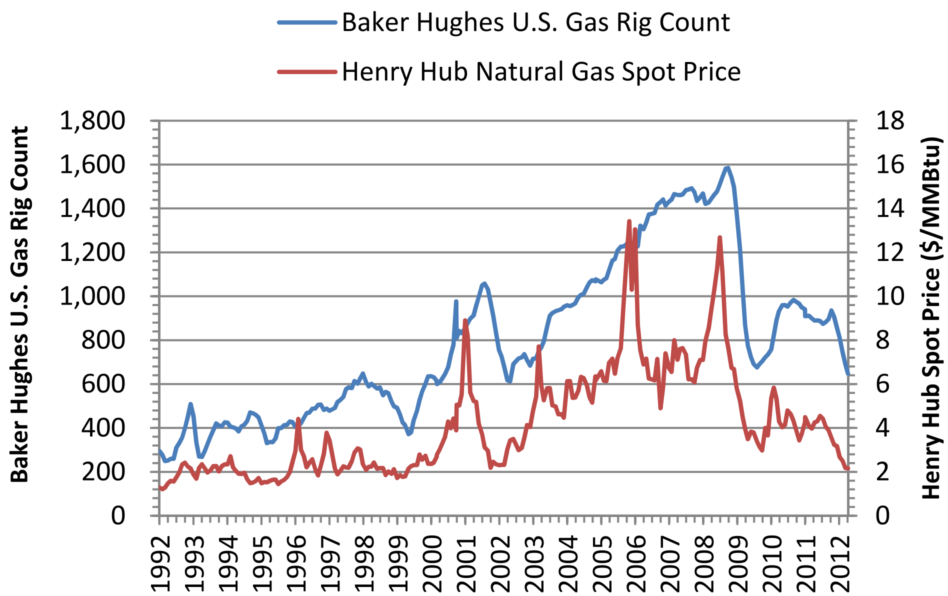
*Policy Driven:* Wind power grew from 0.1% to 2.3% of U.S. electricity generation between 2000 and 2010. This growth was made possible by electricity production tax credits, due to expire in 2012.

*Policy Driven:* Growth of U.S. nuclear power depends on number of facility license renewals and policies on long-term waste disposition.

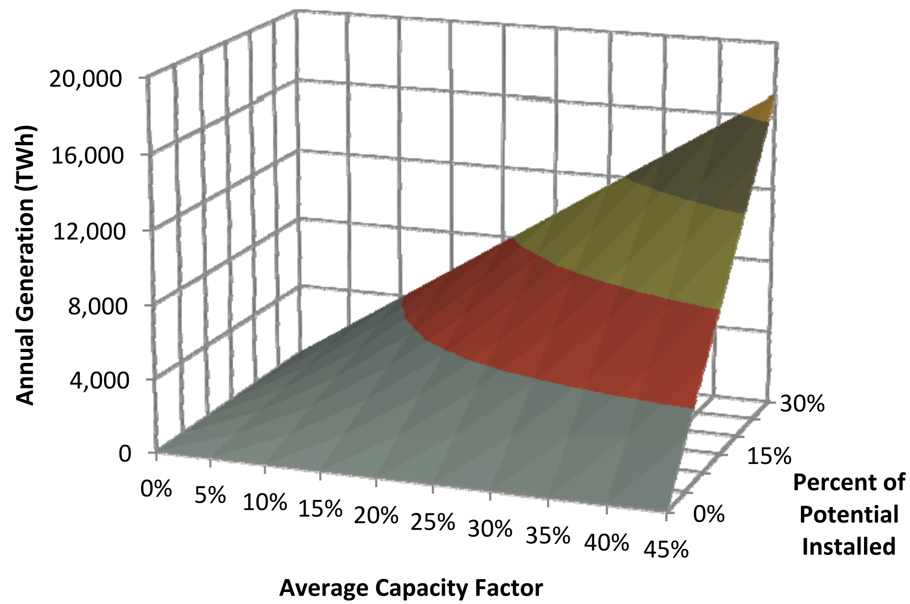
*Technology Driven:* Torrefaction reduces biomass supply chain uncertainty and could increase the growth rate of co-firing.

# Resource Base and Growth

## Example 2: Technically vs. Economically Recoverable




Sources: EIA, 2012; Baker Hughes, 2012




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

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

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.

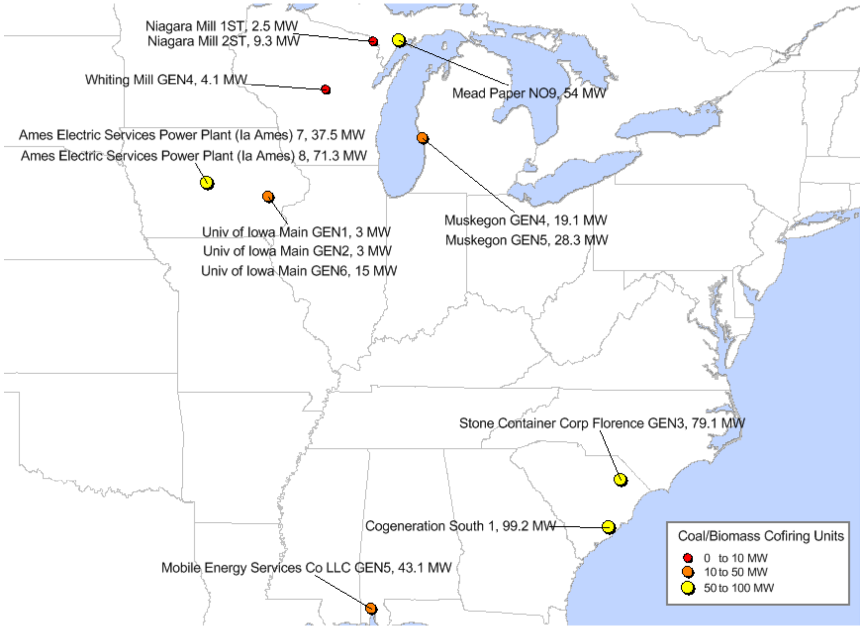
**Other examples**

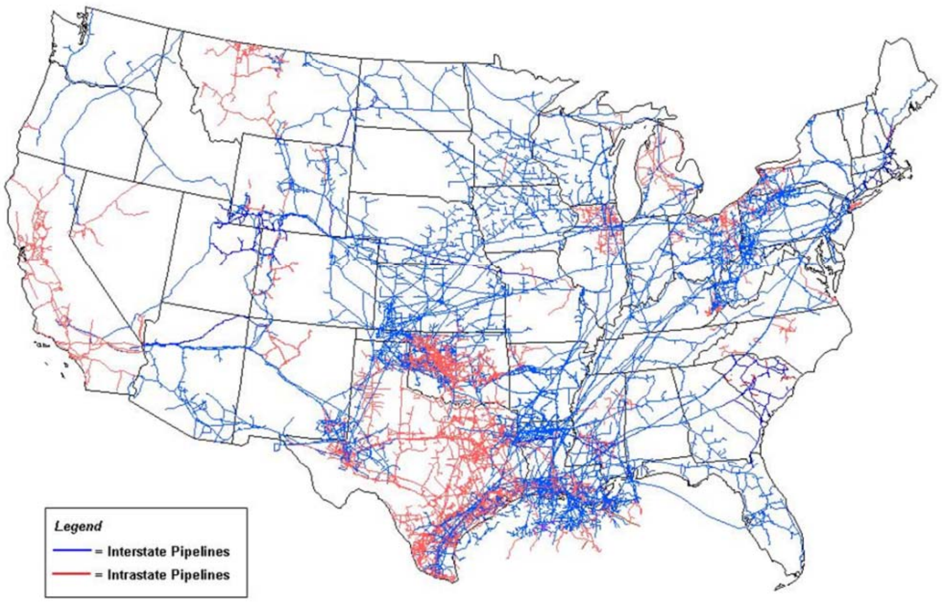
High drilling costs hinder recovery of deep geothermal resources.

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 logistics 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 NG 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.

# Resource Base and Growth

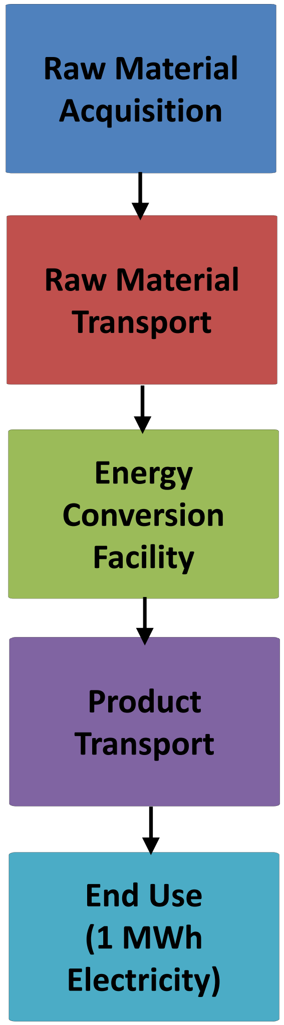
## Key Conclusions

- 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:  Key drivers for growth of renewable energy

# 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 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

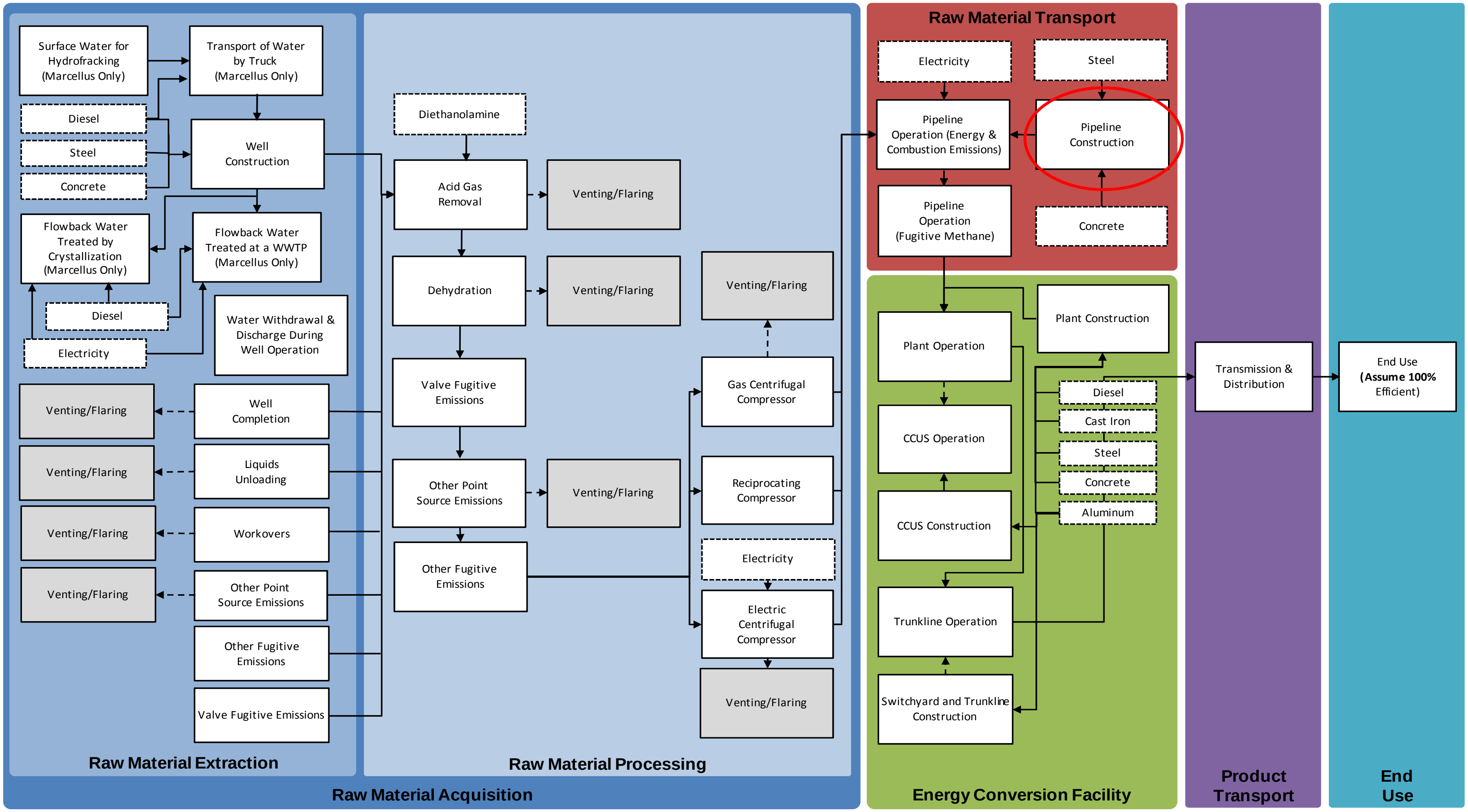



## Environmental Metrics

- Greenhouse gas (GHG) and other air emissions of concern
- Water withdrawal, discharge, and consumption
- Cost of Electricity (COE)

## Functional Unit = 1 MWh delivered electricity

# Natural Gas LCA Boundaries

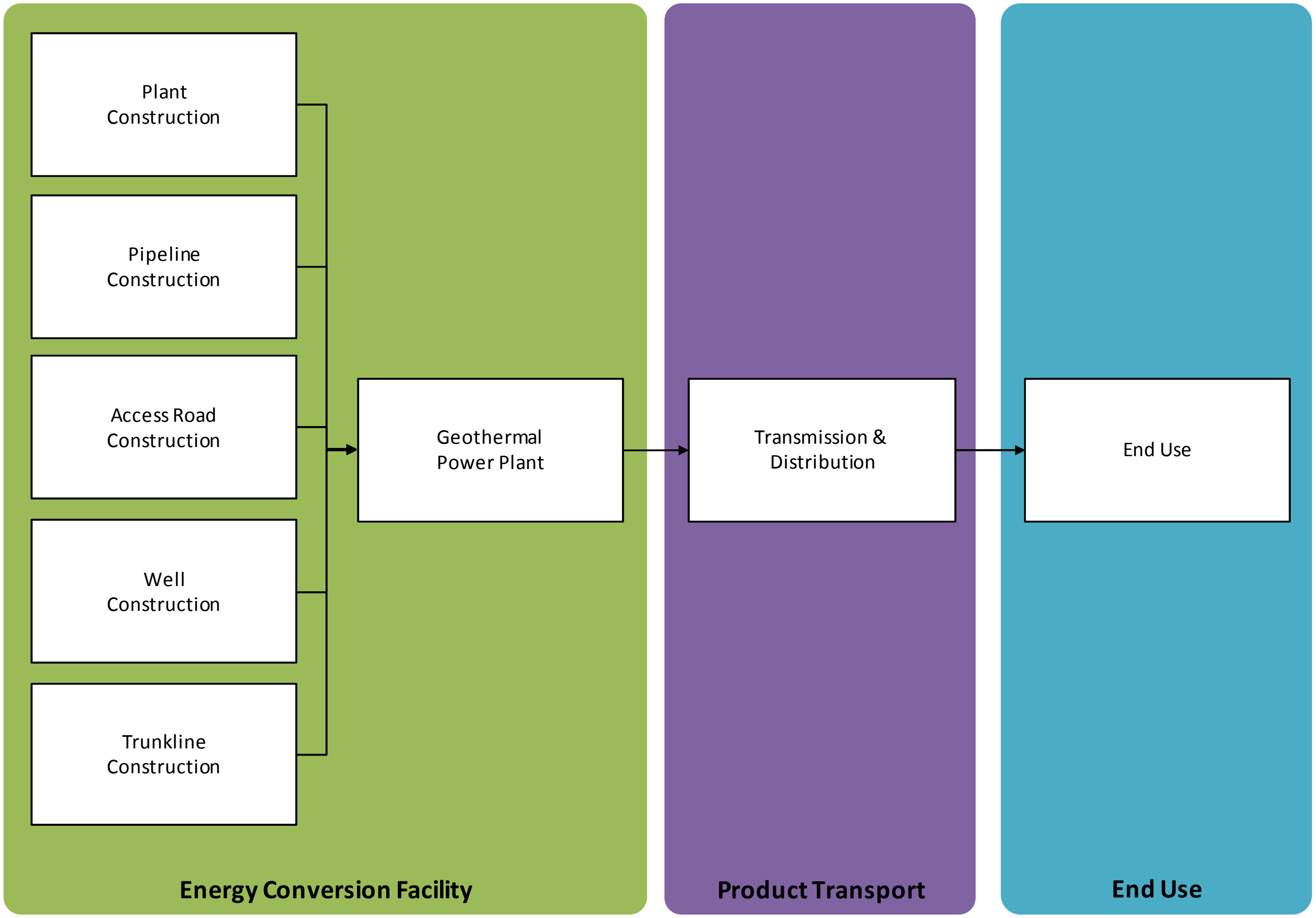



**Complex network of many unit processes**

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

– Various switches within the energy conversion facility

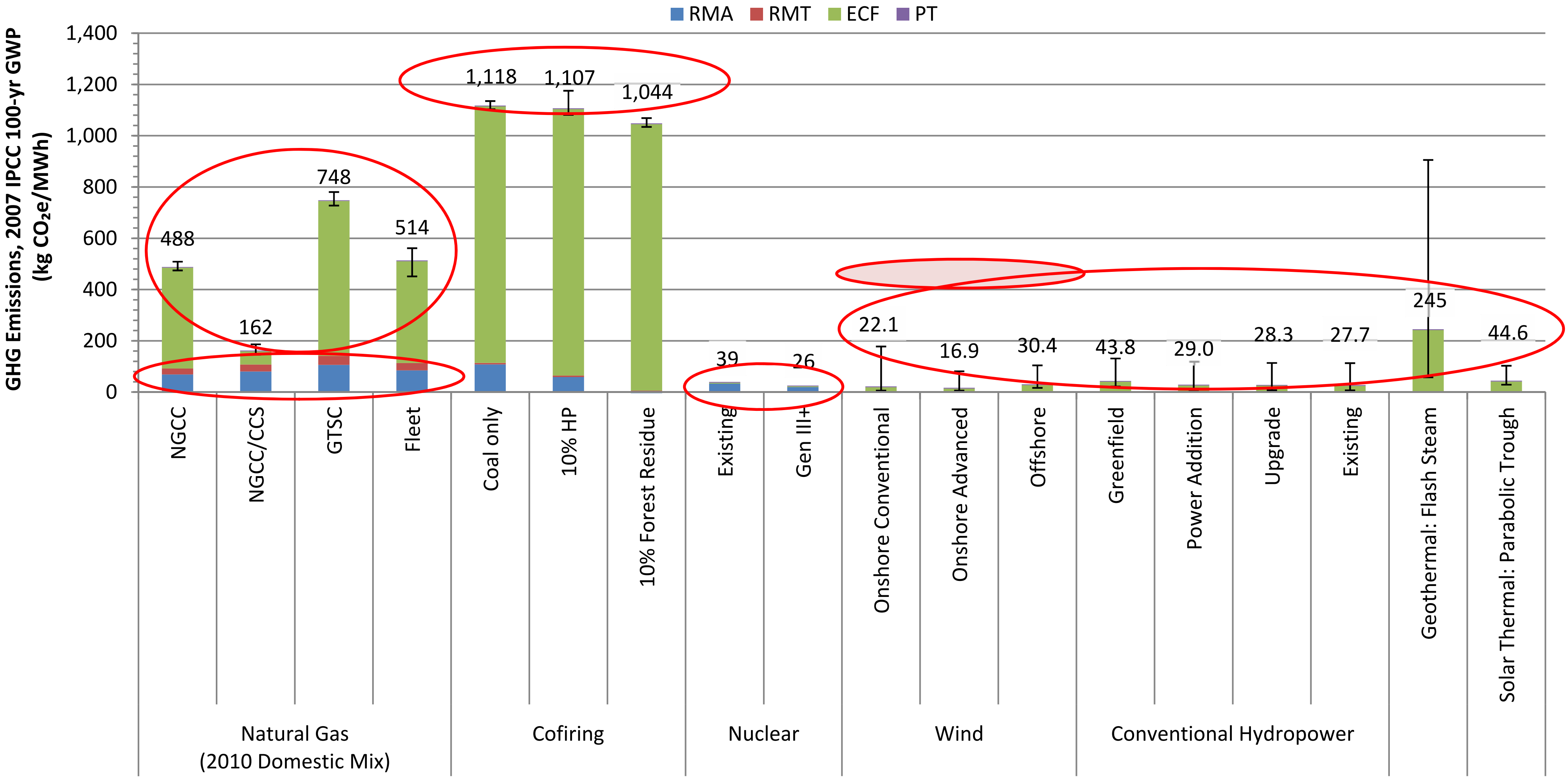
# Geothermal LCA Boundaries




**Simple network of a few unit processes**

– Most unit processes were adapted from other NETL LCAs

# Life Cycle GHG Emissions




- 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 PC coal plants.
- Nuclear is the only technology where RMA dominates the 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 $CO_2$e/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.

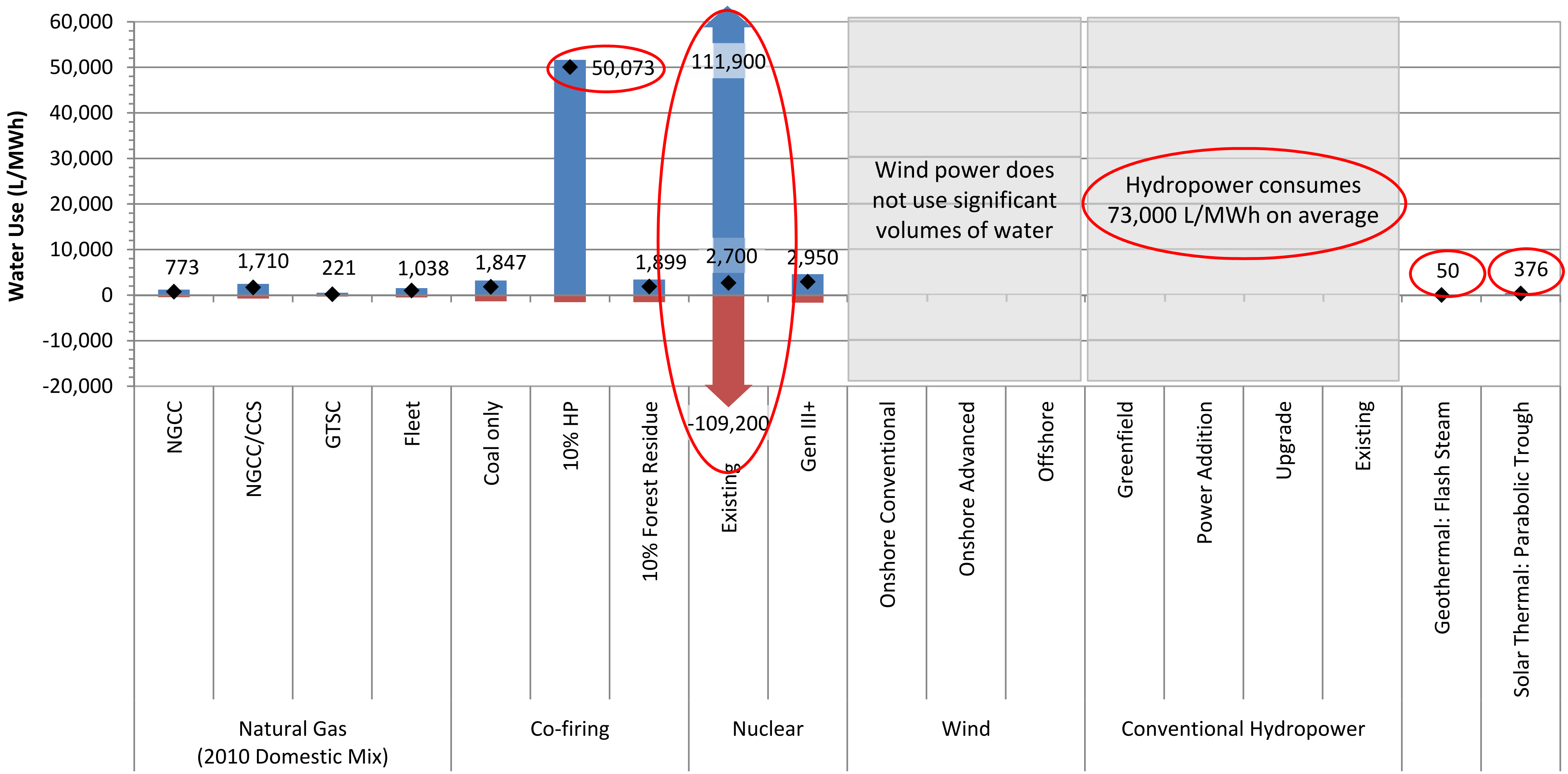
Negative Pb emissions for onshore conventional wind power are due to displacements caused by recycling.

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




- 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 the 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

# Life Cycle Cost (LCC) Approach

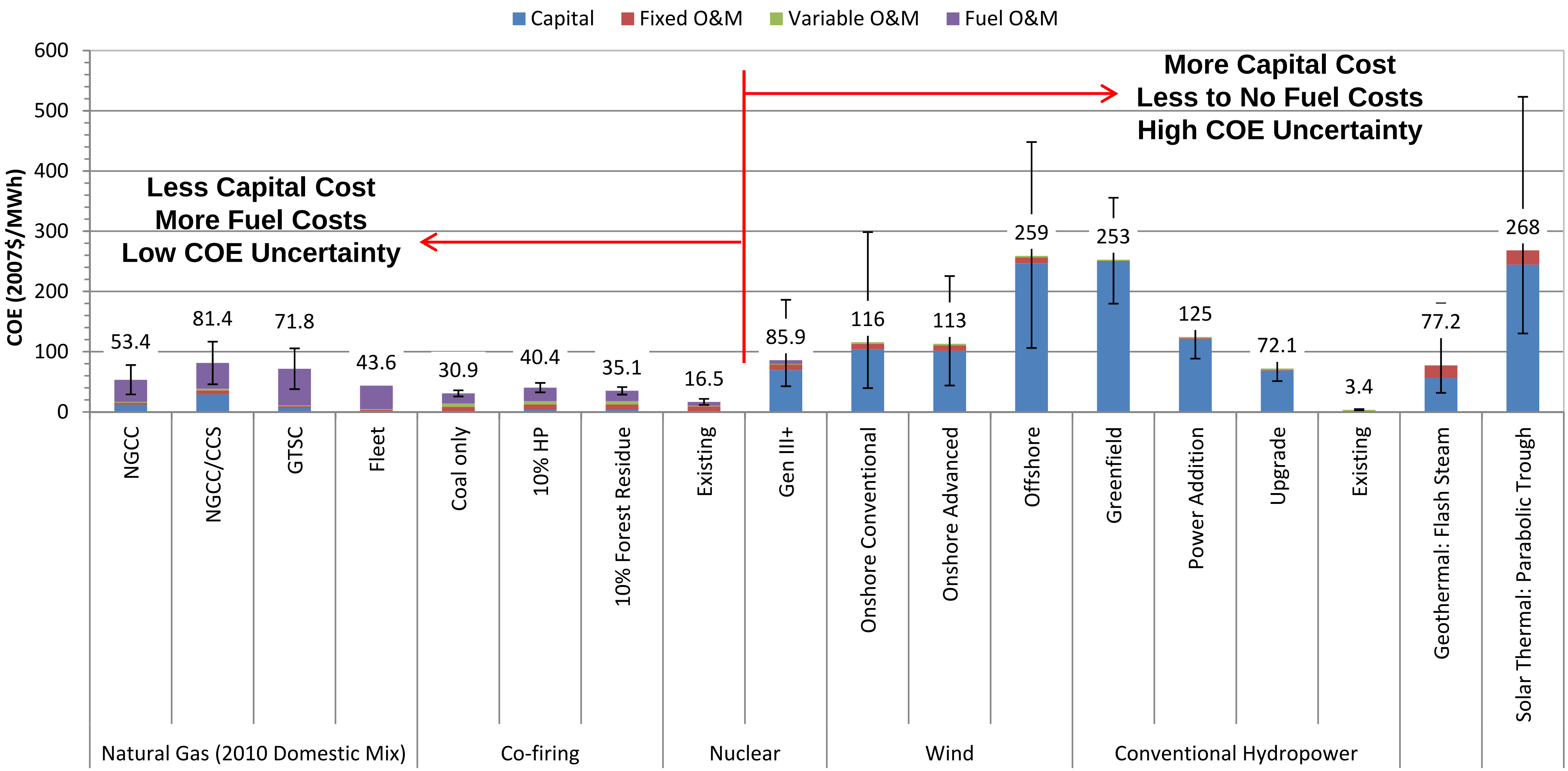
- **Discounted cash flow model**
  - Accounts for cash flows over the life of the power plant
- **Calculates cost of electricity (COE)**
  - Uses the same boundaries as LCA environmental models
- **Delivered price of fuels to ECF**
  - Captures all costs of RMA and RMT
- **Key financial assumptions:**
  - 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%

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)

# 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) |
|---|---|---|---|---|---|---|---|
| Natural Gas | NGCC | 85.0% | 30 | $802 | $1.32 | $22,065 | $4.74 |
| | NGCC/CCS | 85.0% | 30 | $1,913 | $2.68 | $44,222 | $4.74 |
| | GTSC | 85.0% | 30 | $428 | $0.96 | $22,065 | $4.74 |
| | Fleet | N/A | N/A | N/A | $1.32 | $22,065 | $4.74 |
| Co-firing | Coal Only | 85.0% | 30 | N/A | $7.65 | $86,600 | $1.64 |
| | 10% Hybrid Poplar | 85.0% | 30 | $230 | $7.65 | $86,600 | $1.64 (I-6 Coal)<br>$4.27 (HP) |
| | 10% Forest Residue | 85.0% | 30 | $230 | $7.65 | $86,600 | $1.73 |
| Nuclear | Existing | 90.6% | N/A | N/A | $0.86 | $69,100 | $0.61 |
| | Gen III+ | 90.6% | 49 | $4,267 | $0.86 | $69,100 | $0.61 |
| Wind | Onshore Conventional | 30.0% | 20 | $1,970 | $2.62 | $24,050 | N/A |
| | Onshore Advanced | 30.0% | 20 | $1,920 | $2.62 | $24,050 | N/A |
| | Offshore | 39.0% | 20 | $5,470 | $2.62 | $34,188 | N/A |
| Hydropower | Greenfield | 37.1% | 80 | $6,300 | $1.86 | $4,120 | N/A |
| | Power Addition | 37.1% | 80 | $3,200 | $1.86 | $4,120 | N/A |
| | Upgrade | 37.1% | 80 | $1,900 | $1.86 | $4,120 | N/A |
| | Existing | 37.1% | 80 | $0 | $1.86 | $4,120 | N/A |
| Geothermal | Flash Steam | 90.0% | 25 | $3,000 | $0.00 | $164,640 | N/A |
| Solar Thermal | Parabolic Trough | 27.4% | 30 | $4,693 | $0.00 | $56,780 | N/A |

# LCC Results




– 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

- Limited pipeline capacity near new extraction sites **(natural gas)**
- Long-term storage of waste fuel **(nuclear)**

## Resource is not easily accessible

- Complicated biomass supply chain logistics **(co-firing)**
- Large-scale hydropower has been fully developed **(hydropower)**
- Resource base is far from electricity grid **(wind, geothermal, and solar thermal)**

## Cost uncertainty

- Construction contingencies **(offshore wind and geothermal)**
- Learning curves for new technologies **(offshore wind and solar thermal)**

# Risks of Implementation

## Legislative uncertainty and policy hurdles

- Policy debates on hydrofracking of Marcellus Shale **(natural gas)**
- Legislative uncertainty regarding renewable incentives **(co-firing and renewables)**
- Lengthy environmental review/approval **(hydropower and offshore wind)**

## Security and safety concerns

- Negative perceptions engendered by historic system failures **(nuclear)**
- Long-term storage of waste fuel **(nuclear)**
- Induced seismic activity **(geothermal)**

## Aesthetic and ecological concerns

- Bird and bat strikes **(wind)**
- Obstruction of scenery **(wind)**
- Land use change and habitat loss **(all)**

# 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),
  - 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

- **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
  - – 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
  - – No long-term waste repository

# Summary (Cont.)

- **Wind**
  - + Low GHG emissions and low water consumption
  - – Future growth depends on tax incentives
  - – 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
  - – 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
  - – Best solar resources are far from population centers

# Contact Information



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