NATIONAL ENERGY TECHNOLOGY LABORATORY

Overview of Energy Life Cycle Analysis at NETL

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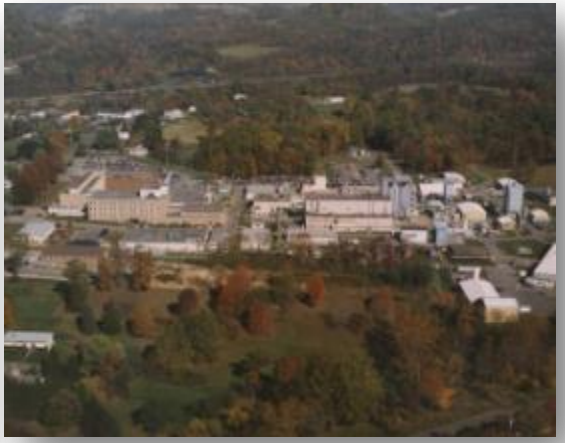
U.S. DEPARTMENT OF ENERGY

National Energy Technology Laboratory

MISSION
Advancing energy options to fuel our economy, strengthen our security, and improve our environment

Oregon

Pennsylvania



West Virginia

Overview of Energy Life Cycle Analysis at NETL
(The Agenda)

1. **LCA Definitions & Methods**
2. **NETL LCA Tools**
   - Power Life Cycle Analysis Tool (LCAT)
   - Calculating Uncertainty in Biomass Emissions (CUBE)
   - Upstream Life Cycle Emissions Dashboard
3. **Life Cycle Analysis Studies**
   - Natural Gas Extraction, Delivery and Electricity Production
   - Alternative Aviation Fuels
   - Nuclear Power
   - Wind Power with Gas Backup
   - Cofiring Coal and Biomass for Power
4. **Forthcoming Studies**
   1. Geothermal, Solar Thermal, Conventional Hydro
   2. Dynamic Coal-Biomass Power with Emissions Control Options

Purpose of Energy Systems LCA Program

1. **Produce Energy System LCAs**
   - Inform and defend the Technology Programs
   - Baseline different energy system technologies
   - Understand technology strengths and weaknesses when viewed from a life cycle perspective
   - Identify opportunities for R&D innovation (through depth and transparency of analysis)

2. **Improve LCA methods**
   - Expand inventory
   - Characterize uncertainty and variability
   - Build flexible and dynamic models
   - Keep data collection and modeling current with state-of-the-art LCA

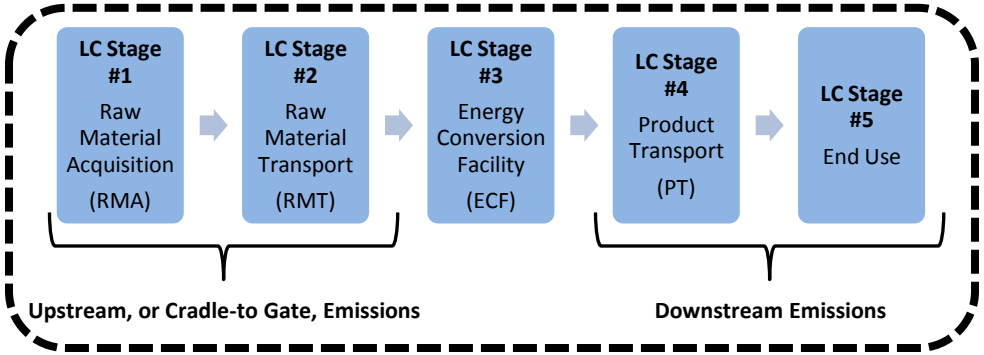
3. **Enhance interpretation and comparability of inventory results without losing depth and transparency**
   - Stochastic simulation of life cycle inventory
   - Tools to explore uncertainty and variability

NETL has a library of over 300 custom Unit Processes, and dozens of models to characterize energy systems and address questions from stakeholders

LCA: Definitions, Boundaries, Metrics

- **Compilation and evaluation of inputs, outputs, and potential environmental impacts of a product or service throughout its life cycle, from raw material acquisition to final use and disposal**

- **The ability to compare different technologies depends on functional unit (denominator); e.g., for energy studies:**
  - 1 MWh of electricity delivered to end user
  - 1 MJ of fuel combusted



Converted to Carbon Dioxide equivalents using 2007 IPCC Global Warming Potential (GWP)

GHG	20-year	100-year (Default)	500-year
CO_2	1	1	1
CH_4	72	25	7.6
N_2O	289	298	153
SF_6	16,300	22,800	32,600

- **Greenhouse Gases**
  - CO_2, CH_4, N_2O, SF_6
- **Criteria Air Pollutants**
  - NO_X, SO_X, CO, PM10, Pb
- **Air Emissions Species of Interest**
  - Hg, NH_3, radionuclides
- **Solid Waste**
- **Raw Materials**
  - Energy Return on Investment (EROI)
- **Water Use**
  - Withdrawn water, consumption, water returned to source
  - Water Quality
- **Land Use**
  - Direct & indirect, Acres transformed, greenhouse gases
- **Life Cycle Cost**
  - Cost of Electricity (COE), Total Overnight Cost (TOC)

LCA Basic Building Blocks: Unit Processes

NETL Life Cycle Inventory Data - Detailed Spreadsheet Documentation
Data Module Summary

Process Name:	Gaseous Diffusion Uranium Enrichment, Operations						
Reference Flow:		1	kg	of	UF6 (enriched) [energy carrier]	DQI	2,1,2,1,1
Brief Description:	This process recieves UF6 from a conversion facility and enriches the percent composition of uranium-235 in the fuel. This process includes energy consumption, air emissions, water use, water emissions, and solid waste.						

SECTION I: META DATA

Geographical Coverage:	US
Region	N/A
Year Data Best Represents:	2010
Process Type:	Energy Conversion (EC)
Process Scope:	Gate-to-Gate Process (GG)
Allocation Applied:	No
Completeness:	Individual Relevant Flows Captured
Flows Aggregated in Data Set:	☑ Process ☑ Energy Use ☐ Energy P&D ☐ Material P&D

Goal and Scope:
Reference Flow: 1 kg of enriched uranium

This unit process provides a summary of relevant input and output flows associated with the enrichment of uranium by gaseous diffusion. UF6 with natural levels of U235 is received from conversion facilities. Using the gaseous diffusion technology, the concentration of U-235 is increased to 5% by mass which is needed for commercial nuclear reactors. The enriched uranium out of this proces is ready to be formed into fuel assemblies. For additional documentation, please see the associated DF sheet for this unit process.

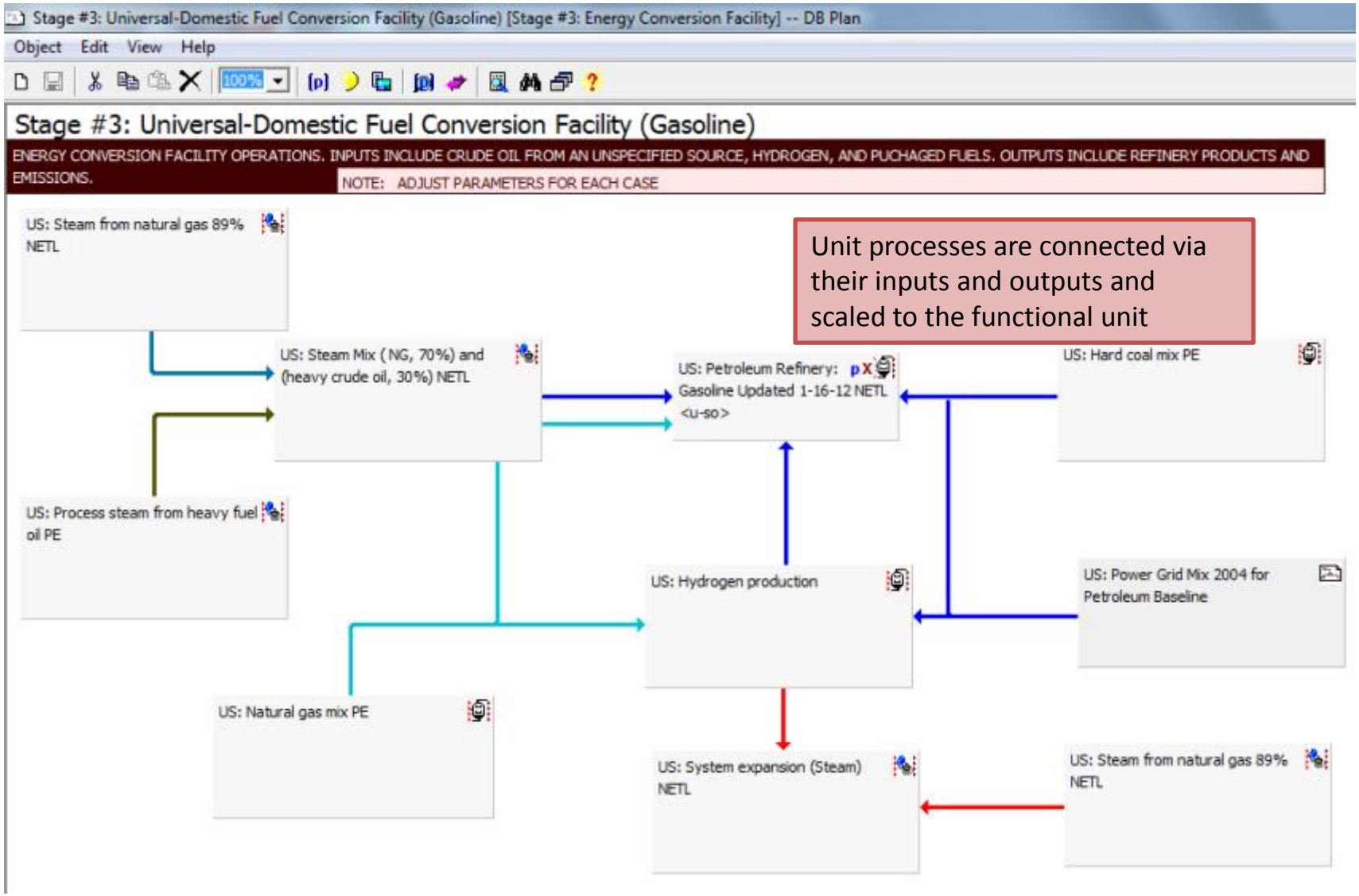
SECTION II: PARAMETERS

This section includes adjustable parameters, calculations needed to support adjustable parameters, and flow calcu

	Parameter Name	Formula	Value	Min. Value	Max. Value	Unit	Reference	
9	ELC_POWER		1600			MW		
6	SWU_KG		7.90		8.9	SWU/kg		
0	SWU_ANNUAL		1.13E+07			SWU/yr		
	cap		0.82		0.85	decima	percen	
6	air_Cr		1430	860	2000	kg/yr	1	[kg/yr] Emission of Chromium to air per year of operation
6	air_HF		5500	3800	7200	kg/yr	1	[kg/yr] Emission of Hydrogen Fluoride to air per year of operation
7	air_VOC		32085	1270	62900	kg/yr	1	[kg/yr] Emission of VOC to air per year of operation
9	air_radio		1.02E+09	8.49E+06	2.03E+09	Bq/yr	1	[Bq/yr] Emission of Radionuclides to air per year of operation
2	w_heavymetal		1.51E+05			kg/yr	1	[kg/yr] Emission of Heavy Metals to water per year of operation
0	w_fluoride		5.79E+03			kg/yr	1	[kg/yr] Emission of Fluoride to water per year of operation
9	w_nitrate		1.38E+04			kg/yr	1	[kg/yr] Emission of Nitrates to water per year of operation
9	w_sulfate		5.98E+05			kg/yr	1	[kg/yr] Emission of Sulfates to water per year of operation
9	w_chlorHC		5.25E+01			kg/yr	1	[kg/yr] Emission of chlorinated hydrocarbons (TCE+PCB) to water per year of operation
2	w_withdrawal		2.07E+10			kg/yr	2	[kg/yr] Water withdrawal per year of operation
9	w_outfall		5.53E+09			kg/yr	2	[kg/yr] Water outfall per kg of production
4	Product_annual	SWU_ANNUAL/SWU_KG	1.4304E+06			kg/yr		[kg/yr] Annual production of enriched uranium; UF6 with 5% U235.
3	RFelectricity	ELC_POWER*24*365*cap/Product_annual	8.0			MWh/kg		[MWh/kg] Electricity consumption per reference flow; power (MW) was converted to ener year (24*365) factored by the capacity factor of the power plant.
8	RFair_Cr	air_Cr/Product_annual	1.00E-03			kg/kg		[kg/kg] Chromium emissions to air per reference flow
8	RFair_HF	air_HF/Product_annual	3.85E-03			kg/kg		[kg/kg] HF emissions to air per reference flow
9	RFair_VOC	air_VOC/Product_annual	2.24E-02			kg/kg		[kg/kg] VOC emissions to air per reference flow
1	RFair_radio	air_radio/Product_annual	7.11E+02			Bq/kg		[Bq/kg] Radionuclide emissions to air per reference flow
4	RFw_heavymetal	w_heavymetal/Product_annual	1.06E-01			kg/kg		[kg/kg] Heavy metal emissions to water per reference flow
2	RFw_fluoride	w_fluoride/Product_annual	4.04E-03			kg/kg		[kg/kg] Fluoride emissions to water per reference flow
1	RFw_nitrate	w_nitrate/Product_annual	9.63E-03			kg/kg		[kg/kg] Nitrate emissions to water per reference flow
1	RFw_sulfate	w_sulfate/Product_annual	4.18E-01			kg/kg		[kg/kg] Sulfate emissions to water per reference flow
1	RFw_chlorHC	w_chlorHC/Product_annual	3.67E-05			kg/kg		[kg/kg] Chlorinated hydrocarbon emissions to water per reference flow
4	RFw_withdrawal	w_withdrawal/Product_annual	1.45E+04			kg/kg		[kg/kg] Water withdrawal per reference flow
1	RFw_outfall	w_outfall/Product_annual	3.86E+03			kg/kg		[kg/kg] Water outfall per reference flow
8	UF6input	18.3-SWU_KG	10.40			kg/kg		[kg/kg] Mass ratio of natural U input per enriched U output; based on 5% U235 in produ

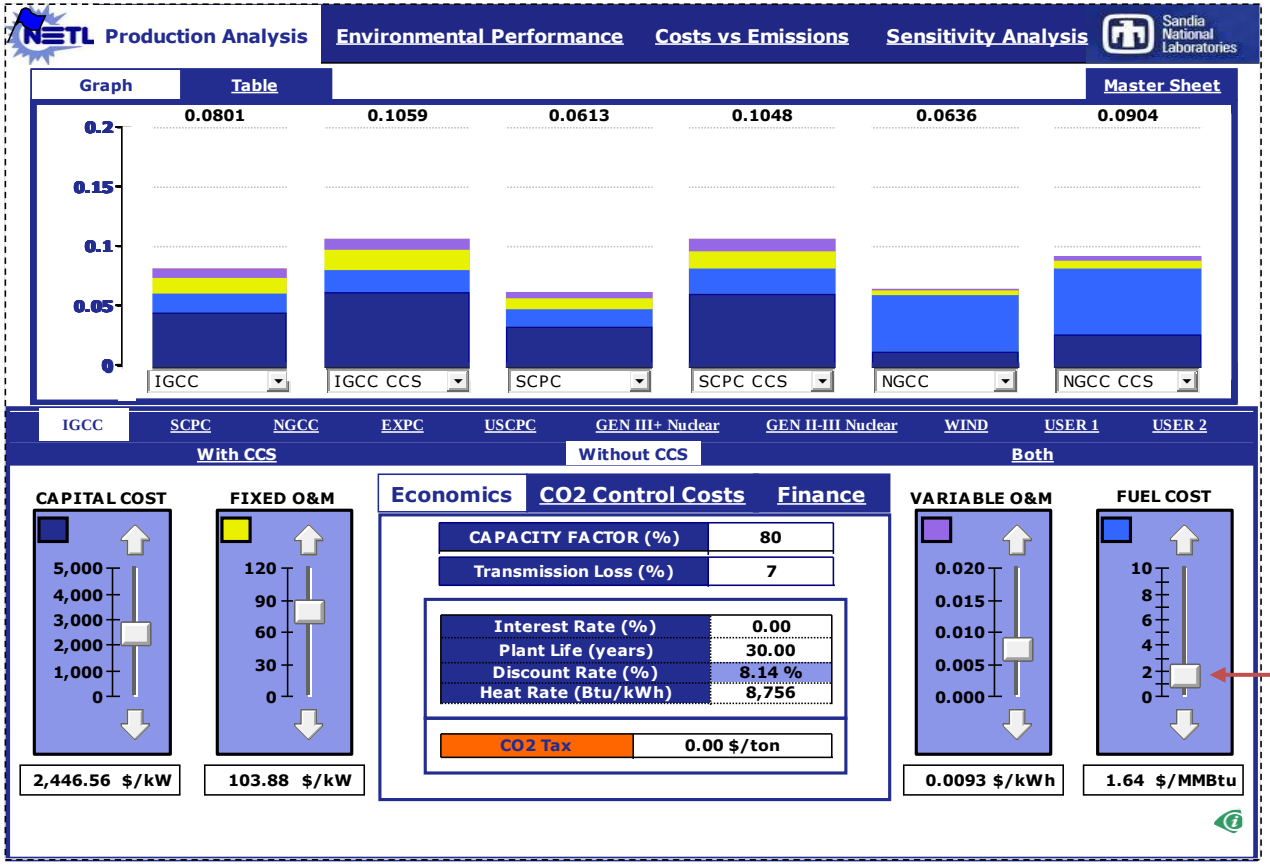
The unit process describes how to scale collected environmental data to the reference flow

Life Cycle Process Flow



Unit processes are connected via their inputs and outputs and scaled to the functional unit

Power Life Cycle Analysis Tool (LCAT)



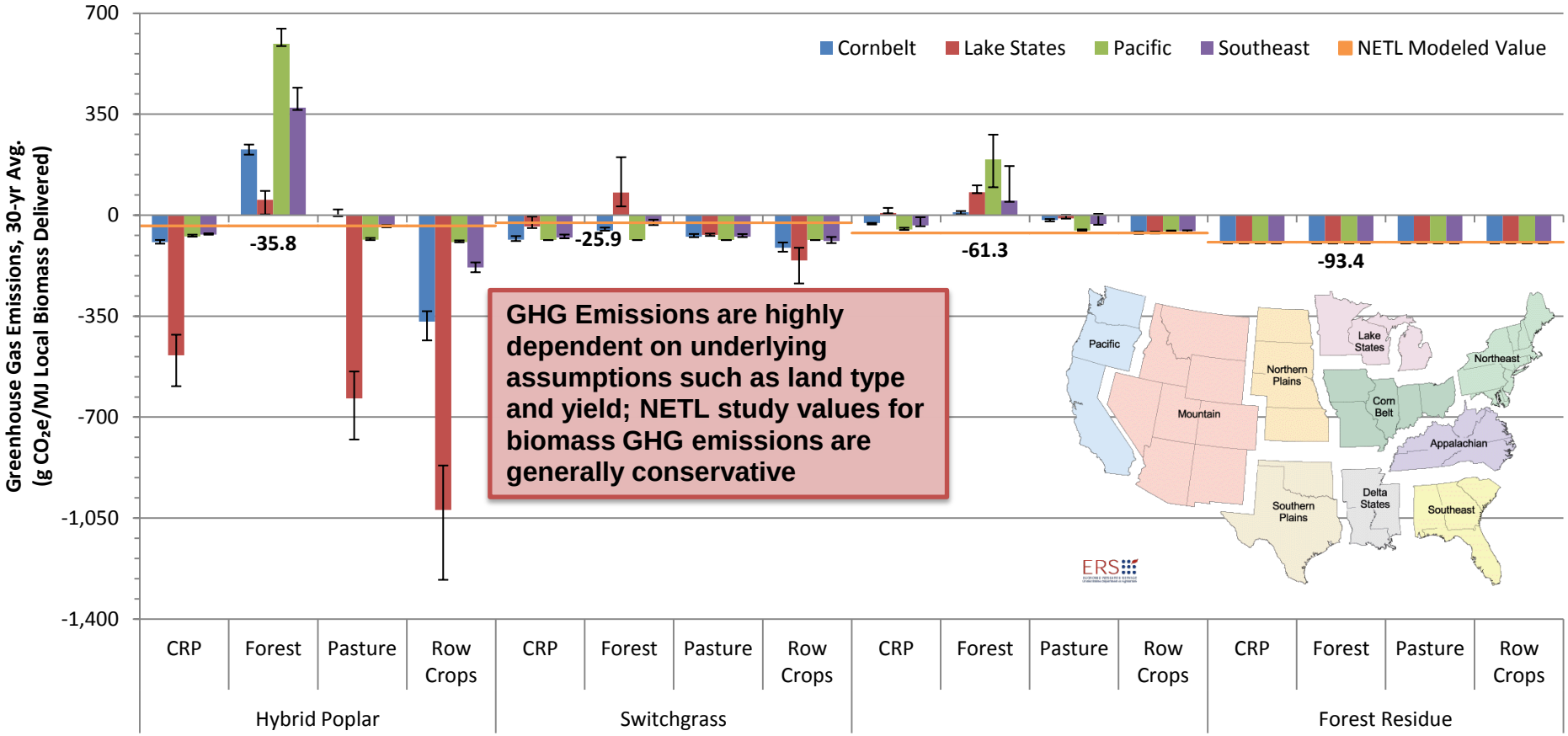
Included Technologies:

- IGCC
- IGCC/ccs
- EXPC
- EXPC/ccs
- EXPC/ccs + RP
- SCPC
- SCPC/ccs
- NGCC
- NGCC/ccs
- Onshore Wind
- Gen III+ Nuclear

Sliders allow user to control assumptions and see results update in real time

- Interactive comparison tool (PowerSim) which gives users access to key financial and environmental results and parameters from detailed power LCAs
- Ongoing partnership between NETL and Sandia National Laboratory

Calculating Uncertainty in Biomass Emissions (CUBE)



- Allows users to explore the uncertainty and variability of greenhouse gas emissions from various biomass types in an Analytica-based tool
- Collaboration between NETL and RAND

Upstream Dashboard: Input Sheet

NETL UPSTREAM DASHBOARD

Inputs

Please enable Macro to use this tool How to enable?

The purpose of the Upstream Dashboard is to develop a fast and easy to use tool to determine the environmental profile of various energy feedstocks. The model provides NETL's preferred variables as the default values, but allows the user to input information for their specific scenarios.

The model includes 16 different feedstocks, 11 modes of transportation, and 26 transportation fuel conversion combinations. The dashboard can calculate the inventory of extracted and processed feedstocks, delivered feedstocks, or converted feedstocks.

To use the model, answer the questions below. They will set up the Dashboard to focus on the specified feedstock by only showing options in that category and return all calculations in the requested units. To open up the available inputs, please push the Expert Mode button on the Dashboard tab. This will clear any of the desired output selections from Question 1 on the Inputs tab. the Expert Mode is only suggested after the user has become familiar with the Dashboard.

Legend for Dashboard

Blue are headings descr

Orange are user adjusta menus or input fields fo

Question 1

Please choose the desired primary energy sources to calculate the upstream emissions inventory for:

Coal | Natural Gas | Crude Oil | Uranium | Biomass

Gasoline | Ethanol | Jet Fuel | Diesel (Petroleum or FT Process)

Question 2

Please choose the desired units for reporting metrics:

kg | lb

Per:

Mass	Volume	Energy	IPCC Time Horizon*
kg	Liter	MMBtu	20 Year
lb	Gallons	MJ	100 Year
Tonne	Barrels		500 Year
Short Ton	Cubic meter		
	Cubic ft		

* IPCC 2007

Show Results

Dashboard allows users to easily add upstream life cycle environmental information to their process of interest such as a coal plant or refinery

- Ability for user adjusted parameter values
- User chooses which portions of life cycles to include
- Implemented in Excel

Populates values for feedstocks & transportation modes based on user selection

Converts results based on user selected output units & GWP time horizon factors

The Upstream Dashboard

NETL UPSTREAM DASHBOARD

Selected Output: NaturalGas

Expert Mode

Raw Material Acquisition (RMA)

Include RMA	On
RMA Process List	Natural Gas. Tight Gas

Parameters	Value
Production (kg/day)	2095
Extraction Flaring (fraction)	0.15
Process Flaring (fraction)	1

Include RMA 2*	Off
RMA Process List	*Not Set*

Parameters	Value
Not Set	*Not Set*
Not Set	*Not Set*
Not Set	*Not Set*
Not Set	*Not Set*

*Should only be used for FT Diesel

Raw Material Transport (RMT)

Include RMT	On
Num of Transp. Mode	1
RMA Suggested RMT	Natural Gas Pipeline

Transportation Mode**	Unit	Value
Natural Gas Pipeline	km	971

**Add sequential modes with the first at the top
**For FT Diesel, coal should be above the biomass transport

Energy Conversion Facility (ECF)

Include ECF	Off
ECF Process List	*Not Set*

Parameters	Option
Not Set	*Not Set*
Not Set	*Not Set*
Not Set	*Not Set*

Dashboard controls

Units	US

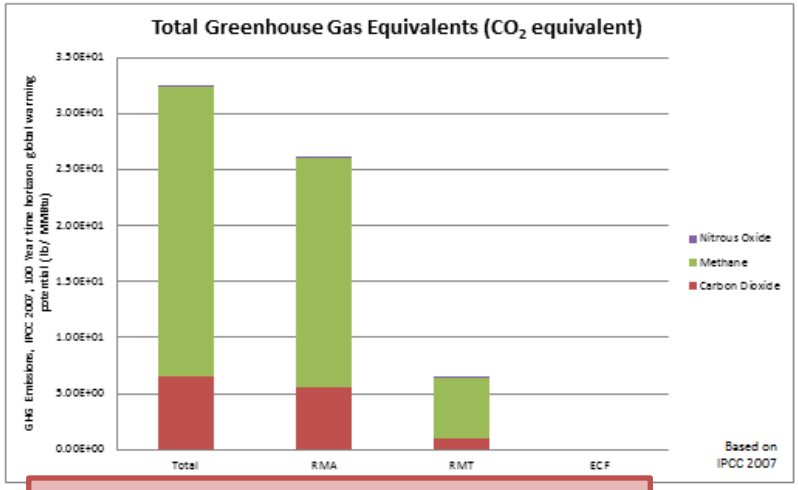


Chart shows total life cycle CO_2e based on calculated results

Emission Inventory (Unit = lb / MMBtu)

Life Cycle Inventory		Total	RMA	RMT	ECF
Air Emissions	Carbon Dioxide	6.61E+00	5.54E+00	1.07E+00	0.00E+00
	Methane	1.03E+00	8.18E-01	2.14E-01	0.00E+00
	Nitrous Oxide	1.60E-04	1.58E-04	1.63E-06	0.00E+00
	Nitrogen Oxides	1.61E-01	1.61E-01	2.45E-04	0.00E+00
	Sulfur Dioxide	9.39E-04	7.97E-04	1.42E-04	0.00E+00
	Carbon Monoxide	1.44E-02	1.43E-02	1.77E-04	0.00E+00
	Particulate Matter	3.25E-04	3.06E-04	1.86E-05	0.00E+00
	Lead	6.46E-07	5.99E-07	4.61E-08	0.00E+00
	Mercury	1.82E-08	1.65E-08	1.75E-09	0.00E+00
	Ammonia	6.66E-07	1.00E-07	5.65E-07	0.00E+00
	Radiation	1.04E-10	9.41E-11	1.03E-11	0.00E+00
	Non Methane VOC	1.72E-01	1.71E-01	1.23E-03	0.00E+00
Solid Waste	Heavy Metals to Soil	3.94E-04	2.04E-04	1.90E-04	
	Solid Waste	5.39E-06	4.71E-06	6.79E-07	
Water Emissions	Aluminum	3.72E-08	2.25E-08	1.47E-08	
	Ammonium/ammonia	9.93E-06	5.11E-06	4.81E-06	
	Heavy Metals	1.29E-04	1.22E-04	7.65E-06	
	Nitrate	1.30E-07	9.74E-08	3.29E-08	
	Nitrogen	3.02E-07	1.57E-07	1.46E-07	
	Phosphate	6.69E-10	4.89E-10	1.80E-10	
	Phosphorus	1.31E-05	1.24E-05	6.99E-07	
Water	Water Withdrawal (Gal.)	1.95E+00	1.93E+00	2.25E-02	
	Water Consumption (Gal.)	1.59E+00	1.53E+00	5.34E-02	0.00E+00
Land Use	Area Changes (Acres)	4.16E-03	2.86E-03	1.30E-03	0.00E+00
EROI	Energy Input (MMBtu)	6.14E-02	6.13E-02	1.28E-04	0.00E+00

Table results auto-update based on parameter values above

Greenhouse Gas Equivalents (Unit = lb CO_2 equivalent / MMBtu) Based on IPCC 2007

GHG Inventory		Total	RMA	RMT	ECF
Air Emissions	Carbon Dioxide	6.61E+00	5.54E+00	1.07E+00	0.00E+00
	Methane	2.58E+01	2.05E+01	5.34E+00	0.00E+00
	Nitrous Oxide	4.75E-02	4.71E-02	4.85E-04	0.00E+00
	Total	3.25E+01	2.60E+01	6.40E+00	0.00E+00

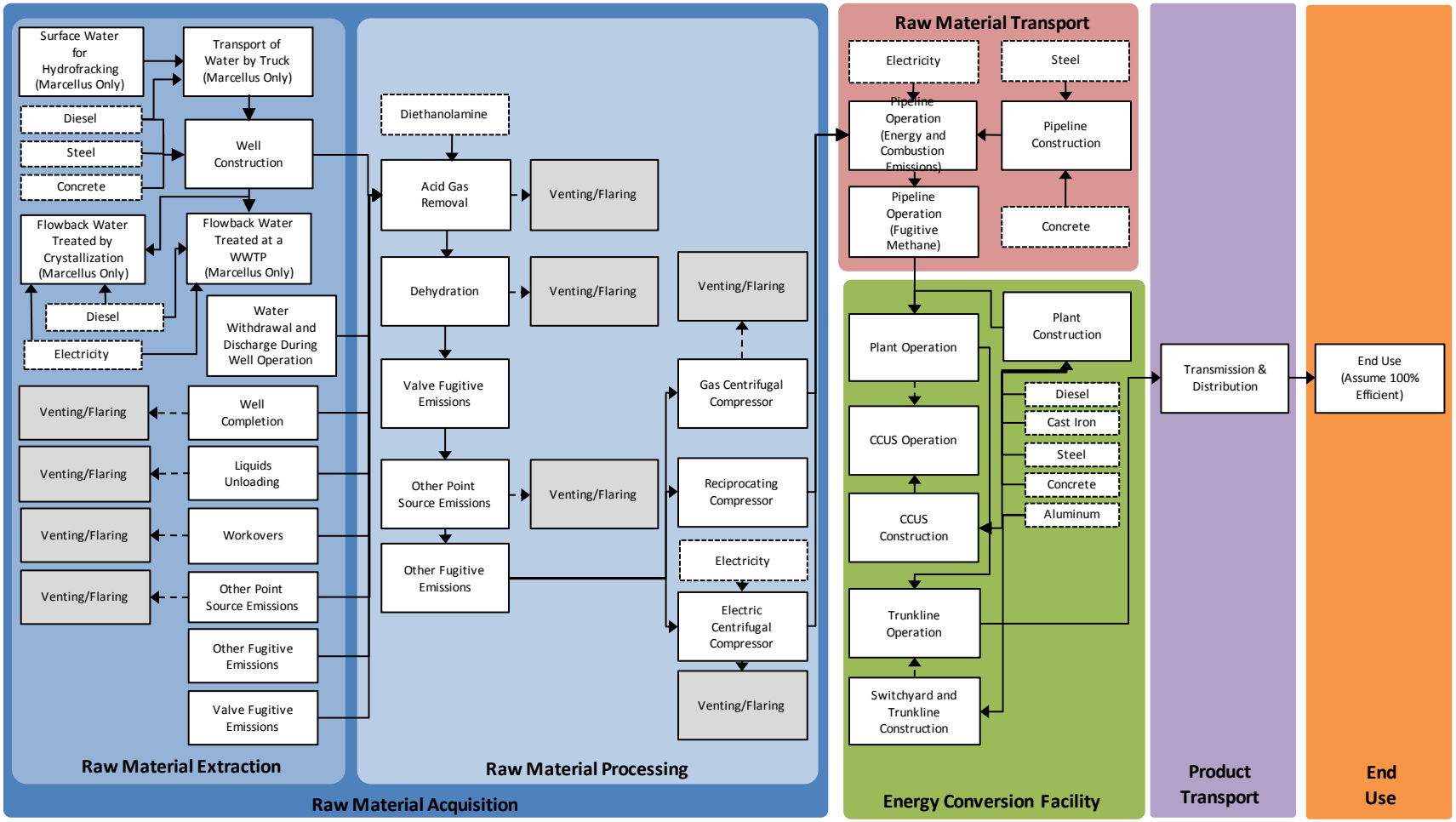
Boundaries for Natural Gas Life Cycle

Cradle-to-grave

- 1 MWh of electricity delivered to the end customer
- Compared 12 different fuel/baseload plant combinations (6 natural gas, 6 coal)

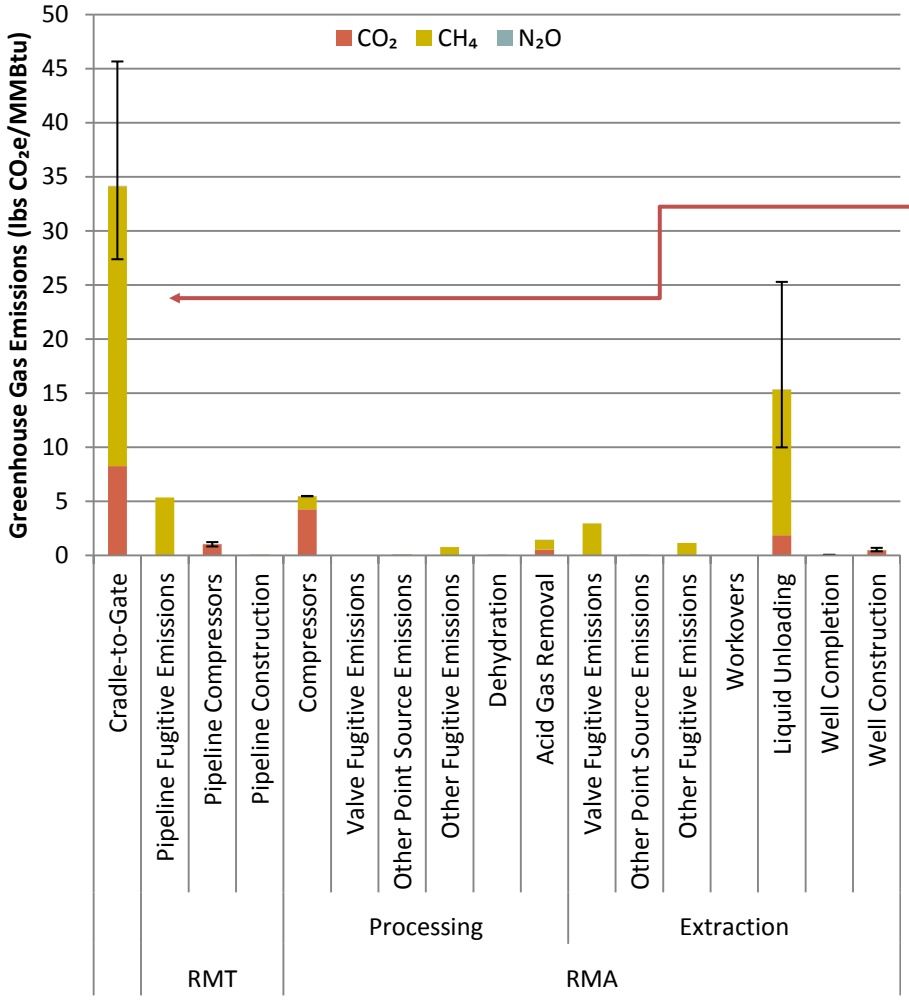
Cradle-to-gate

- 1 MMBtu of domestic fuel delivered to large end user
- Compared 13 fuel sources/mixes (10 natural gas, 3 coal)

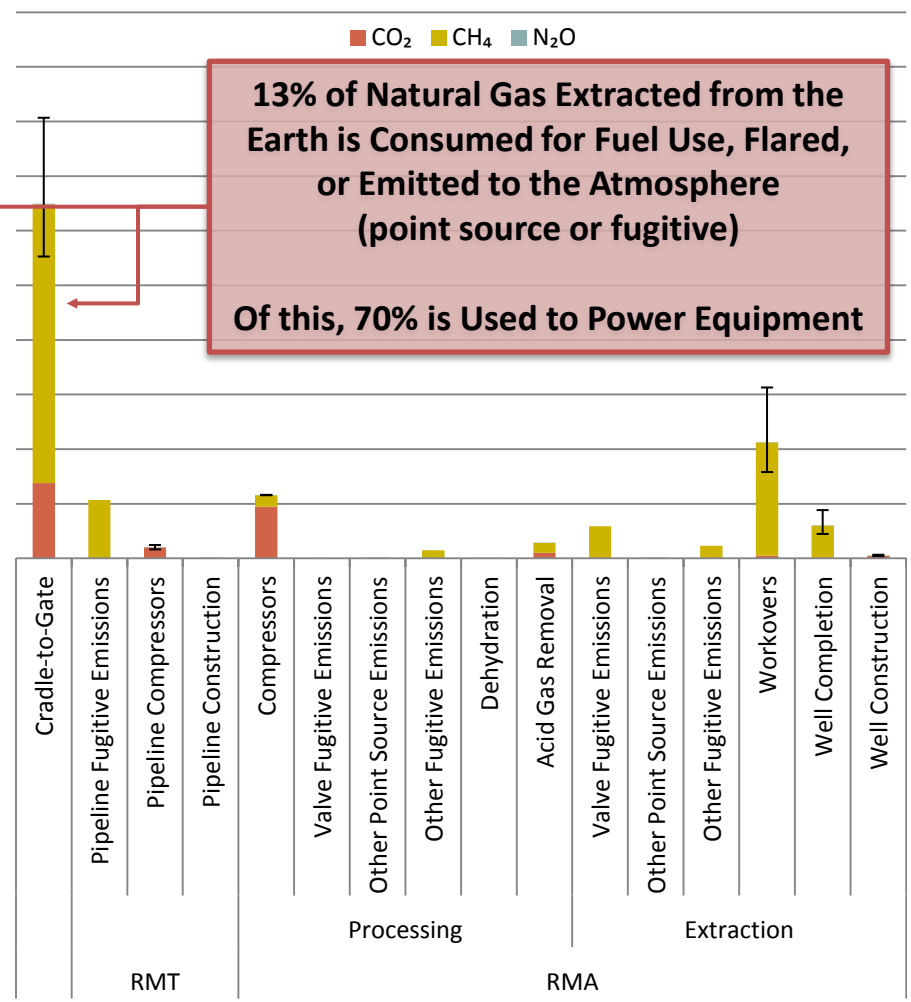


Onshore vs. Shale GHG Emission Profiles

Onshore Gas (34.2 lbs CO_2e/MMBtu)



Shale Gas (32.5 lbs CO_2e/MMBtu)



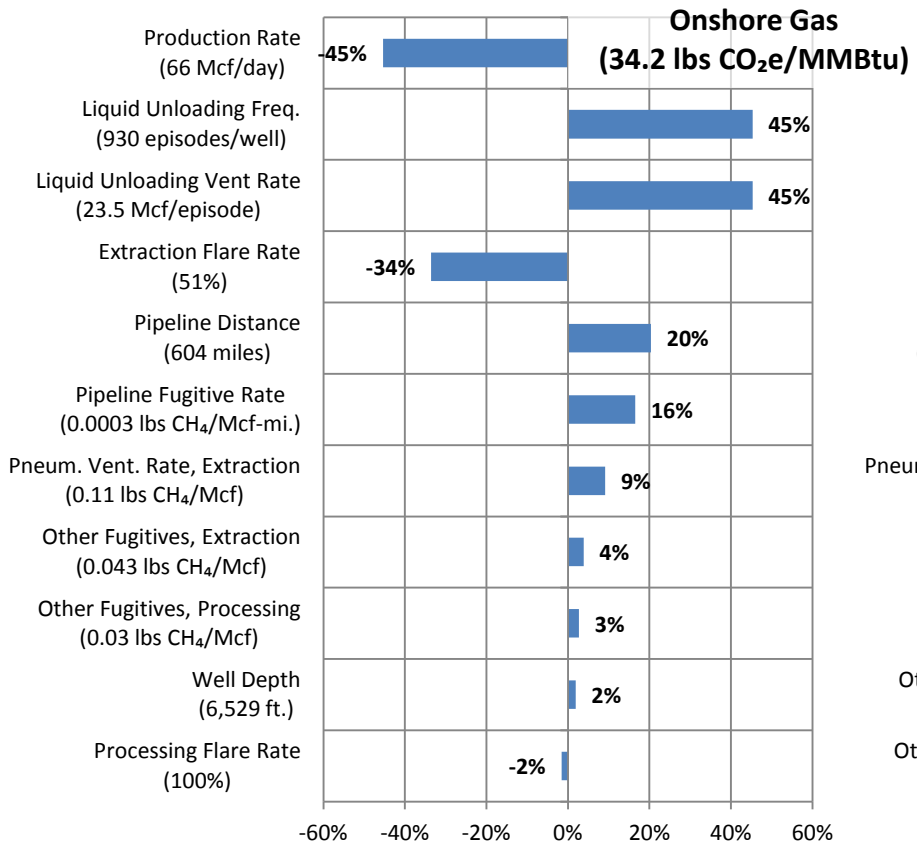
13% of Natural Gas Extracted from the Earth is Consumed for Fuel Use, Flared, or Emitted to the Atmosphere (point source or fugitive)

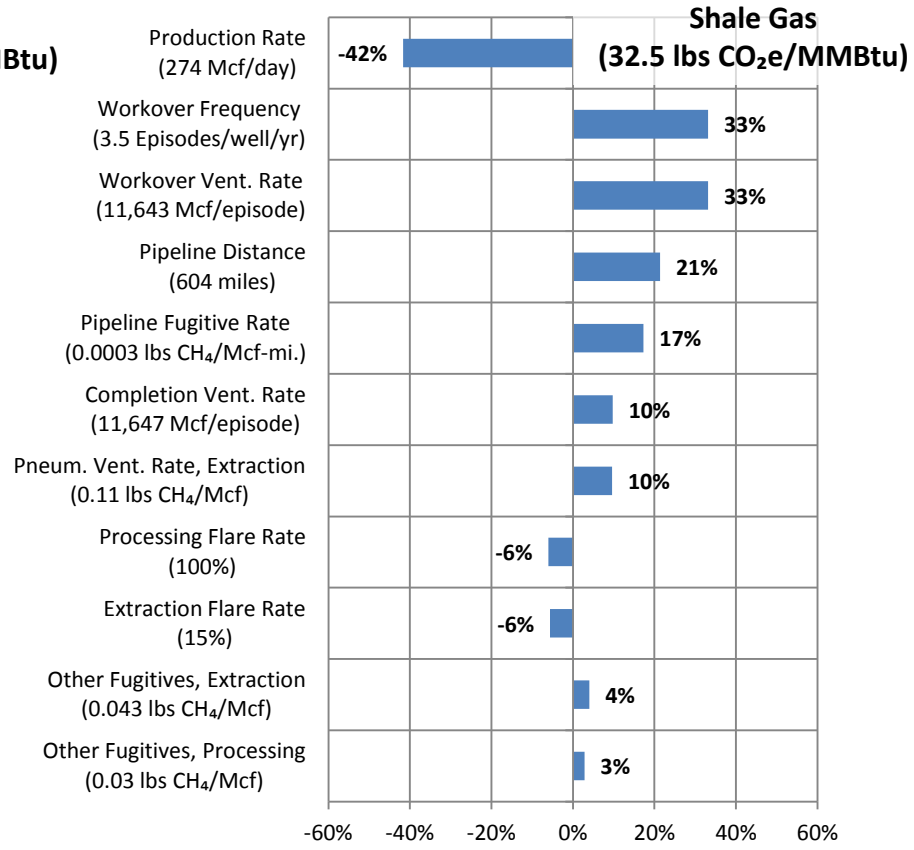
Of this, 70% is Used to Power Equipment

Carbon dioxide equivalents calculated using 2007 IPCC 100-year GWP

Onshore vs. Shale GHG Emission Profiles

Sensitivity of Model Result to Changes in Parameter Values



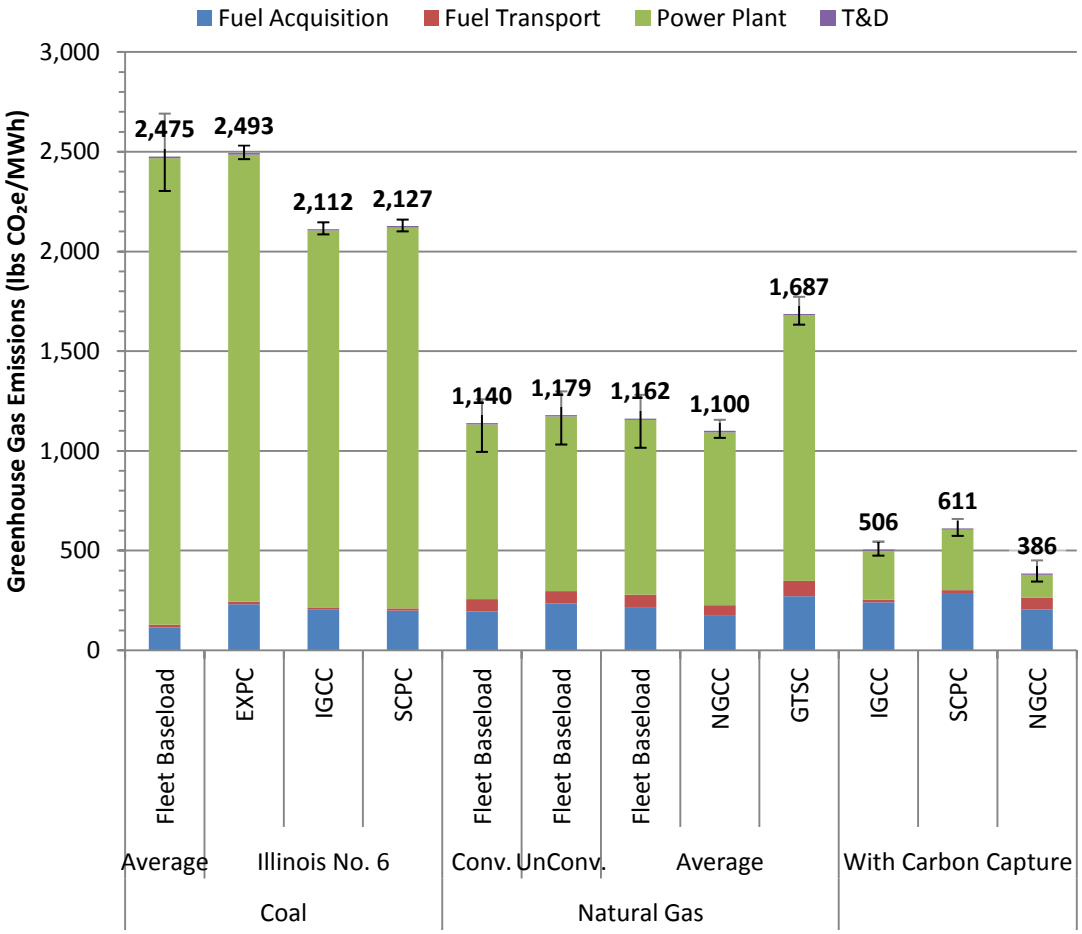


Percentages above are relative to a unit change in parameter value; all parameters are changed by the same amount, allowing comparison of the magnitude of change to the result across all parameters.

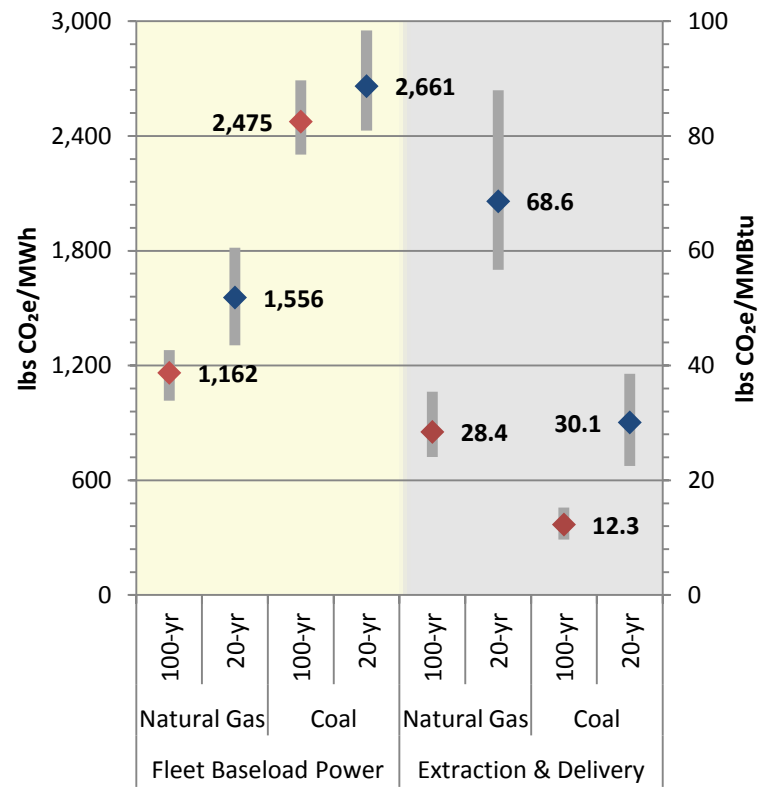
Example: A 10% increase in Onshore Production Rate from 66 Mcf/day to 73 Mcf/day would result in a 4.5% (10% of 45%) decrease in cradle-to-gate emissions, from 34.2 to 32.6 lbs CO_2e/MMBtu.

Carbon dioxide equivalents calculated using 2007 IPCC 100-year GWP

Comparison of Power Generation Technology Life Cycle GHG Footprints

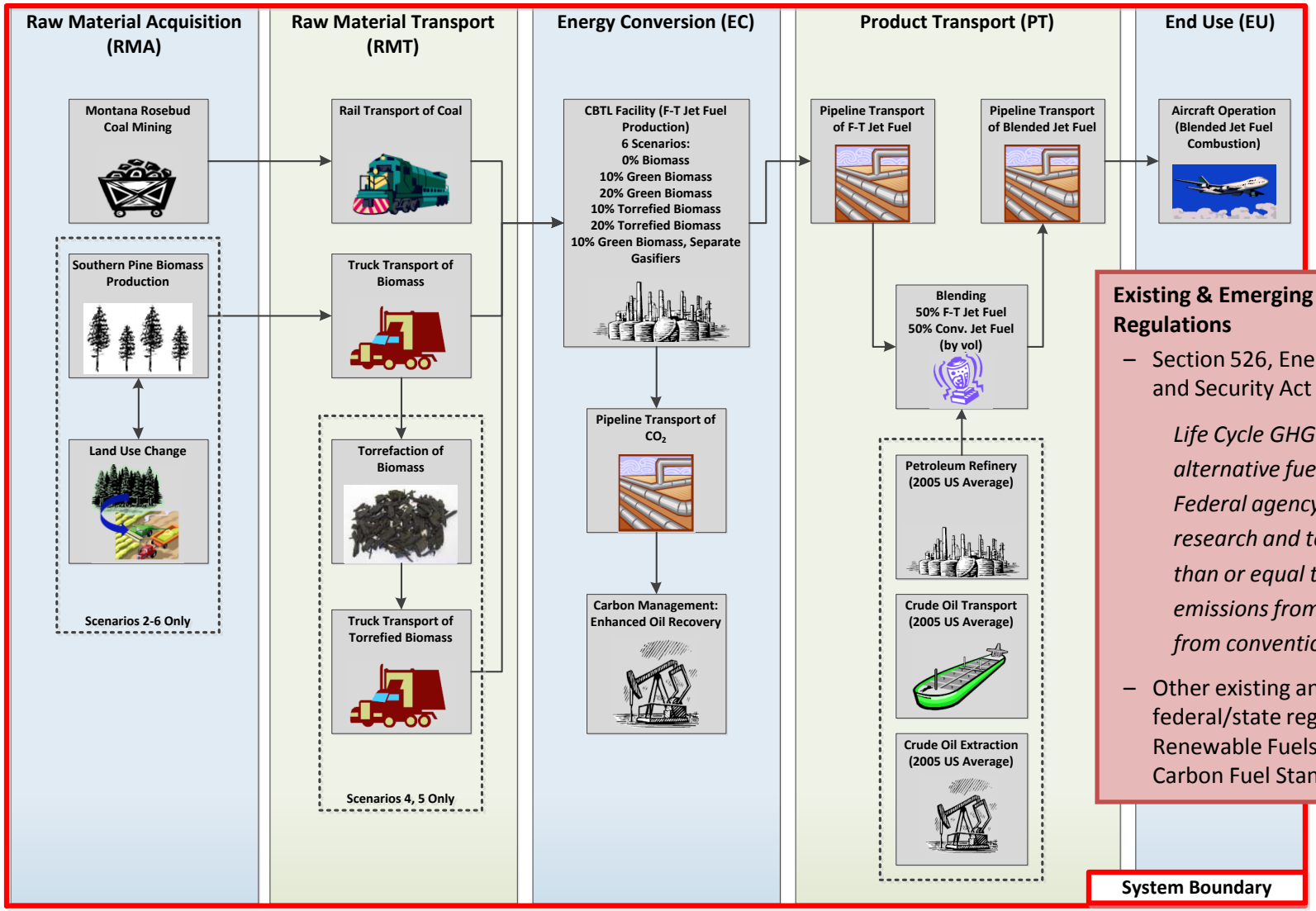


Upstream GHG emissions are greater for natural gas than coal; full life cycle emissions are larger for coal than natural gas



Source of natural gas or coal has little effect on full life cycle emissions for GHGs

High Level Process Flow for Alternative Jet Fuel



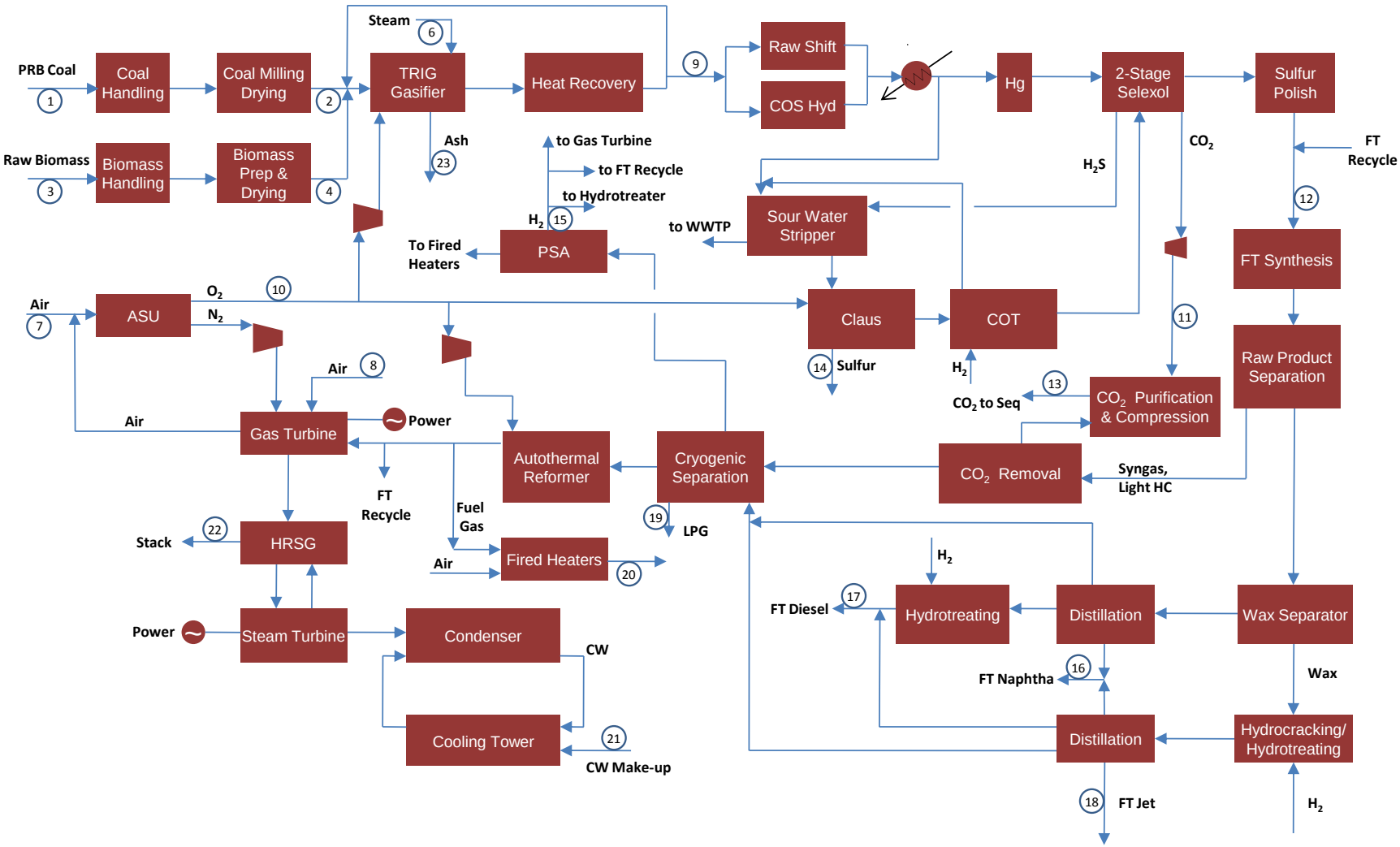
Existing & Emerging GHG Emissions Regulations

- Section 526, Energy Independence and Security Act (EISA) of 2007:

  Life Cycle GHG emissions for alternative fuels contracted by a Federal agency other than for research and testing must be less than or equal to life cycle emissions from conventional fuel from conventional sources

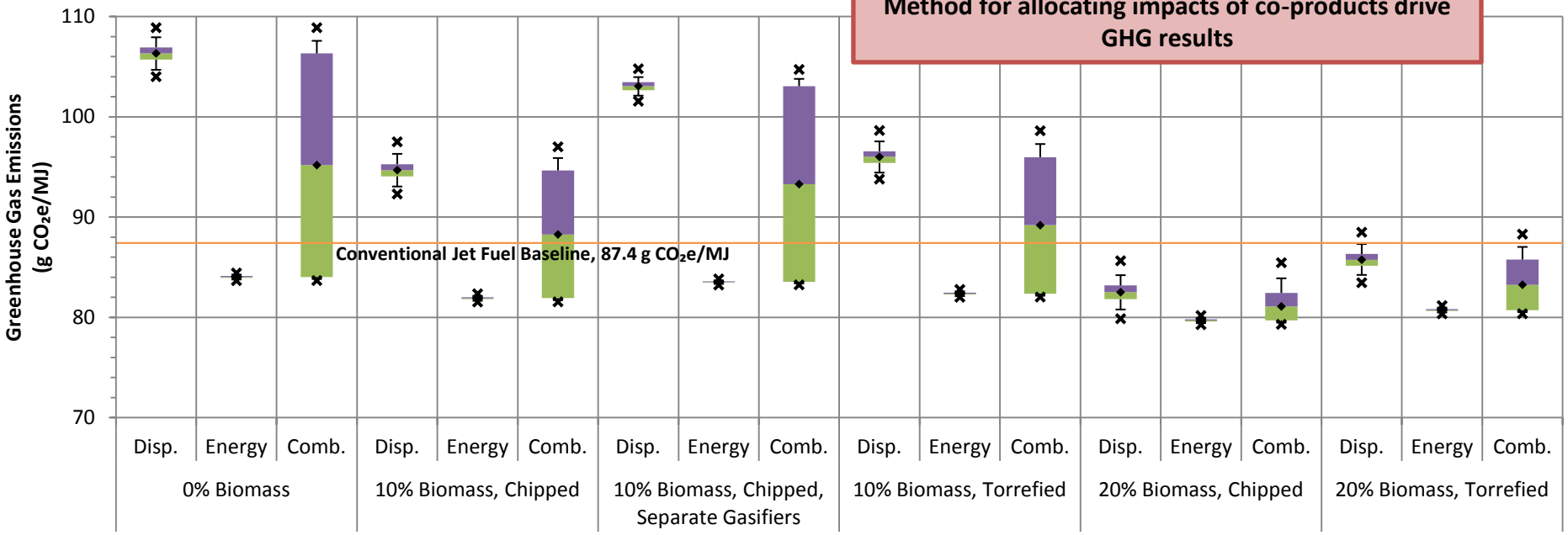
- Other existing and emerging federal/state regulations: US EPA Renewable Fuels Standard; CA Low Carbon Fuel Standard, etc.

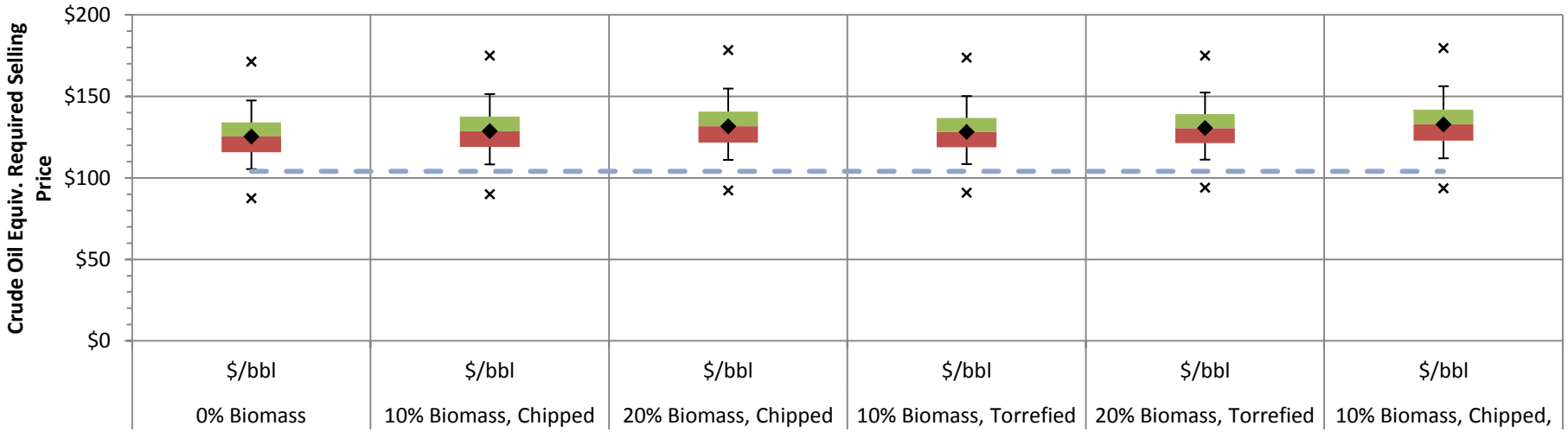
Underlying Data Based on Detailed Mass and Energy Balance of an F-T Process



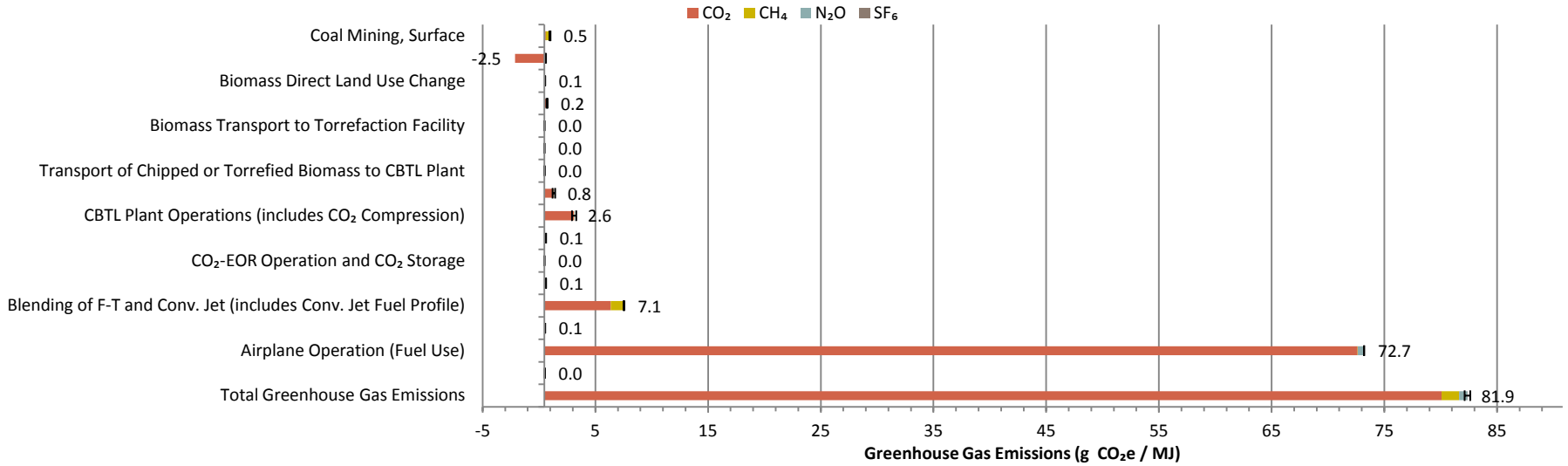
Overall CBTL Jet Results, with 90% Capture and CO_2-EOR

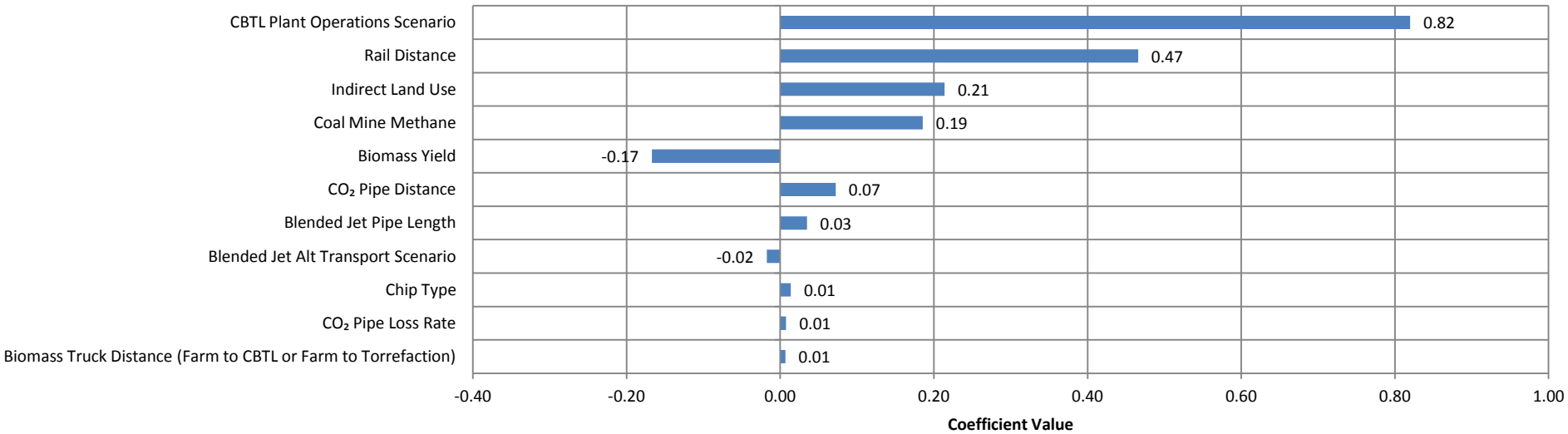
Method for allocating impacts of co-products drive GHG results



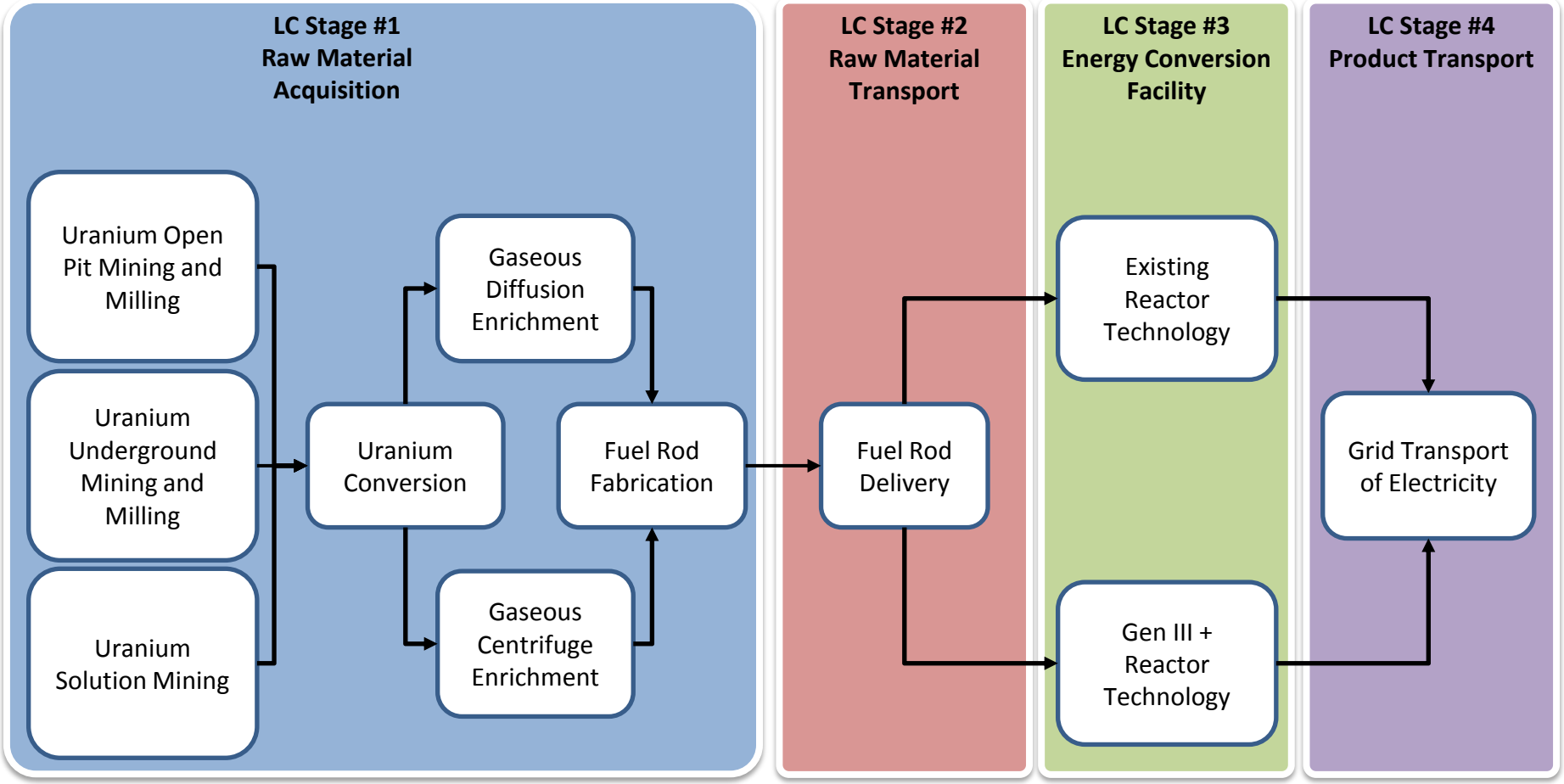


Underlying Detail Allows for Detailed Results with Sensitivity and Uncertainty



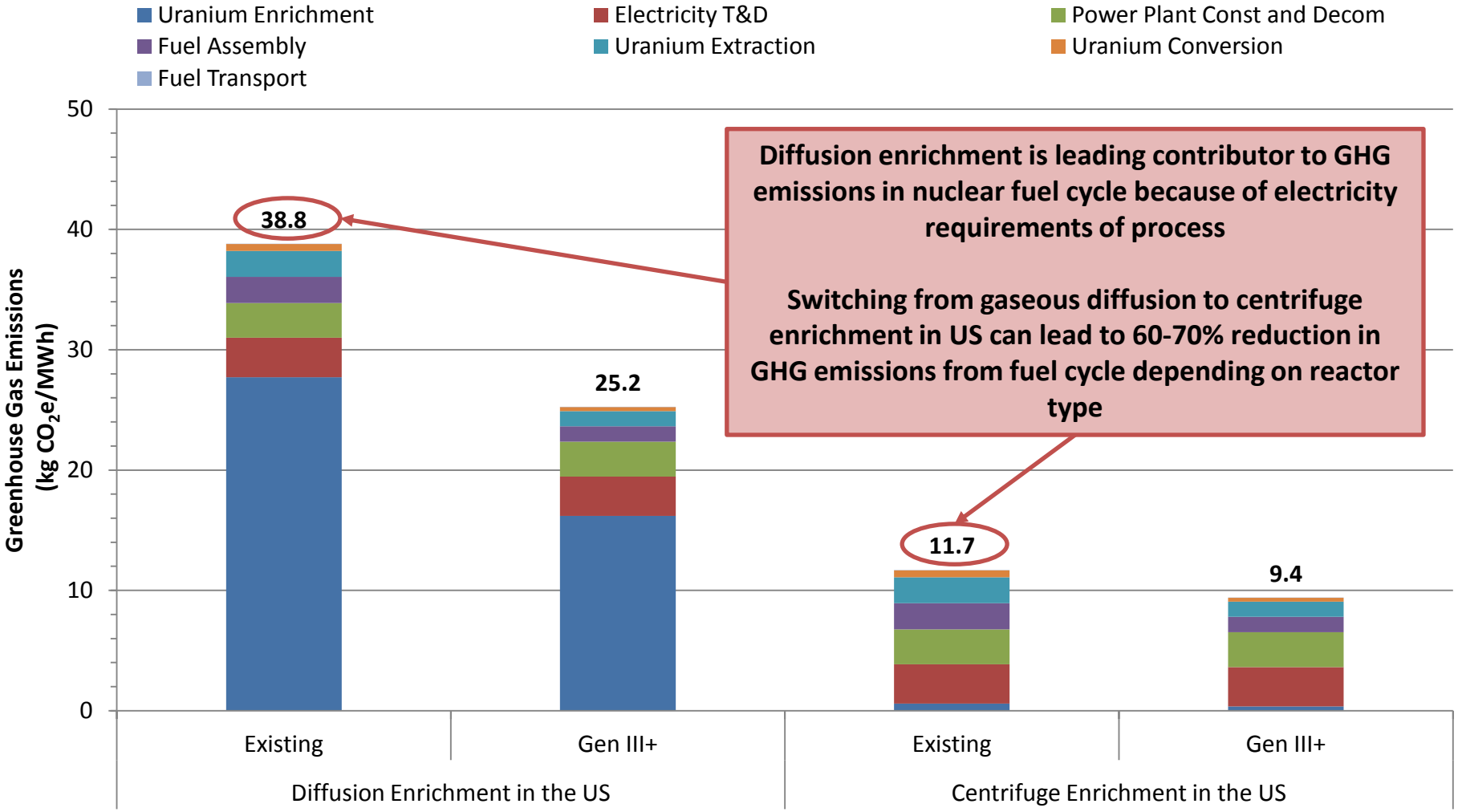


Life Cycle Boundaries for Nuclear Power



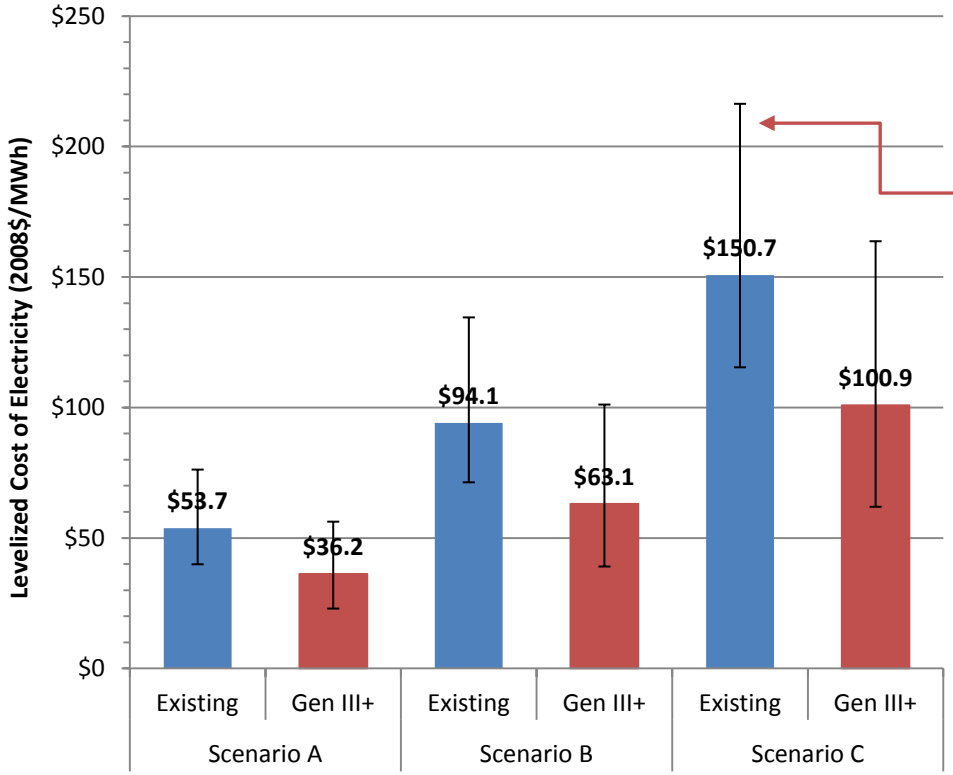
Study focuses on life cycle comparison of existing reactor technology currently installed in US with the Gen III+ reactor designs currently under review at the NRC

Life Cycle GHG Profile for Existing and Gen III+ Nuclear Power in the United States



Carbon dioxide equivalents calculated using 2007 IPCC 100-year GWP

Nuclear Power Life Cycle Cost Results

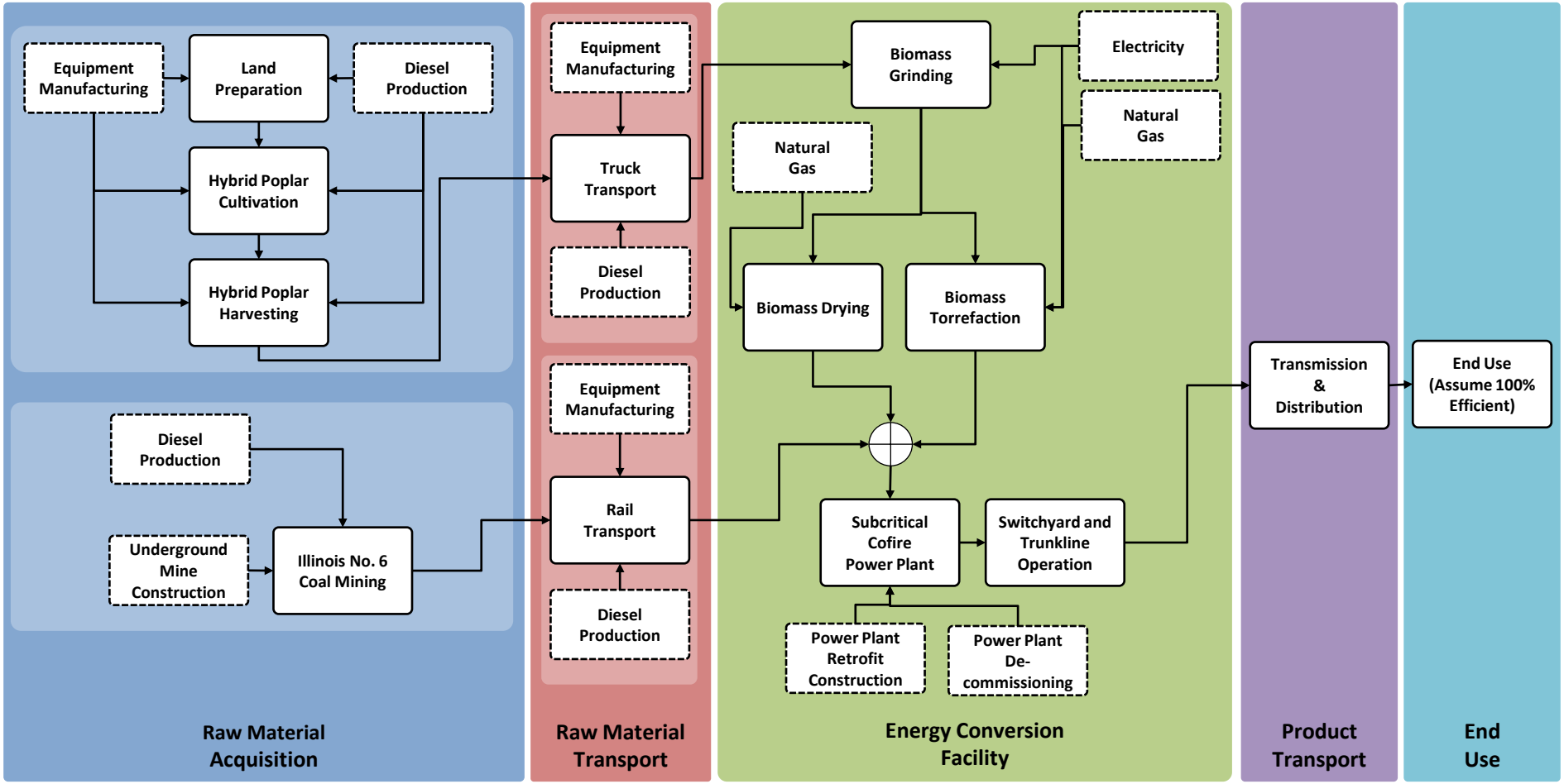


Uncertainty bars represent range of LCOE for a given financial scenario based on range of LCC plant operations parameters (capital costs, plant capacity, fuel costs, operating & maintenance costs, and decommissioning costs)

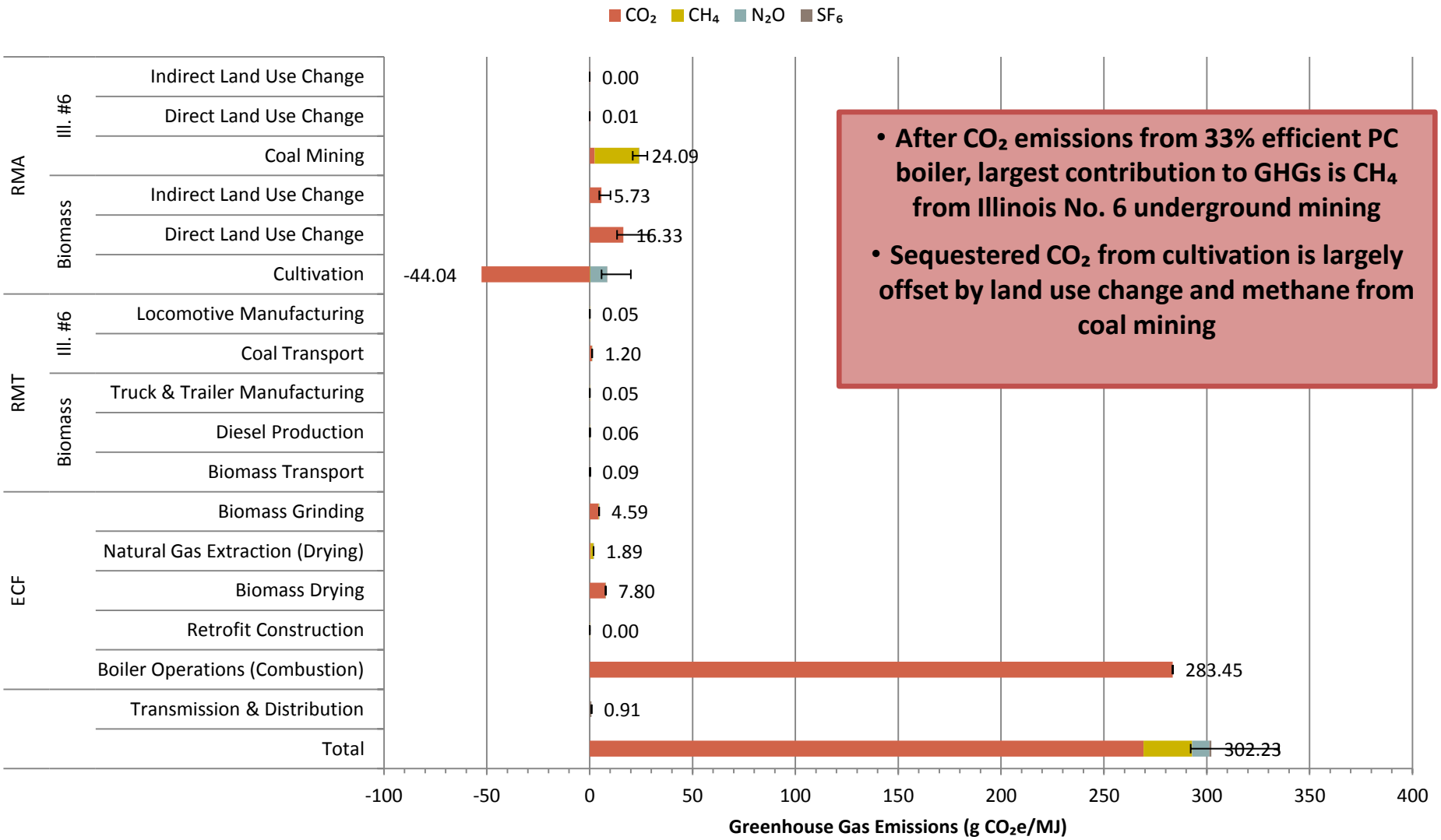
Financial Parameter Input	Scenario A Minimize LCOE	Scenario B Best Estimate	Scenario C Maximize LCOE
Debt Term (Years)	30	20	10
Interest Rate on Loan (%)	5%	8%	10%
Depreciation Period (Years)	7	10	20
Expected Rate of Return (%)	7%	15%	20%

Plant Operations Input	Existing			Gen III+		
	Min LCOE	Best Est. LCOE	Max LCOE	Min LCOE	Best Est. LCOE	Max LCOE
Plant Capacity (MWe)	1,500	1,000	850	1,500	1,000	850
Unit Cost of Fuel ($/MMBtu)	0.29	0.67	1.08	0.17	0.40	0.63
Overnight Costs ($/kWe)	3,500	4,500	6,500	1,800	3,000	5,000
Fixed O&M ($/kWe/yr)	55	64	75	35	42	50
Variable O&M ($/kWh)	0.0047	0.0075	0.0100	0.0047	0.0075	0.0100
Decommissioning Costs (Million $)	350	600	1,000	350	600	1,000

Life Cycle Process Flow for Retrofit Cofire Power

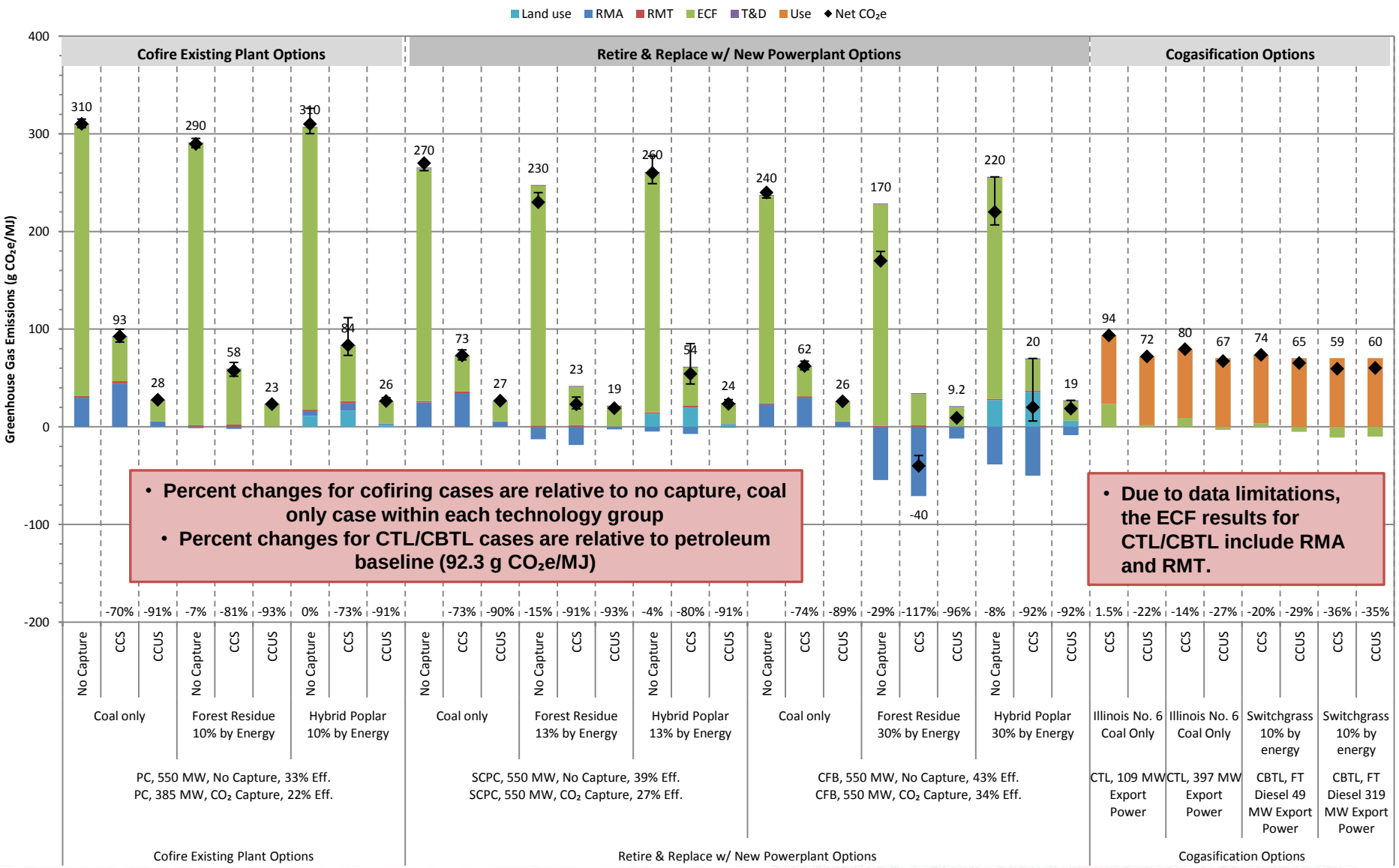


GHG Drilldown: 20% Hybrid Poplar Cofire

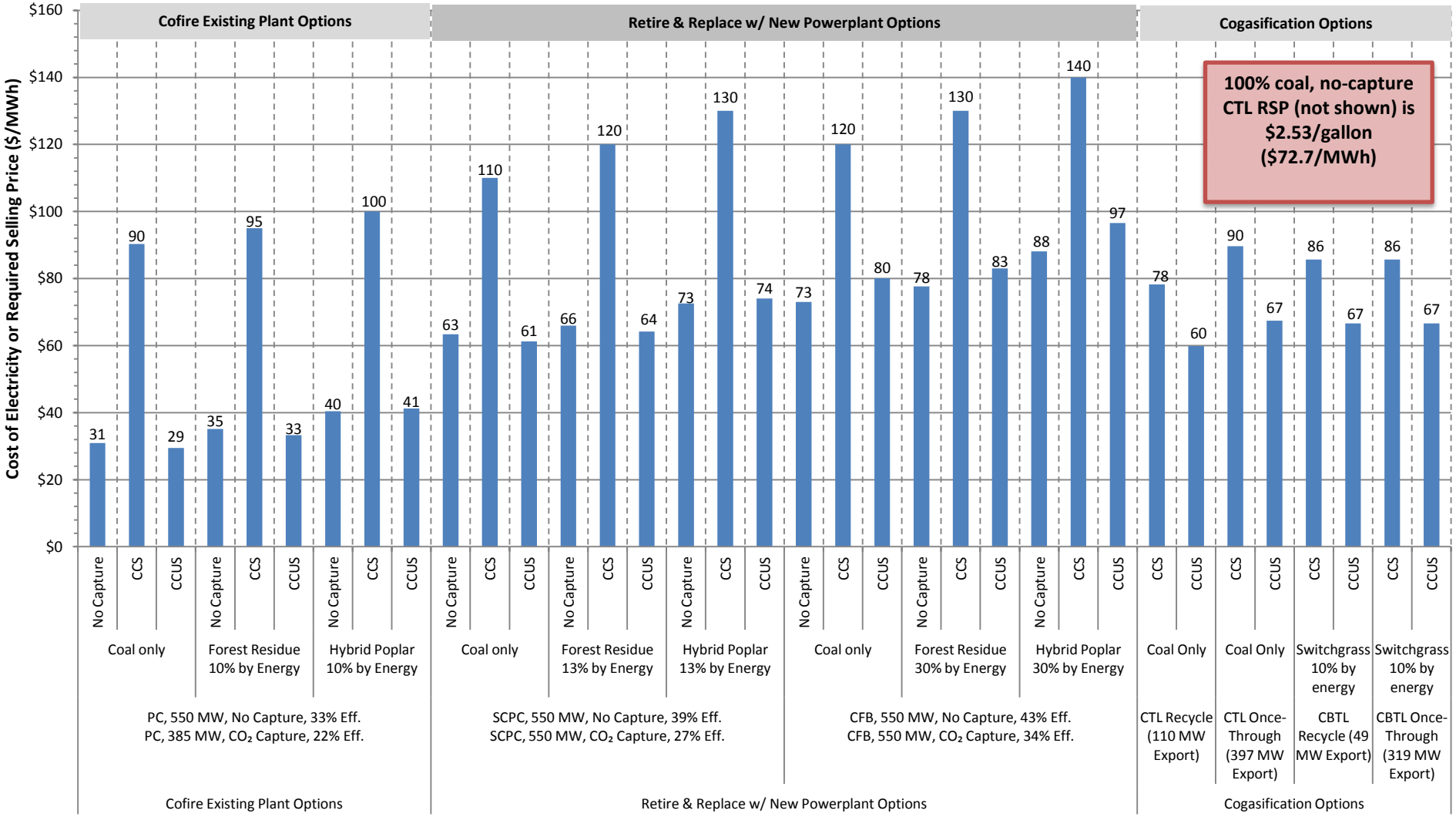


- After CO_2 emissions from 33% efficient PC boiler, largest contribution to GHGs is CH_4 from Illinois No. 6 underground mining
- Sequestered CO_2 from cultivation is largely offset by land use change and methane from coal mining

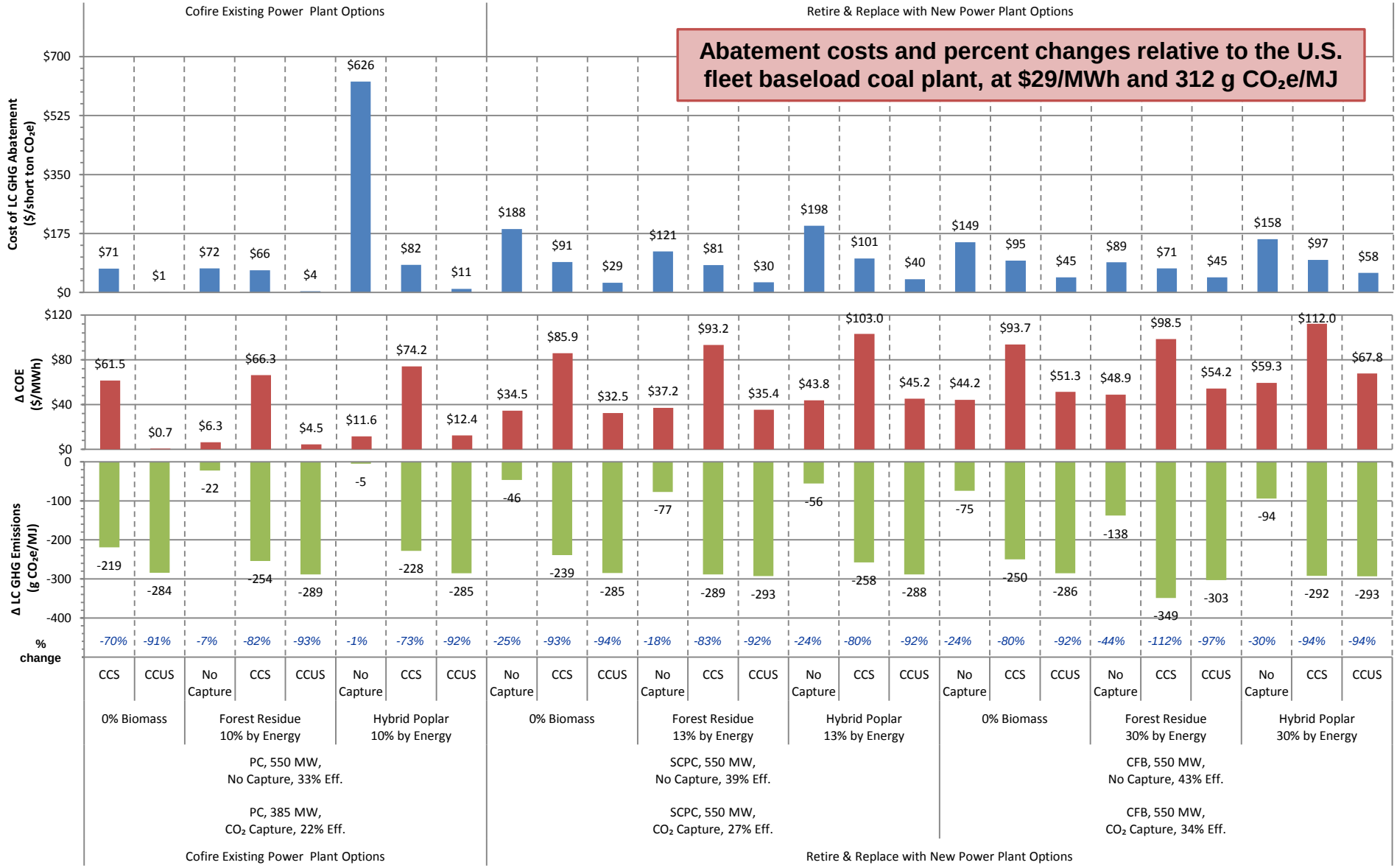
Life Cycle GHG Emissions of Cofiring Options



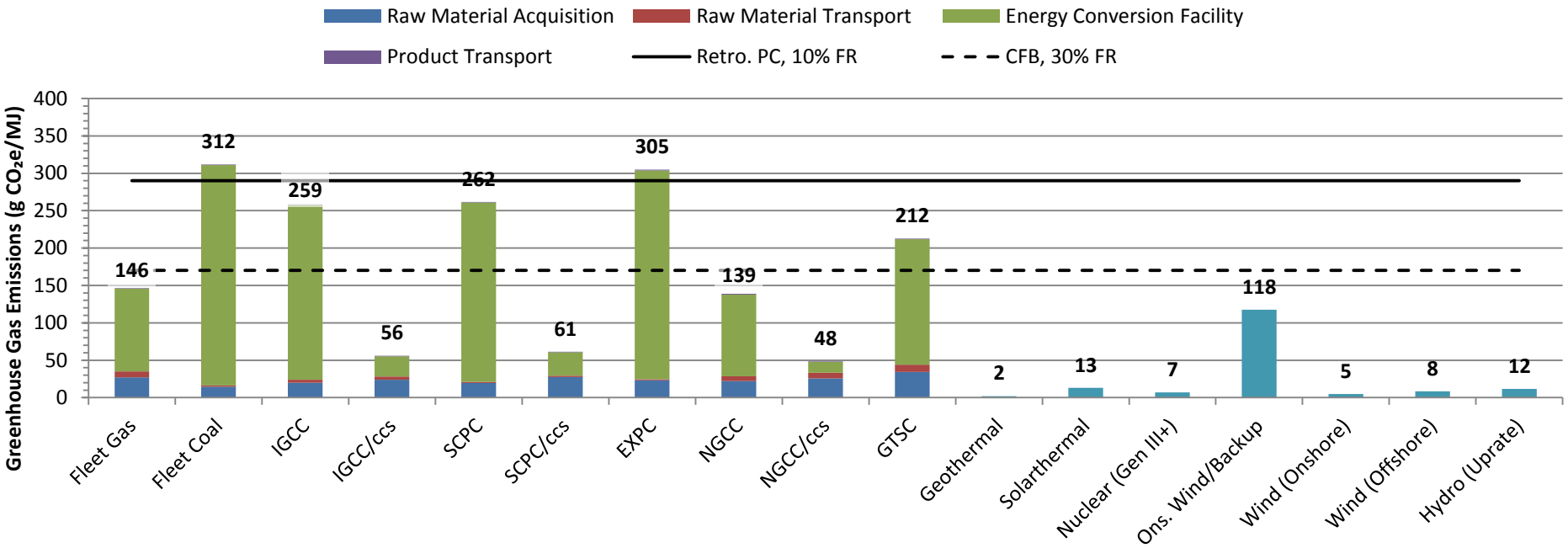
Cofire Plant Options: COE (Power) and Required Selling Price (Fuel)

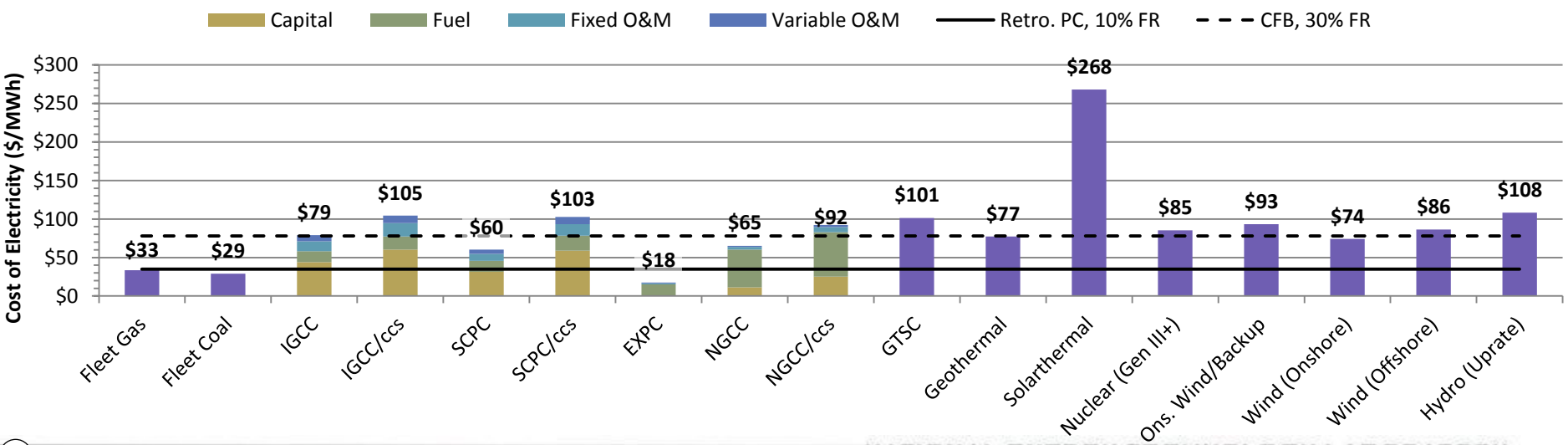


Cost of Improving the Existing Coal Fleet

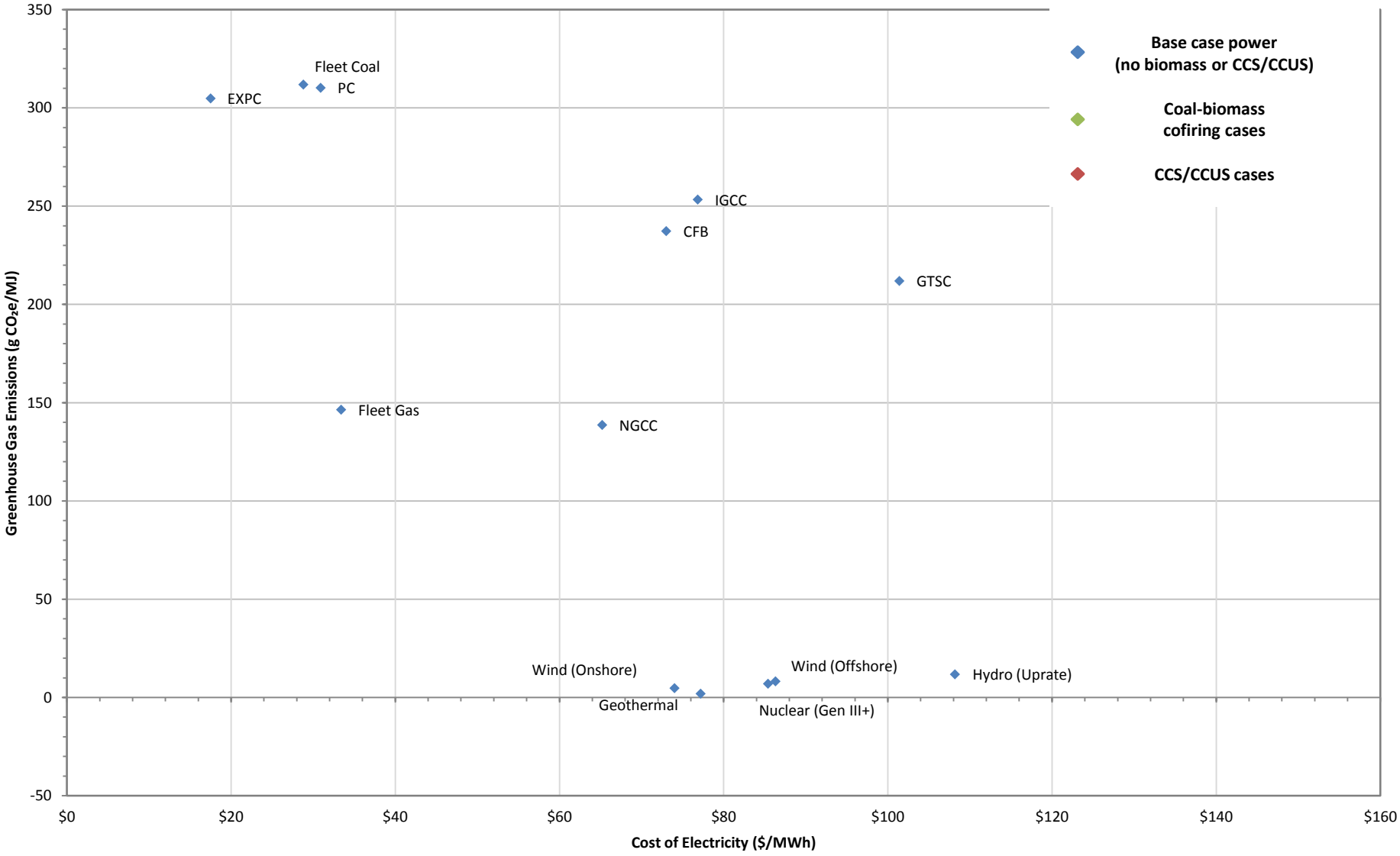


How does cofiring compare to other power technology options?

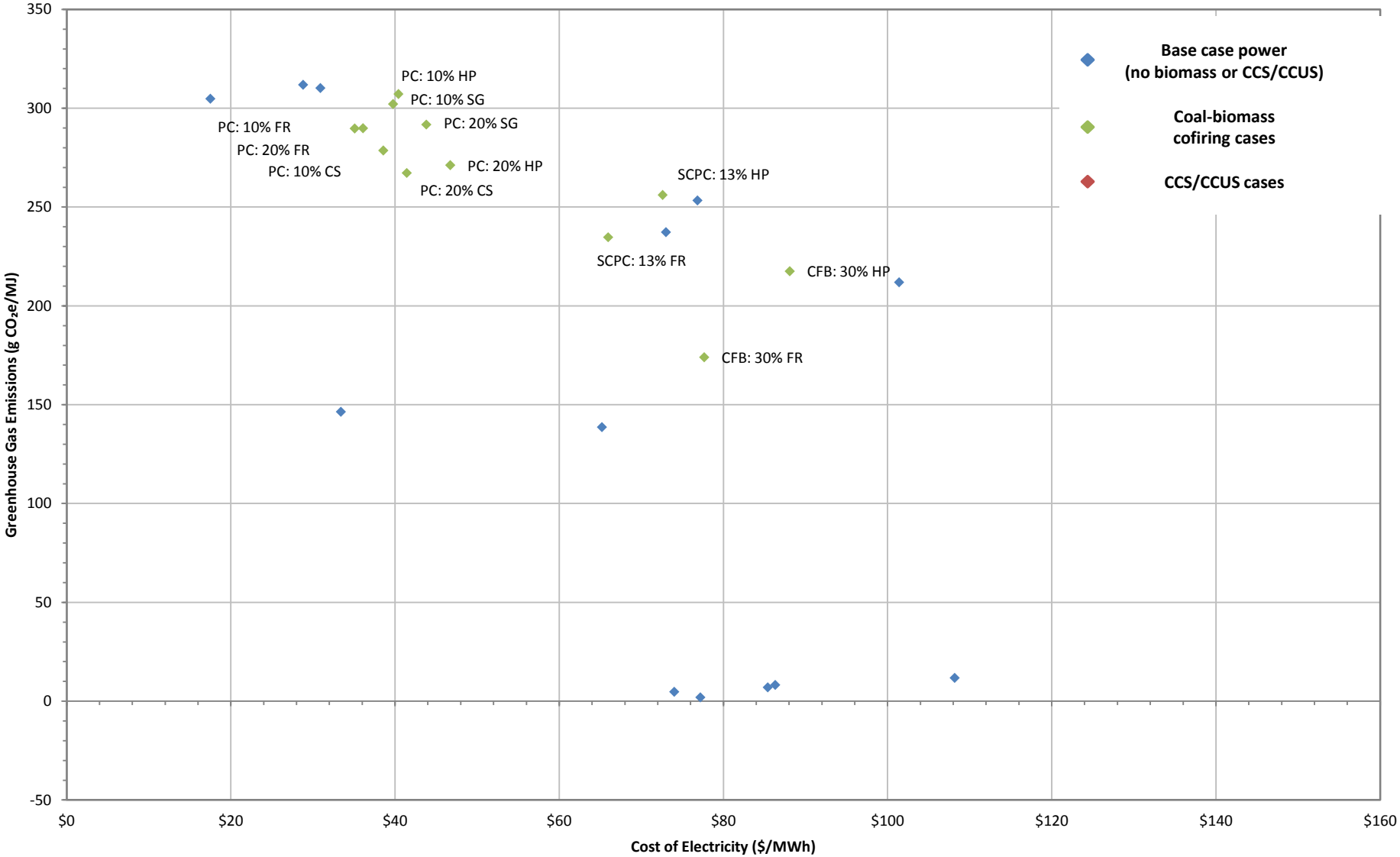




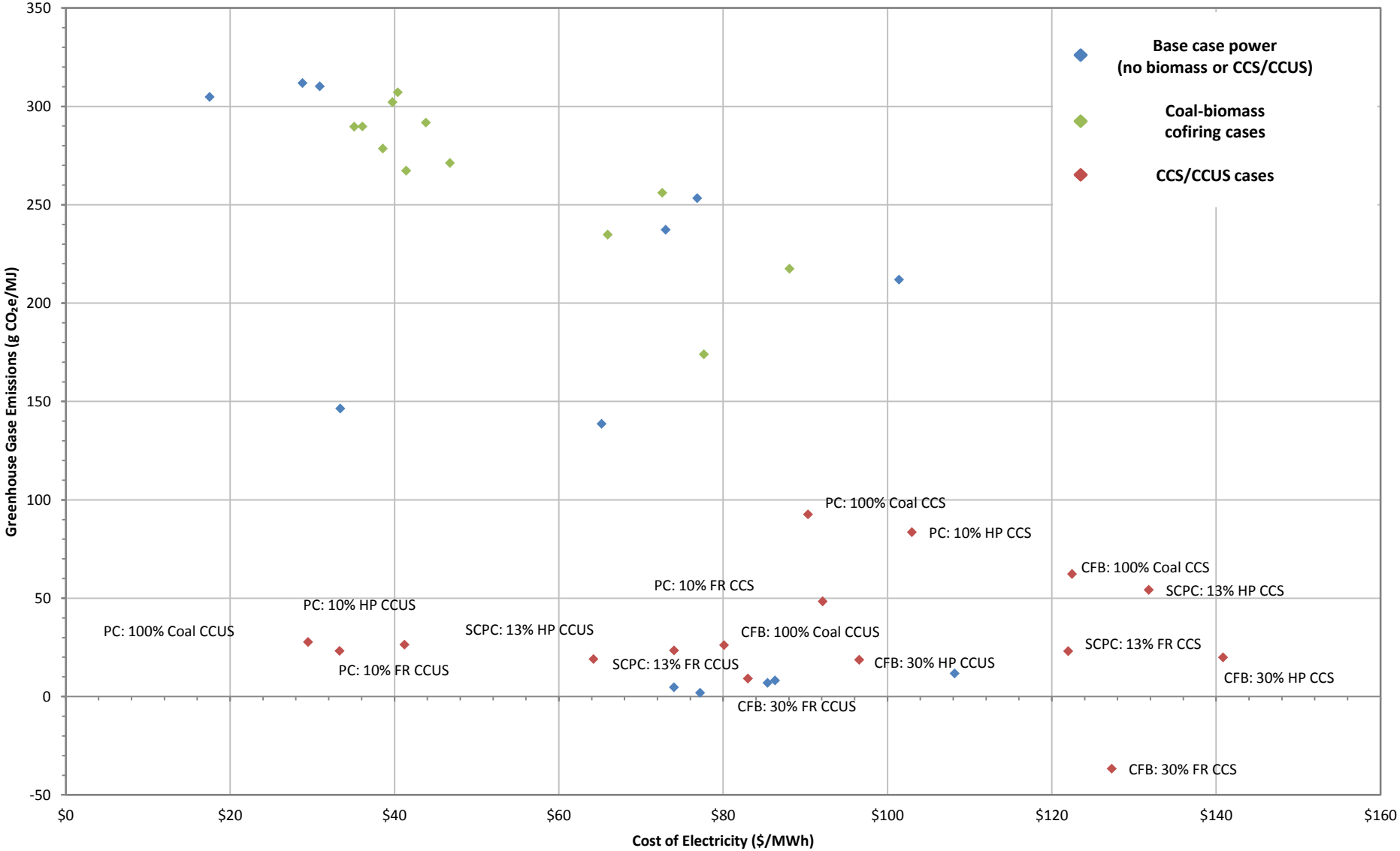
Life Cycle GHG Emissions versus Cost of Electricity



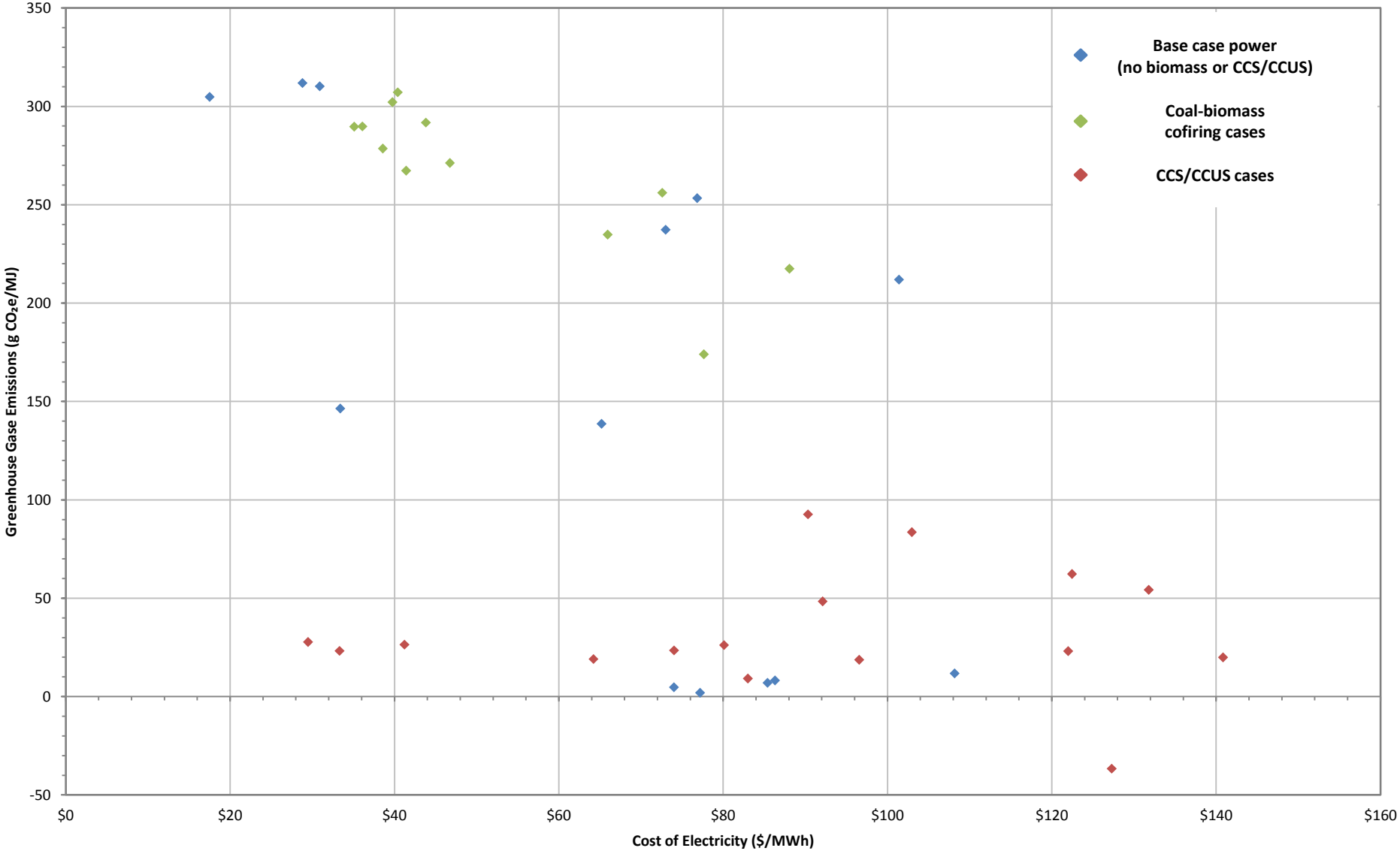
Life Cycle GHG Emissions versus Cost of Electricity



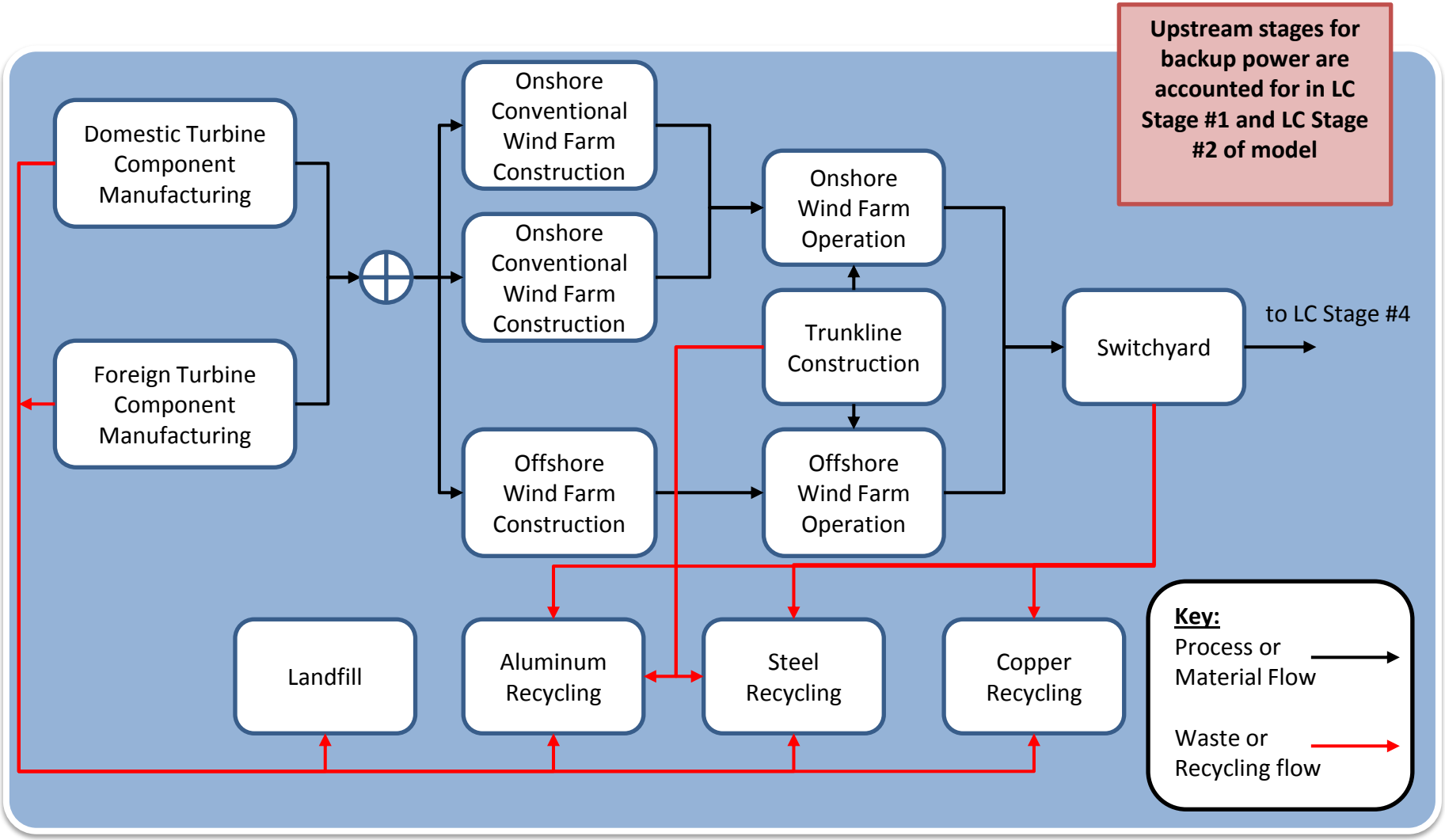
Life Cycle GHG Emissions versus Cost of Electricity



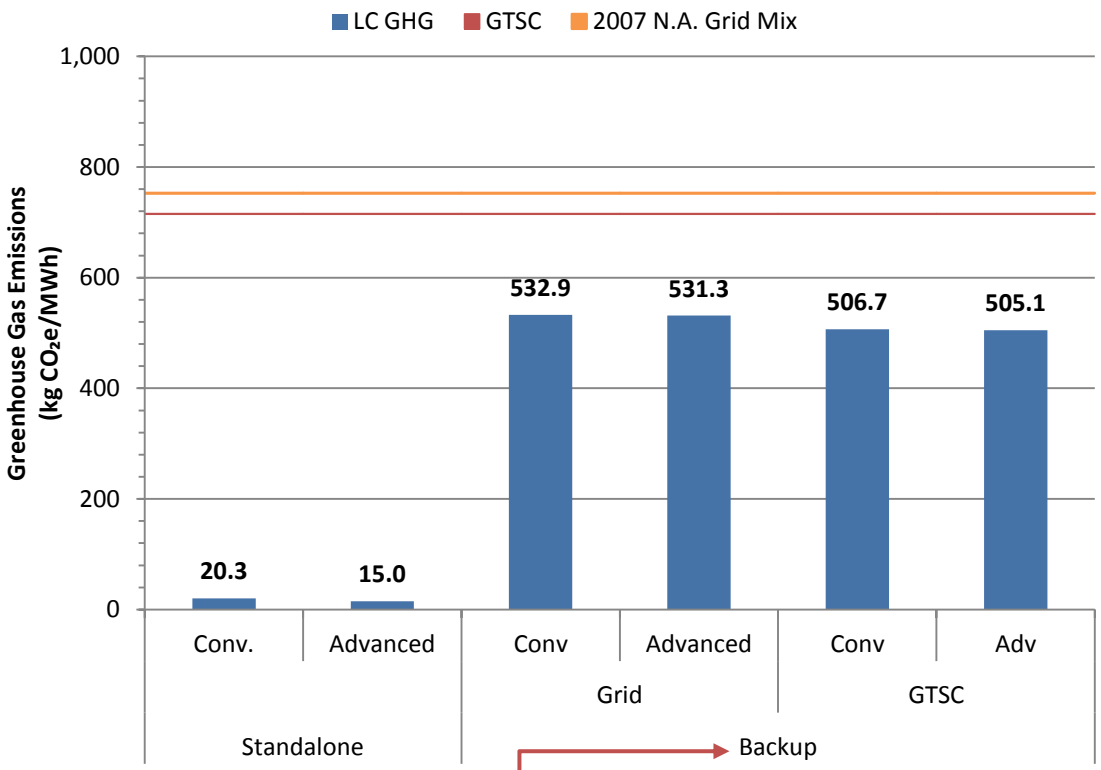
Life Cycle GHG Emissions versus Cost of Electricity

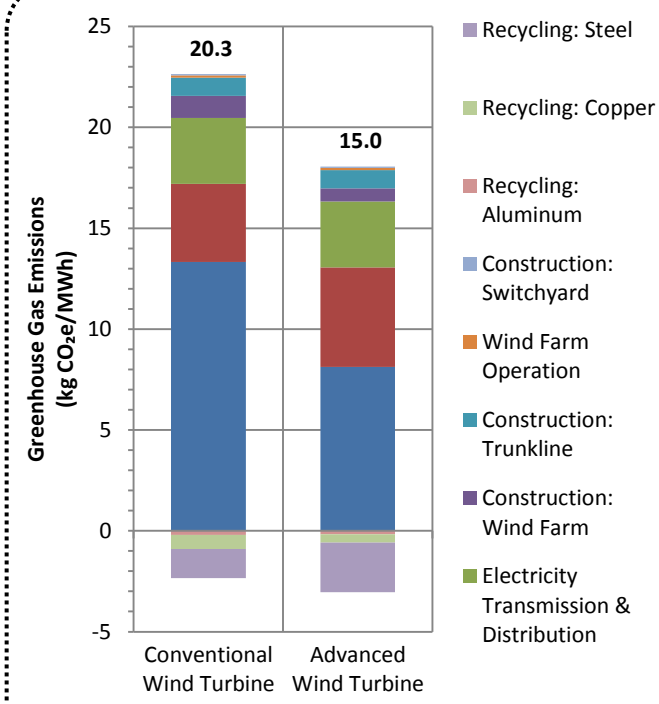


Modeling Structure of Wind Farm



GHG Emissions for Wind with Backup Power



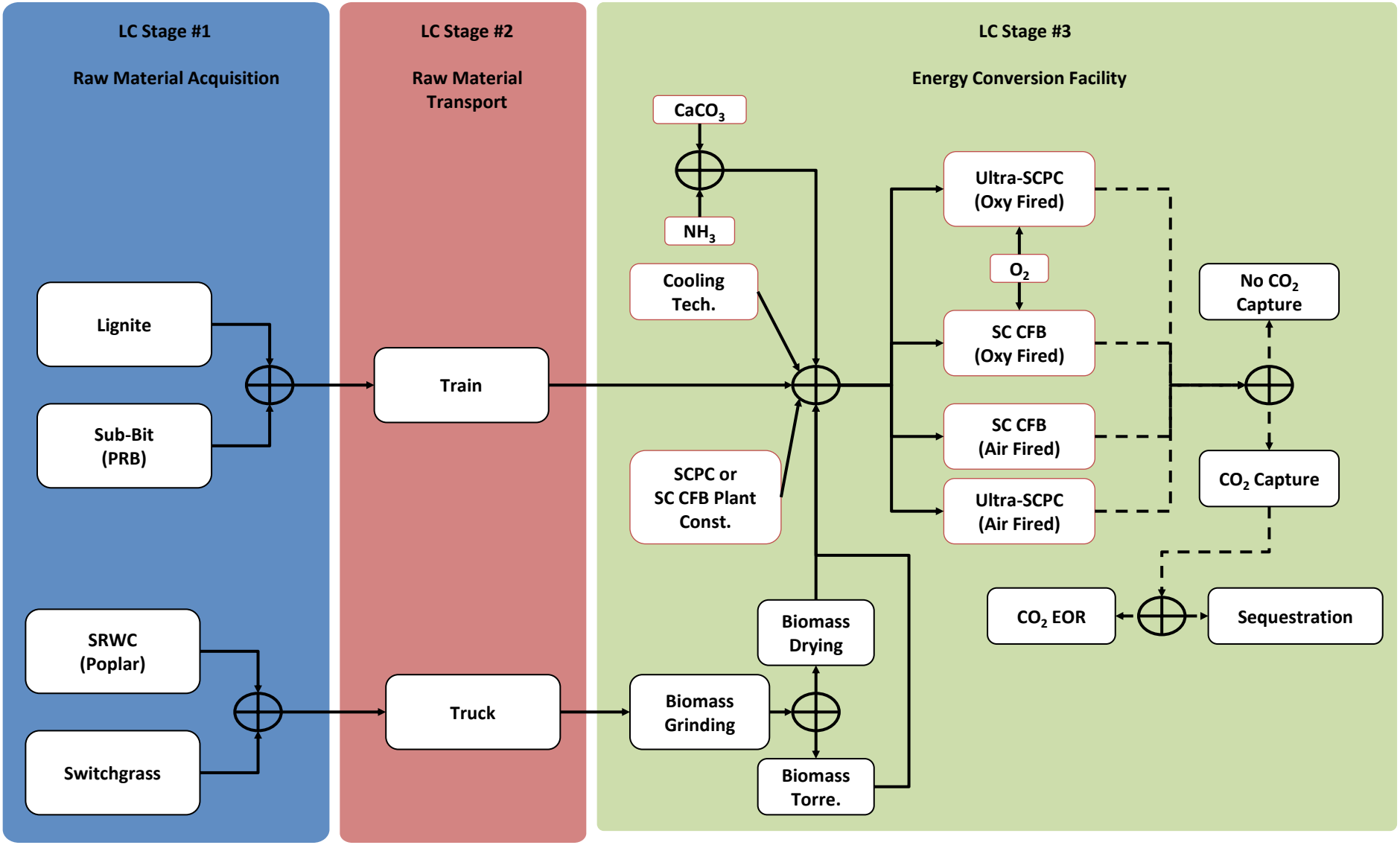


- **If availability of wind power is considered, environmental burdens of wind power must also account for backup power**
  - Nominal onshore wind farm capacity factor is 30%
- **Two backup power sources were modeled:**
  - Average U.S. power mix
  - Load-following GTSC plant

Negative GHG emissions represent displacement caused by recycling of manufacturing scrap and materials recovered from end-of-life management of turbines

Upcoming Work:
Dynamic Coal-Biomass Power with Emissions Control Options

Building a Dynamic Power Plant with Linear Programming



Ultra-Supercritical PC and Circulating Fluidized Bed (CFB) Cases

Coal type	Lignite	Sub-bit	
Biomass %	0	10	20
Biomass Type	Switchgrass	SRWC (Poplar)	
Torrefaction	Yes	No	
Plant Type	Ultra SC	CFB	
Combustion	Oxy	Air	
Cooling	Dry	Wet-dry	
CO_2 Capture	90	95	99
CCUS	EOR	Saline	

- **Potential for hundreds of possible permutations, not including options for emissions control technology such as advanced scrubbers and filters**

Recently Published and Forthcoming Work

www.netl.doe.gov/energy-analysis

- LCA of Natural Gas Extraction, Delivery and Electricity Production (1/12)
- LC GHG Analysis of Advanced Jet Propulsion Fuels: Fischer-Tropsch Based SPK-1 Case Study (12/11)
- Calculating Uncertainty in Biomass Emissions: Model and Documentation (11/11)
- LC GHG Inventory of Natural Gas Extraction, Delivery and Electricity Production (12/11)
- LCA: Ethanol from Biomass (8/11)
- LC GHG Analysis of Natural Gas Extraction & Delivery in the U.S. (5/11)
- Comparative Assessment of CO_2 Sequestration through EOR and Saline Aquifer (1/11)
- LCA: Power Studies Compilation (1/2011)
- LCA: Existing Pulverized Coal Power Plant (12/10)
- LCA: Integrated Gasification Combined Cycle Power Plant (12/10)
- LCA: Natural Gas Combined Cycle Power Plant (12/10)
- LCA: Supercritical Pulverized Coal Power Plant (12/10)
- Alternative Liquid Fuels Simulation Model (3/10)
- Balancing Climate Change, Energy Security, and Economic Sustainability: A LC Comparison of Diesel Fuel from Crude Oil and Domestic Coal and Biomass Resources (4/09)
- Framework and Guidance for Estimating GHG Footprints of Aviation Fuels (4/09)
- Evaluation of the Extraction, Transport and Refining of Imported Crude Oils and the Impact on LC GHG Emissions (3/09)
- Consideration of Crude Oil Source in Evaluating Transportation Fuel GHG Emissions (3/09)
- Affordable, Low-Carbon Diesel Fuel from Domestic Coal and Biomass (1/09)
- Development of Baseline Data and Analysis of LC GHG Emissions of Petroleum-Based Fuels (11/08)

Forthcoming

- Cofiring Coal & Biomass in the U.S.
- Technology Assessments (Comb. LCA, LCC & Resource Projection)
  - Nuclear
  - Cofiring
  - Wind
  - Natural Gas
  - Hydro
  - Geothermal
  - Solar Thermal
- Updated Baseline LCAs
  - NGCC
  - IGCC

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