

Economic Input- Output Life Cycle Assessment for Power Plant Construction

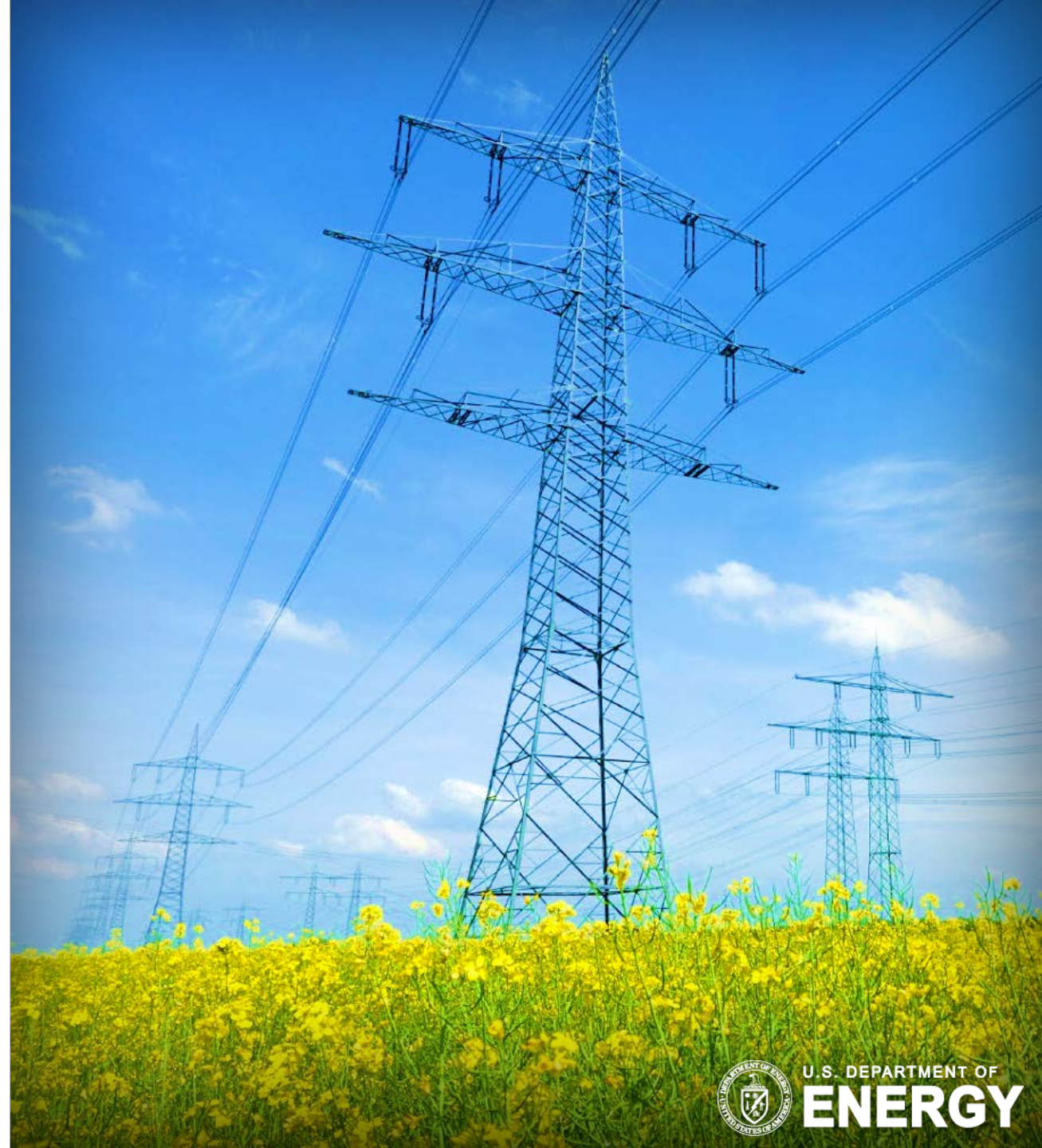
June 25-29, 2017

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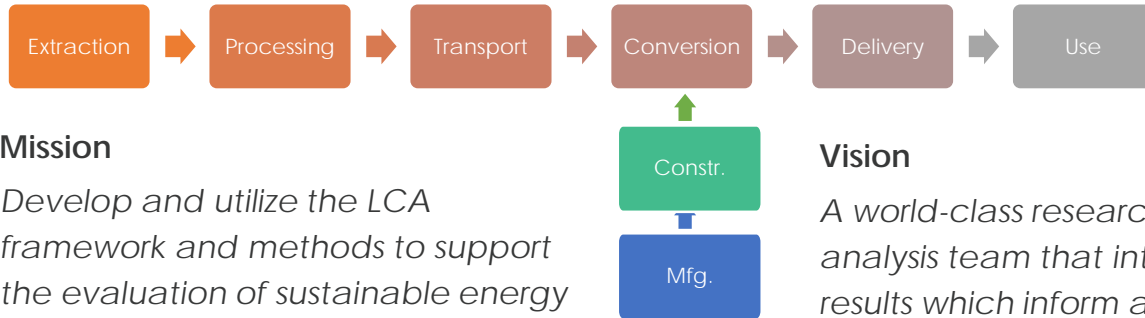
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Energy Life Cycle Analysis

Cradle-to-grave environmental footprint of energy systems



Mission

Develop and utilize the LCA framework and methods to support the evaluation of sustainable energy systems both in and outside of the Department of Energy

Vision

A world-class research and analysis team that integrates results which inform and recommend sustainable energy strategy and technology development



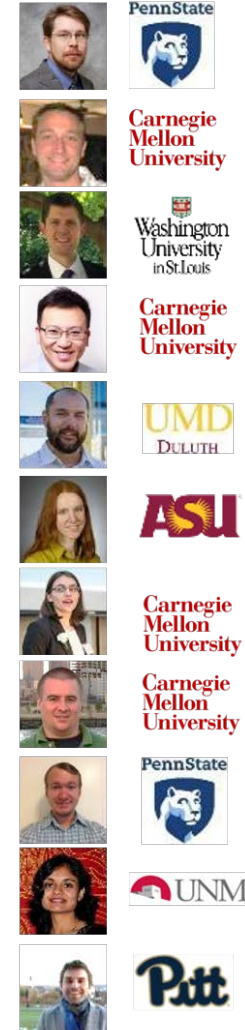
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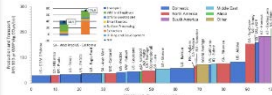
Recent and Ongoing LCA Studies



Petroleum

Updating the U.S. Life Cycle GHG Petroleum Decline to 2014 with Projections to 2040 Using Open-Source Engineering-Based Models
 Update to the U.S. Life Cycle GHG Petroleum Decline to 2014 with Projections to 2040 Using Open-Source Engineering-Based Models
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Updating the U.S. Life Cycle GHG Petroleum Baseline to 2014 with Projections to 2040 Using Open-Source Engineering-Based Models



Natural Gas

Synthesis of recent ground-level methane emission measurements from the US natural gas supply chain
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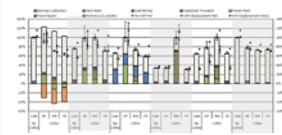
Synthesis of recent ground-level methane emission measurements from the US natural gas supply chain



Coal

Identifying/Quantifying Environmental Trade-offs Inherent in GHG Reduction Strategies for Coal-Fired Power
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Ongoing Work

- Establishing an Electricity Baseline for the U.S.
- Full environmental inventory for the Petroleum Baseline
- Creating a 2016 baseline for natural gas produced in the U.S.
- Creating a regionalized 2017 baseline for coal produced in the U.S.
- Using field EOR data to inform LCA results
- Collaboration with ONE Future for natural gas characterization
- Options for energy in the North Slope of Alaska
- Updated advanced power plant design LCAs

Evaluating the Climate Benefits of CO₂-Enhanced Oil Recovery Using Life Cycle Analysis
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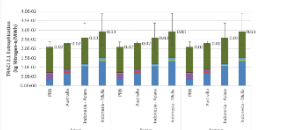
Using Common Boundaries to Assess CH₄ Emissions: a Life Cycle Evaluation of Natural Gas & Coal Power Systems

Using Common Boundaries to Assess Methane Emissions A Life Cycle Evaluation of Natural Gas and Coal Power Systems
 Using Common Boundaries to Assess Methane Emissions A Life Cycle Evaluation of Natural Gas and Coal Power Systems
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Boundary	Relative	Percentage	Relative	Percentage	Relative	Percentage
Coal Production	0.00	0.00	0.00	0.00	0.00	0.00
Coal Processing	0.00	0.00	0.00	0.00	0.00	0.00
Coal Distribution	0.00	0.00	0.00	0.00	0.00	0.00
Coal Combustion	0.00	0.00	0.00	0.00	0.00	0.00
Coal Conversion	0.00	0.00	0.00	0.00	0.00	0.00
Coal Conversion	0.00	0.00	0.00	0.00	0.00	0.00
Coal Conversion	0.00	0.00	0.00	0.00	0.00	0.00
Coal Conversion	0.00	0.00	0.00	0.00	0.00	0.00
Coal Conversion	0.00	0.00	0.00	0.00	0.00	0.00
Coal Conversion	0.00	0.00	0.00	0.00	0.00	0.00

Understanding the Contribution of Mining and Transportation to the Total Life Cycle Impacts of Coal Exported from the United States

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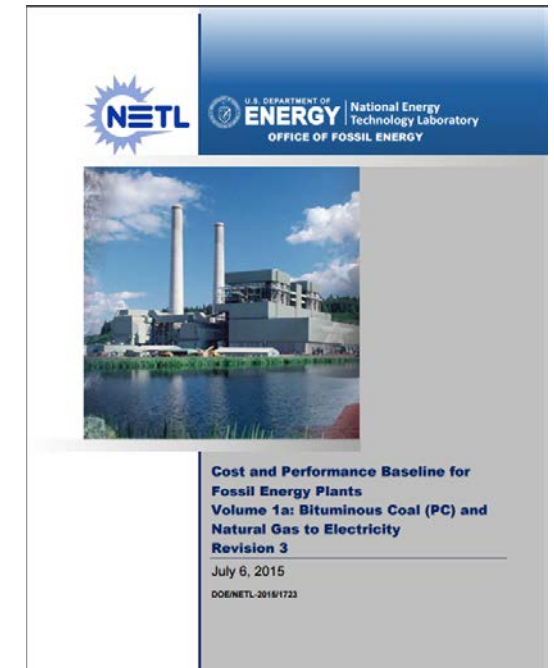


Collaborators



Scope

- LCA at NETL
 - Largely process based, over 450 unit processes
 - www.netl.doe.gov/lca
- Power plant construction modeling has been incomplete
 - Small impacts relative to operation
 - “In case of insufficient input data or data gaps for a unit process, materials and processes can be omitted, if the process contributes with less than 1% of mass or renewable or non-renewable primary energy of the total, and all excluded materials and processes do not exceed 5% of total energy use and mass.” – EeBGuide Project
- Can we improve?



Reference: DOE/NETL-2015/1723 “Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3”

Current UP for Fossil Fuel Power Construction



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

Process Name:	NGCC Power Plant, Construction		
Reference Flow:	1 pcs.	of	NGCC Power Plant (NETL baseline)
Brief Description:	Material input for the construction of the NETL baseline NGCC plant with or without CCS		

SECTION I: META DATA

Geographical Coverage:	US
Region:	
Year Data Best Represents:	2000
Process Type:	Manufacturing Process (MP)
Process Scope:	Gate-to-Gate Process (GG)
Allocation Applied:	No
Completeness:	Individual Relevant Flows Captured
Flows Aggregated in Data Set:	<input checked="" type="checkbox"/> Process <input type="checkbox"/> Energy Use <input type="checkbox"/> Energy P&D <input type="checkbox"/> Material P&D

Goal and Scope:

Reference Flow: 1 pcs. of NGCC Power Plant (NETL baseline)

This unit process provides a summary of relevant input and output flows associated with the construction of a natural gas combined cycle (NGCC) power plant. This process can be used for scenarios with and without carbon capture and sequestration (CCS). Key inputs include concrete, steel, steel pipe, stainless steel, aluminum, and cast iron. The key output is a piece of an NGCC power plant.

Note: All inputs and outputs are normalized per the reference flow (e.g., per piece of construction)

SECTION II: PARAMETERS

This section includes adjustable parameters, calculations needed to support adjustable parameters, and flow calculations based upon adjustable parameters.

Parameter Name	Formula	Value	Min. Value	Max. Value	Unit	References	Comments
3 CCS		1					[binary] If CO2 in flue gas is routed to CO2 recovery, value = 1. If CO2 in flue gas is
12 Net_Mw_noCCS		555.080			Mw	1	[MWh] Net Power Output for NGCC without CCS operation
10 Net_Mw_CCS		473.570			Mw	1	[MWh] Net Power Output for NGCC with CCS operation
6 Net_Mw	IF(CCS=1,Net_Mw_CCS;Net_Mw_noCCS)	473.57000			Mw		[MWh] Net Power Output for NGCC operation with or without CCS, depending on
13 NGCC_Conc_CCS		71456.31			kg/Mw	1,2,4,5,6,7	[kg/Mw] Average/estimated concrete material needs for an NGCC plant with CC
15 NGCC_Conc_noCCS		70245.68			kg/Mw	1,2,4,5,6	[kg/Mw] Average/estimated concrete material needs for an NGCC plant without
13 NGCC_Conc_Ref	IF(CCS=1,NGCC_Conc_CCS;NGCC_Conc_noCCS)	71456.3146			kg/Mw		[kg/Mw] Average/estimated concrete material needs for an NGCC plant with or w
14 NGCC_Steel_CCS		33687			kg/Mw	1,2,3,6,7	[kg/Mw] Average/estimated steel material needs for an NGCC plant with CCS
15 NGCC_Steel_noCCS		33434			kg/Mw	1,2,3,6	[kg/Mw] Average/estimated steel material needs for an NGCC plant without CCS
14 NGCC_Steel_Ref	IF(CCS=1,NGCC_Steel_CCS;NGCC_Steel_noCCS)	33686.7586			kg/Mw		[kg/Mw] Average/estimated steel material needs for an NGCC plant with or witho
13 NGCC_Pipe_Ref		8391			kg/Mw	1,3	[kg/Mw] Average/estimated steel pipe material needs for an NGCC plant
13 NGCC_Iron_Ref		252.45			kg/Mw	1,5,6	[kg/Mw] Average/estimated iron material needs for an NGCC plant
11 NGCC_Al_Ref		217.00			kg/Mw	1,2,6	[kg/Mw] Average/estimated aluminum material needs for an NGCC plant
11 NGCC_SS_Ref		88.26			kg/Mw	1,7	[kg/Mw] Average/estimated stainless steel material needs for an NGCC plant wit
13 NGCC_Conc_Tot	NGCC_Conc_Ref*Net_Mw	3.38E+07			kg		[kg] Amount of concrete required to construct a single NGCC power plant
14 NGCC_Steel_Tot	NGCC_Steel_Ref*Net_Mw	1.60E+07			kg		[kg] Amount of steel required to construct a single NGCC power plant
13 NGCC_Pipe_Tot	NGCC_Pipe_Ref*Net_Mw	3.97E+06			kg		[kg] Amount of steel pipe required to construct a single NGCC power plant
13 NGCC_Iron_Tot	NGCC_Iron_Ref*Net_Mw	1.20E+05			kg		[kg] Amount of iron required to construct a single NGCC power plant
11 NGCC_Al_Tot	NGCC_Al_Ref*Net_Mw	1.03E+05			kg		[kg] Amount of aluminum required to construct a single NGCC power plant
11 NGCC_SS_Tot	IF(CCS=1,NGCC_SS_Ref*Net_Mw;0)	4.18E+04			kg		[kg] Amount of stainless steel required to construct a single NGCC power plant
End of List	<select this entire row, then insert new row>						

Flow Name
Concrete, ready mix, R-5-0 [Valuable substances]
Steel cold rolled (St) [Metals]
Steel pipe [Metals]
Cast iron part [Metal parts]
Aluminum sheet [Metas]
Stainless steel (cold rolled) [Metals]
<select this entire row, then insert new row>

SECTION III: INPUT FLOWS

This section includes all input flows considered for this unit process

Parameter	Flow Name	Value	Units	Parameter	Unit	Total	Units per RF	Tracked	Origin	Reference	Comments
NGCC_Conc_Tot	Concrete, ready mix, R-5-0 [Valuable substances]	1	kg	3.38E+07	kg	3.38E+07	kg	X	Literature	1,2,4,5,6,7	[Technosphere] Amount of concrete required to construct a single NGCC power plant
NGCC_Steel_Tot	Steel cold rolled (St) [Metals]	1	kg	1.60E+07	kg	1.60E+07	kg	X	Literature	1,2,3,6,7	[Technosphere] Amount of steel required to construct a single NGCC power plant
NGCC_Pipe_Tot	Steel pipe [Metals]	1	kg	3.97E+06	kg	3.97E+06	kg	X	Literature	1,3	[Technosphere] Amount of steel pipe required to construct a single NGCC power plant
NGCC_Iron_Tot	Cast iron part [Metal parts]	1	kg	1.20E+05	kg	1.20E+05	kg	X	Literature	1,5,6	[Technosphere] Amount of cast iron required to construct a single NGCC power plant
NGCC_Al_Tot	Aluminum sheet [Metas]	1	kg	1.03E+05	kg	1.03E+05	kg	X	Literature	1,2,6	[Technosphere] Amount of aluminum required to construct a single NGCC power plant
NGCC_SS_Tot	Stainless steel (cold rolled) [Metals]	1	kg	4.18E+04	kg	4.18E+04	kg	X	Literature	1,7	[Technosphere] Amount of stainless steel required to construct a single NGCC power
End of List	<select this entire row, then insert new row>		Factor			Amount			<select from list>		

Moving Beyond Raw Material Inputs

Engineering, Architectural, Chemical, Construction, Design, Government, etc.

Power Plant Construction

Raw Materials

(current modeling)

- Steel
- Aluminum
- Concrete
- Iron

Additional Components

(proposed additions)

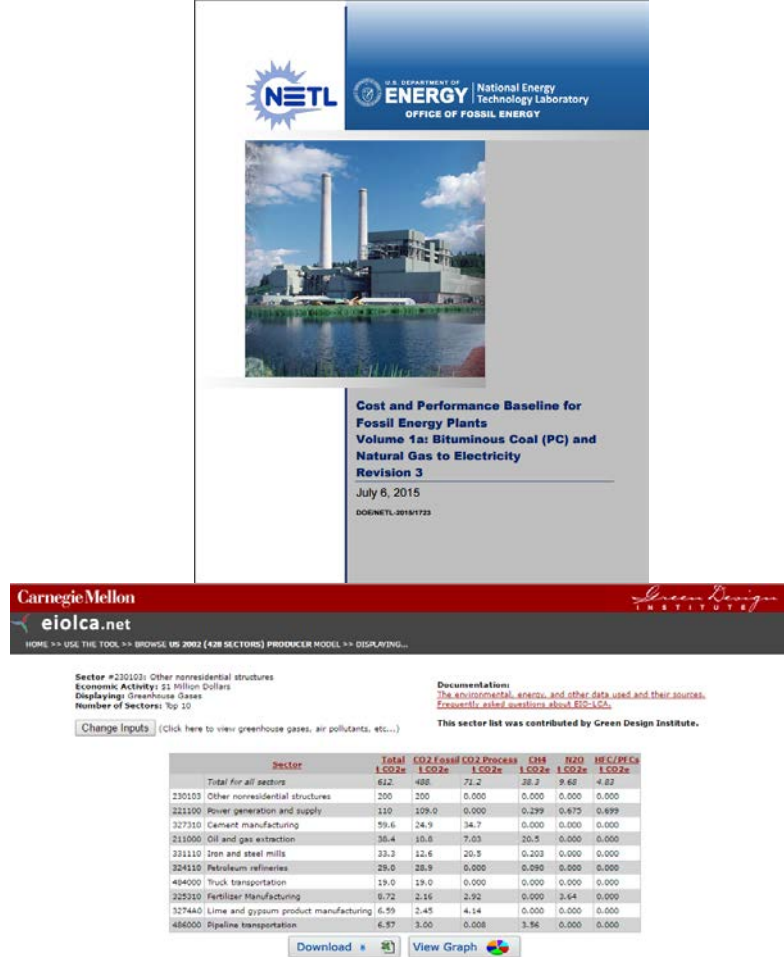
- Manufacturing
- Construction
- Services



- NETL baseline reports for coal and gas plants
- CMU Green Design Institute's EIO-LCA

Data & Plan

- Detailed Cost Engineering Data
 - Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3 (NETL)
- Map to NAICS (EIO sectors)
- Input to EIO-LCA model – Carnegie Mellon University Green Design Institute – 2002 Producer model



**Cost and Performance Baseline for Fossil Energy Plants
Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity
Revision 3
July 6, 2015
DOE/NETL-2015/1723**

Sector #230103: Other nonresidential structures
Economic Activity: 21 Million Dollars
Displaying: Greenhouse Gases
Number of Sectors: Top 10

Documentation:
The environmental, energy, and other data used and their sources.
Especially cited activities about EIO-LCA.
This sector list was contributed by Green Design Institute.

Sector	Total 1,000t	CO2 Fossil 1,000t	CO2 Process 1,000t	CH4 1,000t	N2O 1,000t	HFC/PFCa 1,000t
Total for all sectors	612	458	71.2	28.2	9.68	4.82
230103 Other nonresidential structures	200	200	0.000	0.000	0.000	0.000
221100 Power generation and supply	110	109.0	0.000	0.299	0.675	0.699
327310 Cement manufacturing	59.6	24.9	34.7	0.000	0.000	0.000
211000 Oil and gas extraction	35.4	10.5	7.03	20.5	0.000	0.000
331110 Iron and steel mills	33.3	12.6	20.5	0.203	0.000	0.000
324110 Petroleum refineries	28.0	28.9	0.000	0.090	0.000	0.000
484000 Truck transportation	19.0	19.0	0.000	0.000	0.000	0.000
225210 Fertilizer Manufacturing	8.72	2.16	2.92	0.000	3.64	0.000
327440 Lime and gypsum product manufacturing	6.59	2.45	4.14	0.000	0.000	0.000
486000 Pipeline transportation	6.57	3.00	0.008	3.56	0.000	0.000

Download View Graph

If you are using this output as part of a project or paper, please cite appropriately:
Carnegie Mellon University Green Design Institute. (2017) Economic Input-Output Life Cycle Assessment (EIO-LCA) US 2002 (428 sectors) Producer model [Internet]. Available from: <http://www.eiolca.net/> [Accessed 26 Apr 2017].
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Plant Cost Details (Supercritical PC e.g.)



Case:		B11A – Supercritical PC w/o CO ₂					
Plant Size (MW,net):		550					
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O.& Fee
				Direct	Indirect		
7		HRSG, Ducting, & Stack					
7.3	Ductwork	\$10,663	\$0	\$6,731	\$0	\$17,394	\$1,739
7.4	Stack	\$10,604	\$0	\$6,162	\$0	\$16,766	\$1,677
7.9	Duct & Stack Foundations	\$0	\$1,156	\$1,373	\$0	\$2,528	\$253
	Subtotal	\$21,267	\$1,156	\$14,266	\$0	\$36,689	\$3,669
8		Steam Turbine Generator					
8.1	Steam TG & Accessories	\$75,300	\$0	\$8,211	\$0	\$83,511	\$8,351
8.2	Turbine Plant Auxiliaries	\$418	\$0	\$890	\$0	\$1,308	\$131
8.3	Condenser & Auxiliaries	\$7,830	\$0	\$2,737	\$0	\$10,567	\$1,057
8.4	Steam Piping	\$26,525	\$0	\$10,751	\$0	\$37,276	\$3,728
8.9	TG Foundations	\$0	\$1,247	\$2,059	\$0	\$3,305	\$331
	Subtotal	\$110,073	\$1,247	\$24,647	\$0	\$135,967	\$13,597

- Map each line of the cost tables to EIO-LCA (NAICS) sectors
 - Quick, reliable, & easy way to model small components (vs. full UP)
 - Full UPs are not warranted given size of construction impacts
 - Offers much more detail than raw material UPs

Item No.	Description	EIOLCA Sector
HRSG, Ducting, & Stacks		
7.3	Ductwork	Air purification and ventilation equipment manufacturing
7.4	Stack	Air purification and ventilation equipment manufacturing
7.9	HRSG, Duct & Stack Foundations	Ready-mix concrete manufacturing
Steam Turbine Generator		
8.1	Steam TG & Accessories	Turbine and turbine generator set units manufacturing
8.2	Turbine Plant Auxiliaries	Turbine and Turbine generator set units manufacturing
8.3	Condenser & Auxiliaries	Turbine and Turbine generator set units manufacturing
8.4	Steam Piping	Iron, steel pipe and tube manufacturing from purchased steel
8.9	TG Foundations	Ready-mix concrete manufacturing

Expansion of Impact Categories (EIO-LCA)



Economic Activity (\$ millions)	Conventional Air Pollutants (metric tons)	Greenhouse Gasses (t CO2e)	Energy (TJ)	Toxic Releases (kg)*	Transportation (ton-km)	TRACI LCIA	Others
Total Economic Activity	CO	Total	Total Energy	Fugitive	Air	Glob Warm CO ₂ e	HazWaste Gen
Total Value Added	NH ₃	CO ₂ Fossil	Coal	Stack	Oil Pipe	Acidif Air SO ₂ e	Water Withdrawls
Employee Comp VA	NOx	CO ₂ Process	Natural Gas	Total Air	Gas Pipe	HH Crit Air PM10e	Land Use
Net Tax VA	PM10	CH ₄	Petrol	Surface Water	Rail	Eutro Air Ne	
Profits VA	PM2.5	N ₂ O	Bio/Waste	Underground Water	Truck	Etro Water Ne	
Direct Economic	SO ₂	HFC/PFCs	NonFossElec	Land	Water	OzoneDep CFC-11e	
Direct Economic (%)	VOC			Offsite	Intl Air	Smog Air O ₃ e	
				POTW Metal	Intl Water	EcoTox 2,4D	
				POTW Nonmetal	Total	HH Cancer (benzene eq)	
						HH NonCancer (toluene eq)	

* The table above summarizes toxic emissions by sector by aggregating across all toxic substances regardless of impact. That is not a very good way of summarizing toxics.

Carnegie Mellon University Green Design Institute. (2017) Economic Input-Output Life Cycle Assessment (EIO-LCA) US 2002 (428 sectors) Producer model [Internet], Available from: <<http://www.eiolca.net/>> [Accessed 27 Apr, 2017]

Assumptions

Primarily for scaling up current UPs to total construction impact rather than per MWh

- 30 year lifetime for power plant
- 85% capacity factor
- 550 MWh NGCC plant
- 630 MWh SCPC plant
- 3% discount rate (to match the report year [2011 USD] and the EIO model year [2002 USD])
 - Consistent with national average Consumer Product Index
- **Eng. H.O. and Fee** is 10% of the bare erected cost – modeled as the ‘architectural and engineering services’ sector
 - Architectural
 - landscape architectural
 - engineering, drafting
 - building inspection
 - geophysical surveying and mapping
 - surveying and mapping (except geophysical) services
 - testing laboratories
- **Labor** is modeled as other nonresidential construction

Case:		B11A – Supercritical PC w/o CO ₂					
Plant Size (MW _{net}):		550					
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O.& Fee
				Direct	Indirect		

Preliminary Results – Construction (SCPC)



UPs have mostly underestimated impacts

Selective Releases	UP kg per MWh	UP kg per Plant	EIO-LCA kg per Plant	Ratio EIO to UP
Ammonia	1.2E-06	145.2	28,320	195
Barium	1.4E-08	1.7	11	6.6
Carbon dioxide	0.94	1.1E08	4.0E08	3.5
Carbon monoxide	0.01	1.1E08	2.6E08	2.3
Nitrogen dioxide	1.0E-05	1.2E03	1.8E04	14
Sulphur dioxide	0.0017	2.1E05	1.3E06	6.1
Organic emissions to air (group VOC)	0.0026	3.2E05	3.7E05	1.1
Methane	0.0025	3.1E05	1.6E06	5.4
Particles to air	0.001	1.3E05	5.7E05	4.3

Preliminary Results – NGCC (Construction)



UPs have mostly underestimated impacts

Selective Releases	UP per MWh	UP per Plant	EIO-LCA per Plant	Ratio EIO to UP
Ammonia	5.84E-07	82	15,840	193
Barium	7.91E-09	1.1	1.1	1.0
Carbon dioxide	0.43	6.0E07	2.4E08	3.9
Carbon monoxide	0.0036	5.1E05	1.3E06	2.5
Nitrogen dioxide	3.76E-06	530	8,722	16
Sulphur dioxide	0.00080	1.1E05	6.1E05	5.5
Organic emissions to air (group VOC)	0.0012	1.6E05	2.2E05	1.4
Methane	0.0011	1.5E05	1.2E06	7.8
Particles to air	0.00043	6.1E04	3.8E05	6.2

Does Construction Matter?

Show before and after (old UP vs. new UP)

NGCC 630 Construction Impacts / Total Impacts

Output	% of Impacts (Old UP)	% of Impacts (EIO)
Ammonia	0.003%	0.6%
Carbon Dioxide	0.1%	0.5%
NOx	0.9%	15%

SCPC 550MW Construction Impacts/Operation Impacts

Output	% of Impacts (Old UP)	% of Impacts (EIO)
Ammonia	0.006%	12%
Carbon Dioxide	0.1%	0.4%
NOx	0.2%	3.0%
Particulate Matter	2.1%	9.1%

Fossil Scenarios with CCS?

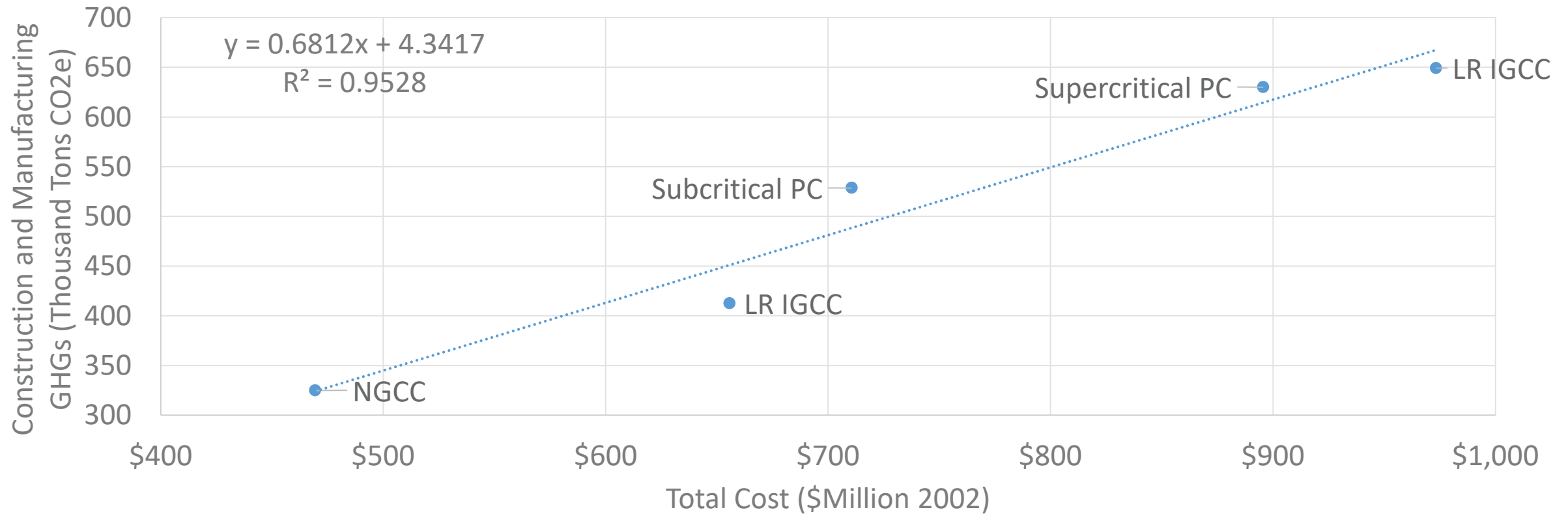
SCPC Plant with CCS

- CCS represents a 40% increase in cost over a power plant without CCS
 - Some uncertainty with the exact numbers as these data are proprietary
 - The 40% adder to construction impacts is a good starting point

SCPC 550MW Construction Impacts/Operation Impacts	
Output	Percentage of Operation Lifetime Impacts
Ammonia	6%
Carbon Dioxide	5%
NOx	4%
Particulate Matter	7%

- Construction is approximately 5% of operational lifetime CO₂ emissions

GHGs Scale with Construction Costs



Conclusions

- EIO-LCA offers an easy and reliable method to estimate construction emissions for power plants and expand inventory.
- Construction, design, processing, and other services are important to the construction impacts (3x -4x increase in CO₂ emissions).
 - Other impacts vary, but ignoring construction or modeling as raw material inputs misses the mark.
- While construction represents <1% of many impacts for the life cycle of a fossil power plant, this is unlikely to be true with the adoption of CCS and renewables.
 - For SCPC w/ CCS – construction emissions are ~5% of the operational CO₂ emissions.

- Is this scalable beyond coal and natural gas?
 - Nuclear, Hydro
 - Wind, Solar
- Decommissioning
 - Data sources
 - Recycling of materials
- Update to USEEIO
 - Yang, Y., Ingwersen, W. W., Hawkins, T. R., Srocka, M., & Meyer, D. E. (2017). USEEIO: A new and transparent United States environmentally-extended input-output model. *Journal of Cleaner Production*, 158, 308-318.

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Preliminary Results – NGCC w/CCS



UPs have mostly underestimated impacts – note that these impacts are uncertain

Selective Releases	UP per MWh	UP per Plant	EIO-LCA per Plant	Ratio EIO to UP
Ammonia	1.2E-06	151	19,670	130
Barium	1.5E-08	2	20	11
Carbon dioxide	1.5E+00	183,536,386	694,445,800	3.8
Carbon monoxide	1.2E-02	1,481,648	4,340,690	2.9
Nitrogen (N-compounds)	1.6E-12	0	1,732,270	6.6
Nitrogen dioxide	1.1E-05	1,365	32,278	24
Sulphur dioxide	2.6E-03	322,267	2,238,620	6.9
Organic emissions to air (group VOC)	3.9E-03	482,083	638,960	1.3
Methane	3.7E-03	458,799	2,910,369	6.3
Particles to air	1.3E-03	165,470	969,400	5.9