Economic Input-Output Life Cycle Assessment for Power Plant Construction

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Derrick R. Carlson

Joe Marriott

H. Scott Matthews

Timothy J. Skone

NATIONAL ENERGY TECHNOLOGY LABORATORY

Energy Life Cycle Analysis

Cradle-to-grave environmental footprint of energy systems

Extraction → Processing → Transport → Conversion → Delivery → Use

Mfg. → Constr. → Conversion

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

Life Cycle Analysis
energy sustainability

Timothy J. Skone, P.E.
Senior Environmental Engineer
(412) 386-4495
timothy.skone@netl.doe.gov

netl.doe.gov/LCA

LCA@netl.doe.gov

@NETL_News

Tim Skone – 18 years
Federal Team Lead
BS Chemical Engineering
PennState

Joe Marriott – 12 years
Contractor Team Lead
PhD Environmental Eng. & Public Policy
Carnegie Mellon University

James Littlefield – 16 years
Natural gas, system & process design
BS Chemical Engineering
Washington University in St. Louis

Chung Shih – 12 years
GIS, Subsurface, Software Dev.
PhD Advanced Infrastructure Systems
Carnegie Mellon University

Matt Jamieson – 8 years
Power systems, CO_2-EOR
BS Mechanical Engineering
UMD Duluth

Michele Mutchek – 5 years
Loan program office, CO_2 Utilization
MS Civil/Env/Sust Engr | BS Env Sciences
ASU

Michelle Krynock – 2 years
Natural gas, fuel cells, coal
BS Civil/Env Engr & Public Policy
Carnegie Mellon University

Derrick Carlson – 7 years
I/O LCA, Efficiency, CO_2 capture
PhD/MS Civ/Env Engr | B.S. Chemistry
Carnegie Mellon University

Dan Augustine – 1 year
Natural gas, visual analytics
BS Energy Engineering
PennState

Ambica Pegallapati – 5 years
Biofuels, bioreactors, wastewater
PhD Environmental Engineering
UNM

Greg Zaimes – 4 years
Energy analysis; transportation fuels
PhD Civ/Env Eng; B.S. Physics
Pitt

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Recent and Ongoing LCA Studies

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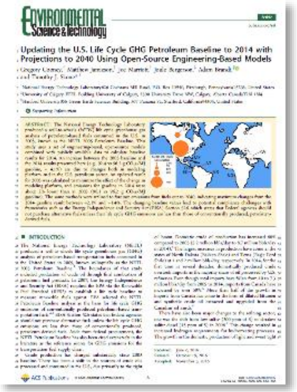
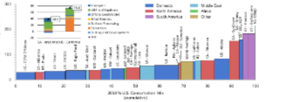
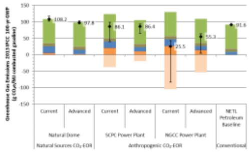
Petroleum



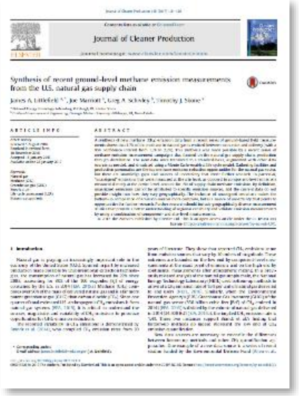
Updating the U.S. Life Cycle GHG Petroleum Baseline to 2014 with Projections to 2040 Using Open-Source Engineering-Based Models



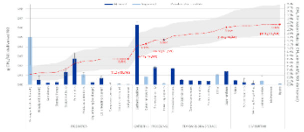
Evaluating the Climate Benefits of CO_2-Enhanced Oil Recovery Using Life Cycle Analysis

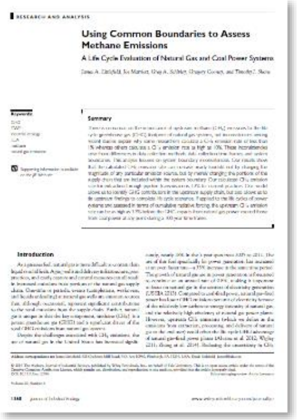


Natural Gas

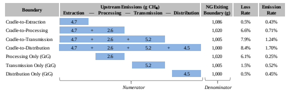


Synthesis of recent ground-level methane emission measurements from the US natural gas supply chain



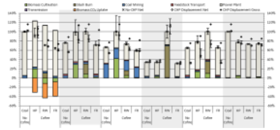


Using Common Boundaries to Assess CH_4 Emissions: a Life Cycle Evaluation of Natural Gas & Coal Power Systems

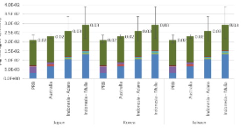


Coal

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



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



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

Collaborators

UNIVERSITY OF CALGARY

ONE OUR NATION'S ENERGY FUTURE

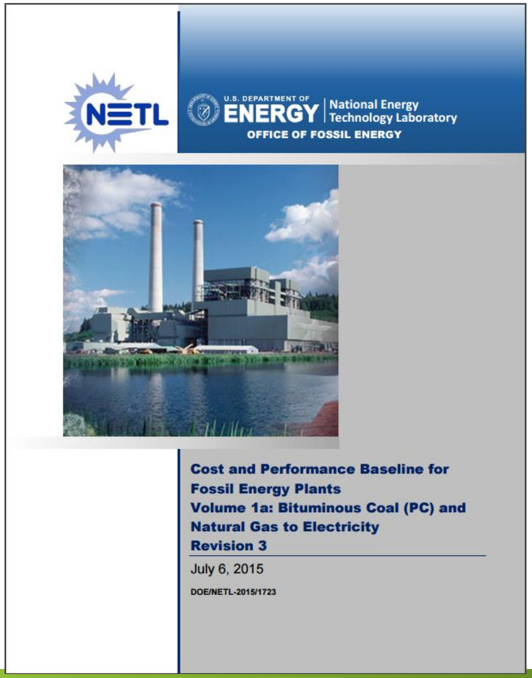
Wyoming INFRASTRUCTURE AUTHORITY

EDF ENVIRONMENTAL DEFENSE FUND Finding the ways that work

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

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?


NETL
U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory
OFFICE OF FOSSIL ENERGY

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

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

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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)	DQI 2,2,4,0,2	(see DQI sheet for explanation)
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:	☑ Process ☐ Energy Use ☐ Energy P&D ☐ 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)	473.5700			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_nCCS		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_nCCS)	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>						

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	References	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>		

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>

Moving Beyond Raw Material Inputs

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

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Power Plant Construction

Raw Materials
(current modeling)

- Steel
- Aluminum
- Concrete
- Iron

Additional Components
(proposed additions)

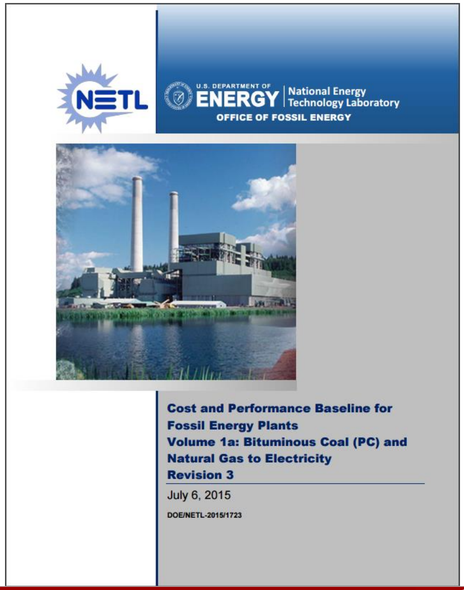
- Manufacturing
- Construction
- Services

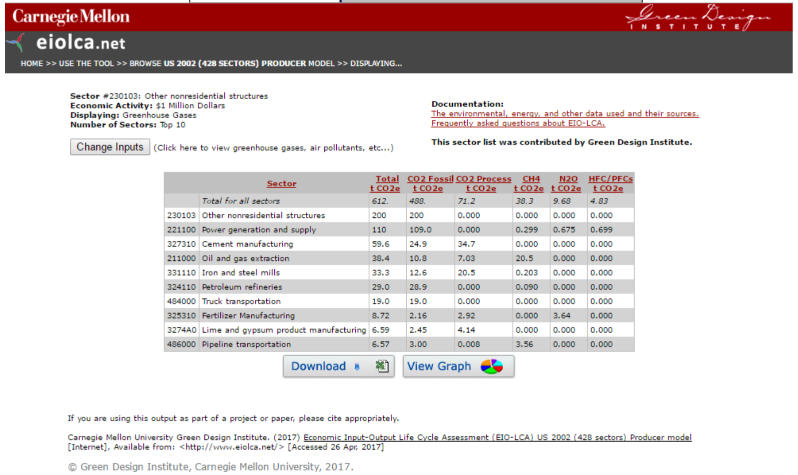
eiolca.net

- 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





	Sector	Total t CO2e	CO2 Fossil t CO2e	CO2 Process t CO2e	CH4 t CO2e	N2O t CO2e	HFC/PFCs t CO2e
	Total for all sectors	*612.*	*488.*	*71.2*	*38.3*	*9.68*	*4.83*
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	38.4	10.8	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	29.0	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
325310	Fertilizer Manufacturing	8.72	2.16	2.92	0.000	3.64	0.000
3274A0	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

Plant Cost Details (Supercritical PC e.g.)

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	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**

Item No.	Description	EIO-LCA 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

- 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

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_2e	HazWaste Gen
Total Value Added	NH_3	CO_2 Fossil	Coal	Stack	Oil Pipe	Acidif Air SO_2e	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_2O	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_3e	
				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

		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		

- 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

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	1.2 E-06	1.3 E04	3.5 E05	**2.5**
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**
NOx	1.0 E-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**

Results – NGCC (Construction)

UPs have mostly underestimated impacts

a	UP kg per MWh	UP kg per Plant	EIO-LCA kg per Plant	Ratio EIO to UP
Ammonia	5.84E-07	14,886	23,800	1.6
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
NOx	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?

Old UP vs. New UP

NGCC 630 Construction Impacts / Total Impacts		
Output	**% of Impacts (Old UP)**	**% of Impacts (EIO)**
Ammonia	0.4%	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	4.8%	12%
Carbon Dioxide	0.1%	0.4%
NOx	0.2%	3.0%
Particulate Matter	2.1%	9.1%

Fossil Scenarios with CCS?

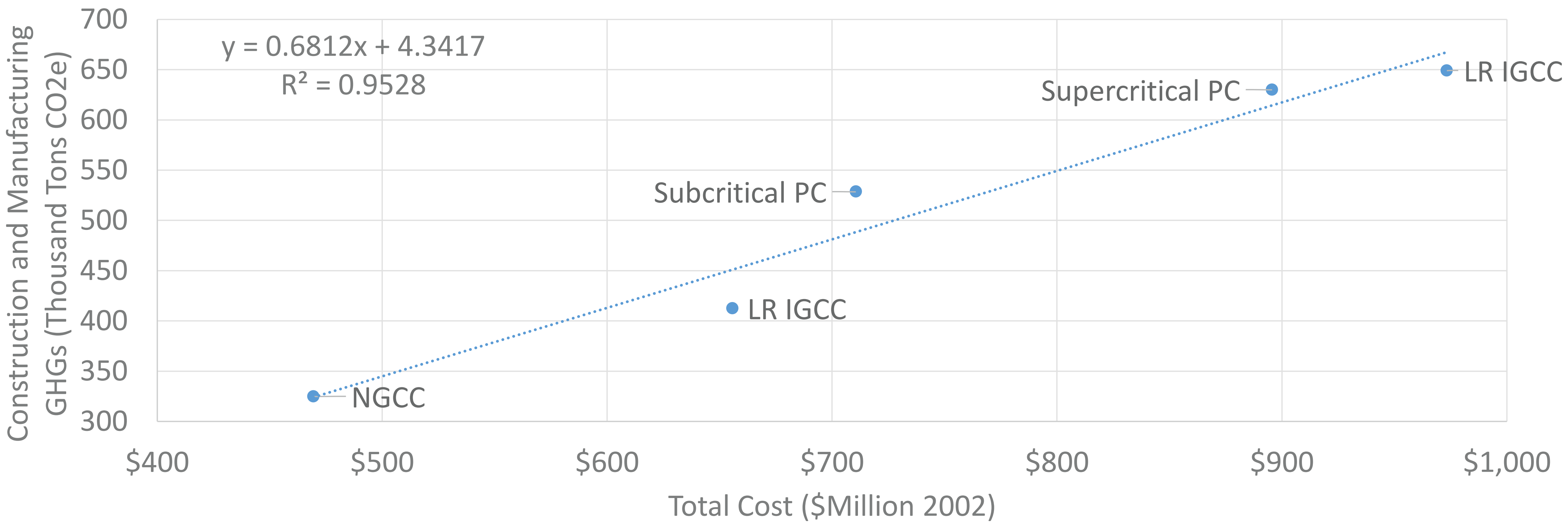
SCPC Plant with CCS

- 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 CO_2 emissions

GHGs Scale with Construction Costs



Conclusions

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- 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 CO_2 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 CO_2 emissions.

Future Work

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- 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.

Contact Information

Timothy J. Skone, P.E.
Senior Environmental Engineer • Strategic Energy Analysis
(412) 386-4495 • *timothy.skone@netl.doe.gov*

Joe Marriott
Principal Engineer • KeyLogic
joseph.marriott@netl.doe.gov

Derrick Carlson
Senior Engineer • KeyLogic
derrick.carlson@netl.doe.gov

H. Scott Matthews
Professor, Carnegie Mellon University
Civil & Environmental Engineering
Engineering and Public Policy
hsm@cmu.edu

Life Cycle Analysis
environmental | economic | social

netl.doe.gov/LCA *LCA@netl.doe.gov* *@NETL_News*

Preliminary Results – NGCC w/CCS

NATIONAL ENERGY TECHNOLOGY LABORATORY

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	1.5E+02	2.0E+04	130
Barium	1.5E-08	2.0E+00	2.0E+01	11
Carbon dioxide	1.5E+00	1.8E+08	6.9E+08	3.8
Carbon monoxide	1.2E-02	1.5E+06	4.3E+06	2.9
Nitrogen (N-compounds)	1.6E-12	0.0E+00	1.7E+06	6.6
Nitrogen dioxide	1.1E-05	1.4E+03	3.2E+04	24
Sulphur dioxide	2.6E-03	3.2E+05	2.2E+06	6.9
Organic emissions to air (group VOC)	3.9E-03	4.8E+05	6.4E+05	1.3
Methane	3.7E-03	4.6E+05	2.9E+06	6.3
Particles to air	1.3E-03	1.7E+05	9.7E+05	5.9