Developing Analytical Techniques for Modeling Construction/Infrastructure of Energy Systems

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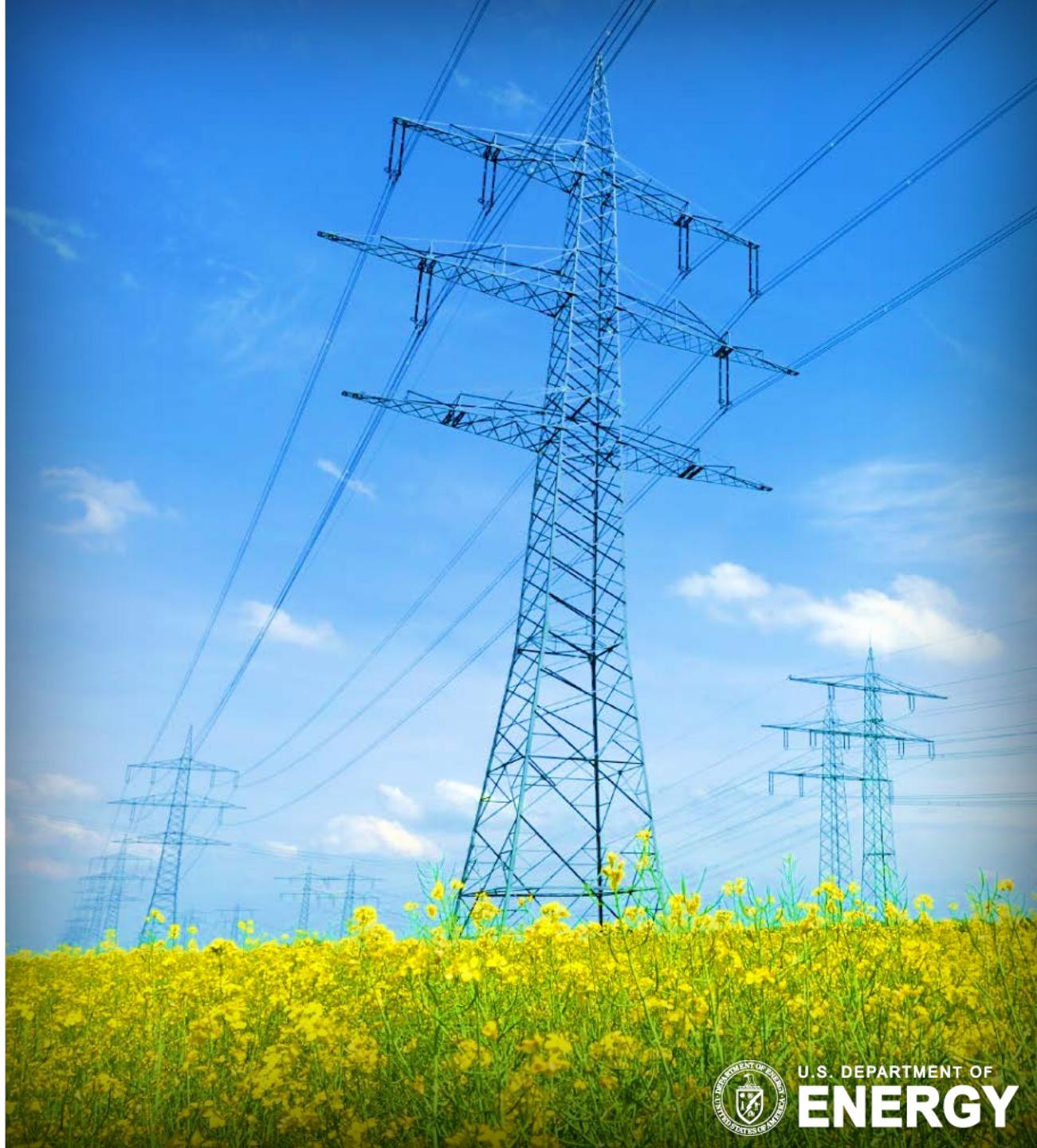


Objective

Life cycle impact assessment (LCIA) of energy systems infrastructure (construction, manufacture, and deconstruction) based on capital costs built on United States Environmentally Extended Input Output[1] model

- Use of baseline cost data in Environmentally Extended Input Output (EEIO) and Economic Input Output (EIO) models to produce life cycle inventory (LCI) for construction and capital investment as opposed to consumer final or intermediate demand
- Using Bureau of Economic Analysis consumer price index[2] to scale high-quality vendor construction estimates
- EIO vs process Life cycle assessment (LCA) - comparison of approaches for a power plant construction application
- Uncertainty considerations for EIO

1. 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.
2. Bureau of Labor Statistics. (2016). Consumer price index - all urban consumers, 1956-2016 [Time series]. Retrieved from http://data.bls.gov

Moving Beyond Raw Material Inputs

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

- Previous NETL detailed process models showed construction impacts were small
  - Construction models were simplified based on mass of primary materials

Power Plant Construction

Raw Materials (current modeling)	**Additional Components** (proposed additions)
- Steel	- Manufacturing
- Aluminum	- Construction
- Concrete	- Services
- Iron	

- Update with
  - Cost data from NETL baseline reports for coal and gas plants
    - Detailed cost data developed in NETL baseline reports
  - US EPA USEEIO Model
    - 1,800+ flows leads to a greater coverage of emissions than many process models

USEEIO Model

Modified from Yang et al. (2017)

- BEA benchmark input/output accounts for 385 commodities in 2007

Environmental Data Item	Primary Source	Year
GHGs	US GHG Inventory	2013
CAPs	NEI	2011
HAPs	NEI	2011
Other Toxins	TRI	2013
Pesticides	USDA Agricultural Chemical Use Program	2009 – 2014
Nutrients	USDA Agricultural Chemical Use Program	2009 – 2014
Land	USDA ERS, EIA MECS	2007
Water	USDA Farm and Ranch Irrigation Survey, USGS	2008 – 2010
Mineral Use	USGS Mineral Commodities Survey	2014
Energy Use	EIA Monthly Energy Review	2014

Yang Y, Ingwersen WW, Hawkins TR, Srocka M, Meyer DE (2017) USEEIO: A New and Transparent United States Environmentally-Extended Input-Output Model. Journal of Cleaner Production 158:308-318. DOI:10.1016/j.jclepro.2017.04.150

USEEIO Model Modifications

- USEEIO v1.1 is designed for Python; adapted Excel-based matrices to run results in Excel (https://github.com/USEPA/USEEIO)
- Revert back to original Make and Use (BEA 2007)
- Modified characterization factors (TRACI 2.1) to match NETL Baseline
- Disaggregated petroleum sector
  - Gasoline
  - Diesel
  - Kerosene
  - Petroleum Products

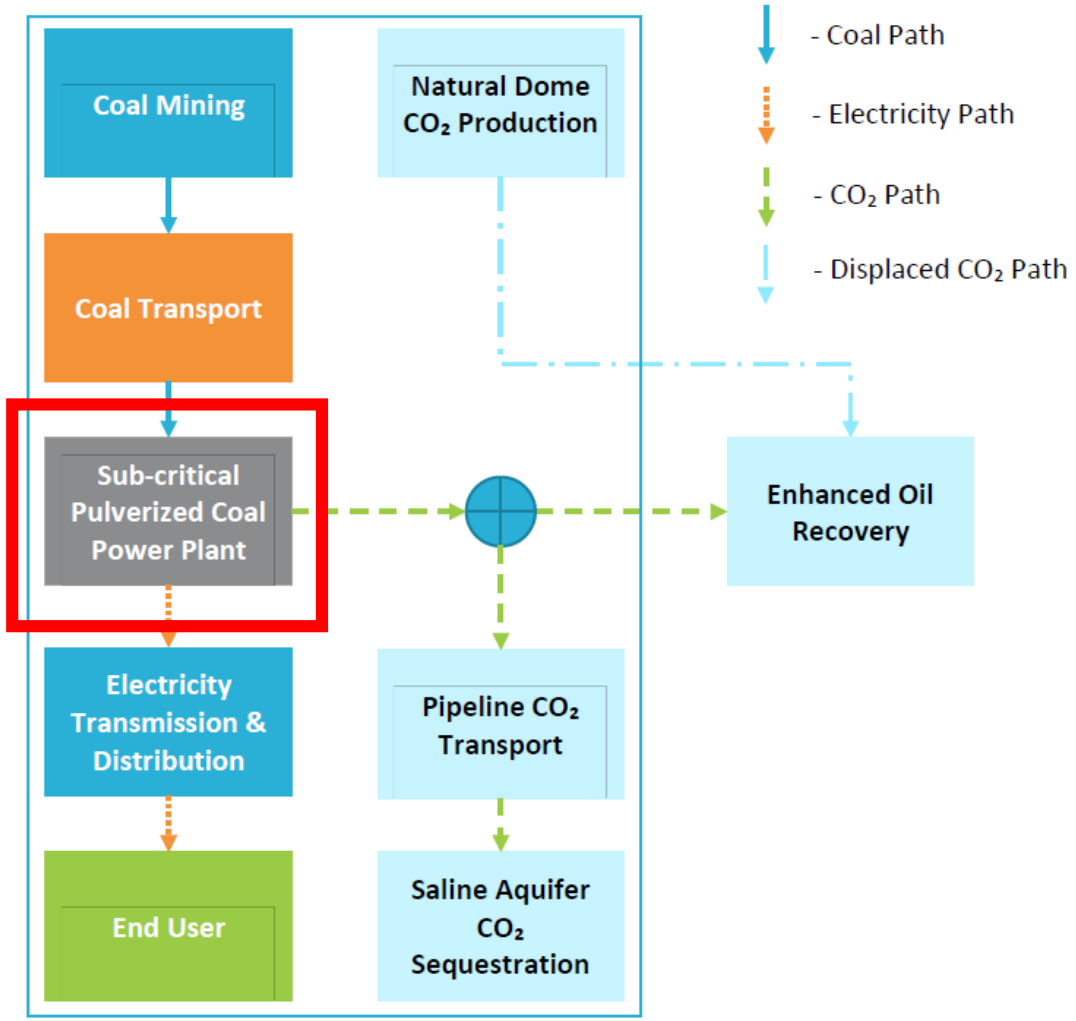
Excel-based USEEIO Infrastructure Model

- Customized results display
  - Production vs. Consumption perspective
  - Contribution by flow
- Detailed impact or inventory results
- Customized demand vectors
  - Built from detailed cost engineering data from NETL baseline reports
- Options for normalized and/or weighted impacts (Ryberg et al. 2014; NIST BEES)

Impacts from Infrastructure

- Scope: Infrastructure impacts relative to total life cycle impacts of Power Plant
- Impacts normalized per MWh consistent with 30-year operating period for the power plant (85% capacity factor)

Figure 1-1. Conceptual study boundary



Demand Vectors for Capital Infrastructure

- Equipment and materials are mapped to BEA sectors
- Correspondence (NETL → BEA) used across power systems

	Case:	B11A – Subcritical PC w/o CO_2					Estimate Type:	Conceptual			
	Plant Size (MW,net):	550					Cost Base:	Jun 2011			
Item No.	Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies Process	Contingencies Project	Total Plant Cost $/1,000	Total Plant Cost $/kW
1	Coal & Sorbent Handling										
1.1	Coal Receive & Unload	$4,103	$0	$1,849	$0	$5,952	$595	$0	$982	$7,529	$14
1.2	Coal Stackout & Reclaim	$5,303	$0	$1,185	$0	$6,488	$649	$0	$1,071	$8,207	$15
1.3	Coal Conveyors	$4,930	$0	$1,173	$0	$6,103	$610	$0	$1,007	$7,720	$14
1.4	Other Coal Handling	$1,290	$0	$271	$0	$1,561	$156	$0	$258	$1,975	$4
1.5	Sorbent Receive & Unload	$164	$0	$49	$0	$212	$21	$0	$35	$269	$0
1.6	Sorbent Stackout & Reclaim	$2,644	$0	$478	$0	$3,122	$312	$0	$515	$3,949	$7
1.7	Sorbent Conveyors	$943	$205	$228	$0	$1,376	$138	$0	$227	$1,741	$3
1.8	Other Sorbent Handling	$570	$134	$295	$0	$999	$100	$0	$165	$1,263	$2
1.9	Coal & Sorbent Hnd. Foundations	$0	$4,756	$6,270	$0	$11,026	$1,103	$0	$1,819	$13,948	$25
	Subtotal	**$19,948**	**$5,095**	**$11,797**	**$0**	**$36,840**	**$3,684**	**$0**	**$6,079**	**$46,602**	**$85**
2	Coal & Sorbent Prep & Feed										
2.1	Coal Crushing & Drying	$2,351	$0	$452	$0	$2,803	$280	$0	$462	$3,545	$6
2.2	Coal Conveyor to Storage	$6,019	$0	$1,296	$0	$7,315	$731	$0	$1,207	$9,253	$17
2.5	Sorbent Prep Equipment	$4,491	$194	$920	$0	$5,605	$560	$0	$925	$7,090	$13
2.6	Sorbent Storage & Feed	$541	$0	$204	$0	$745	$75	$0	$123	$943	$2
2.9	Coal & Sorbent Feed Foundation	$0	$548	$481	$0	$1,029	$103	$0	$170	$1,301	$2
	Subtotal	**$13,401**	**$742**	**$3,353**	**$0**	**$17,496**	**$1,750**	**$0**	**$2,887**	**$22,133**	**$40**
3	Feedwater & Miscellaneous BOP Systems										
3.1	Feedwater System	$18,097	$0	$6,235	$0	$24,332	$2,433	$0	$4,015	$30,780	$56
3.2	Water Makeup & Pretreating	$5,536	$0	$1,751	$0	$7,288	$729	$0	$1,603	$9,620	$17

- Equipment and Material Costs are scaled from producer to consumer costs based on BEA Producer and Purchaser Use Tables

Primary Dashboard

Results Dashboard

Demand Vector: SCPC_CC 550MW

Perspective: Production

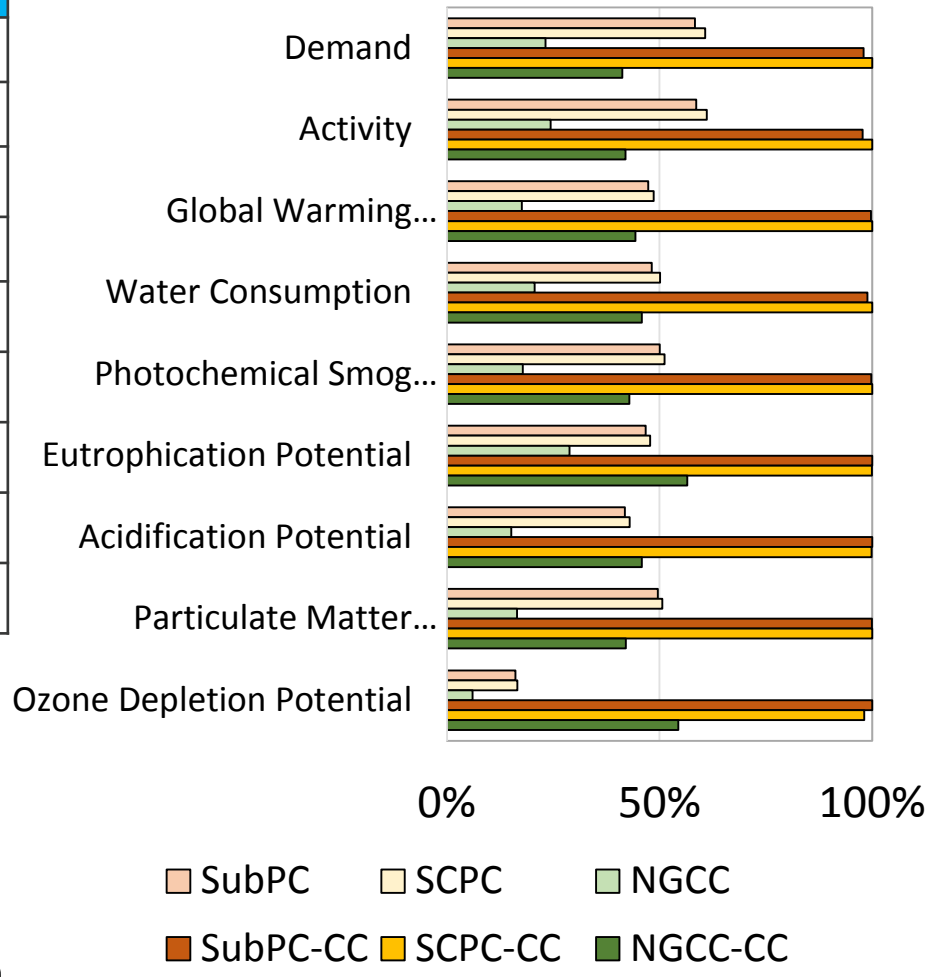
Life Cycle Impact Assessment

Products & Services (USEEIO)	Demand	Induced Activity	Normalized Impacts	Normalized and Weighted Impacts	Value Added	Jobs	Global Warming Potential	Water Consumption	Land Use
	USD 2013	*USD 2013*	*% of national impacts*	*Impact score*	*USD 2013*	*persons*	*kg CO2 eq*	*m3*	*m2*a*
Total	1,546,640,312	3,284,602,703	1.10E-3	1.10E-3	1,585,319,287	11,654	9.15E+8	2.84E+7	5.55E+8
Aggregate Results									
Agriculture, forestry, fishing	-	9,750,969	1.07E-4	1.07E-4	4,805,195	31	7.12E+6	3.86E+6	4.82E+8
Mining	-	127,395,715	2.23E-4	2.23E-4	90,576,511	114	9.30E+7	1.29E+6	4.88E+7
Electricity	-	27,722,042	1.33E-4	1.33E-4	19,963,387	38	1.71E+8	1.24E+7	2.11E+5
Utilities	-	27,751,458	3.88E-5	3.88E-5	15,519,718	35	4.39E+7	1.80E+6	3.45E+4
Construction	536,018,355	548,616,507	6.82E-5	6.82E-5	347,193,282	3,564	7.54E+7	2.01E+5	1.12E+7
Food, textiles, wood & paper	-	55,226,902	1.29E-5	1.29E-5	17,053,620	171	9.77E+6	7.59E+5	1.52E+5
Petroleum & petrochemicals	-	97,349,669	1.56E-5	1.56E-5	30,725,738	19	2.41E+7	5.44E+5	1.54E+6
Industrial mfg	450,445,424	695,598,853	8.50E-6	8.50E-6	288,850,058	2,292	1.55E+7	5.01E+5	1.04E+6
Other mfg	448,984,944	643,817,648	2.04E-4	2.04E-4	276,672,721	1,381	2.03E+8	2.49E+6	1.61E+6
Distribution, retail & wholesale	-	210,245,802	7.17E-5	7.17E-5	130,202,500	914	6.57E+7	1.03E+5	8.19E+6
Professional, business, other svcs	9,416,663	411,351,723	8.43E-6	8.43E-6	241,563,006	2,180	1.54E+7	2.23E+5	4.98E+5
Other, n.e.c.	-	9,850,212	-	-	-	-	-	-	-
* Cement, clays, etc.*	38,036,817	75,836,556	5.20E-5	5.20E-5	37,662,612	321	8.62E+7	2.51E+5	1.78E+5
Steel and other metals	34,235,816	309,863,899	1.55E-4	1.55E-4	74,386,153	472	1.02E+8	3.84E+6	3.05E+5
>> ready-mix concrete	29,502,294	34,224,748	2.16E-6	2.16E-6	10,144,786	121	3.63E+6	9.59E+4	5.03E+4
* Highlighted sector reported separately from Cement, clays, etc.									
Commodity Results									
fresh soybeans, canola, flaxseeds, and other oilseeds	-	679,197	8.59E-6	8.59E-6	319,945	0.1	3.80E+5	1.71E+3	1.52E+6
fresh wheat, corn, rice, and other grains	-	1,258,721	1.86E-5	1.86E-5	(3,207)	0.5	2.55E+6	5.80E+5	1.35E+7
fresh vegetables, melons, and potatoes	-	21,310	2.87E-7	2.87E-7	12,884	0.1	9.74E+3	1.26E+4	3.91E+4
fresh fruits and tree nuts	-	53,723	4.95E-7	4.95E-7	32,521	0.5	1.54E+4	2.45E+4	1.10E+5

Cover | ReadMe | Contents | Dashboard | Contribution by sector - graph | Contrib by commod demand-graph | Detailed Results | Supply Chain Results | LCIA | Inventory | Make and Use | Supporting Calculations | Contr

Net and Relative Impacts of Infrastructure

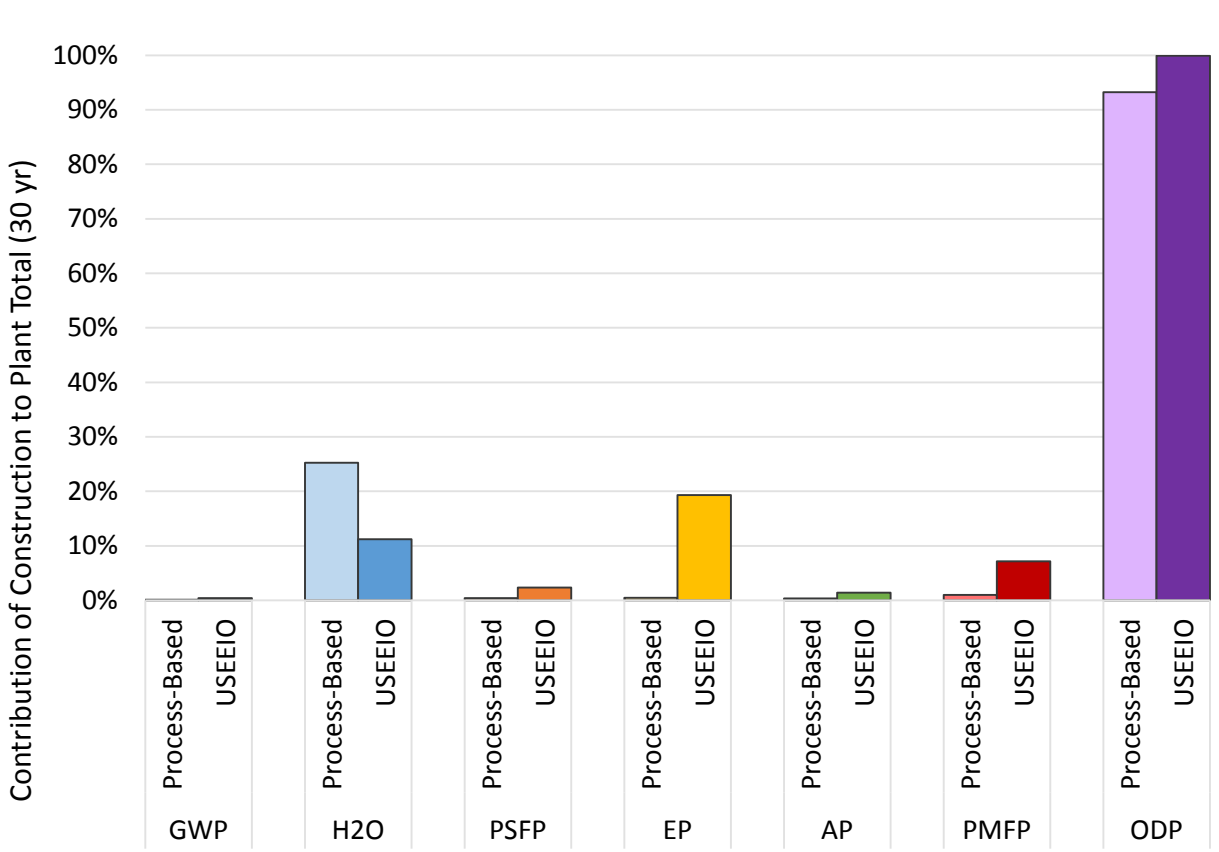
Impact	Units	SubPC 550MW	SubPC-CC 550MW	SCPC 550MW	SCPC_CC 550MW	NGCC 630MW	NGCC_CC 559 MW
Demand	2013 $	9.02E+8	1.52E+9	9.39E+8	1.55E+9	3.59E+8	6.38E+8
Induced Activity	2013 $	1.92E+9	3.21E+9	2.01E+9	3.28E+9	8.00E+8	1.38E+9
Global Warming Potential (AR5, 100-yr)	kg CO_2 e	4.33E+8	9.13E+8	4.45E+8	9.15E+8	1.61E+8	4.06E+8
Water Consumption	M^3	1.37E+7	2.81E+7	1.42E+7	2.84E+7	5.85E+6	1.30E+7
Photochemical Smog Formation Potential	kg O_3 e	2.67E+7	5.32E+7	2.73E+7	5.33E+7	9.51E+6	2.29E+7
Eutrophication Formation Potential	kg N e	7.44E+5	1.59E+6	7.61E+5	1.59E+6	4.59E+5	9.00E+5
Acidification Formation Potential	kg SO_2 e	1.28E+6	3.07E+6	1.32E+6	3.06E+6	4.63E+5	1.41E+6
Particulate Matter Formation Potential	kg $PM_{2.5}$ e	3.10E+5	6.24E+5	3.16E+5	6.24E+5	1.03E+5	2.62E+5
Ozone Depletion Potential	kg CFC-11 e	9.36E+1	5.81E+2	9.62E+1	5.70E+2	3.50E+1	3.16E+2

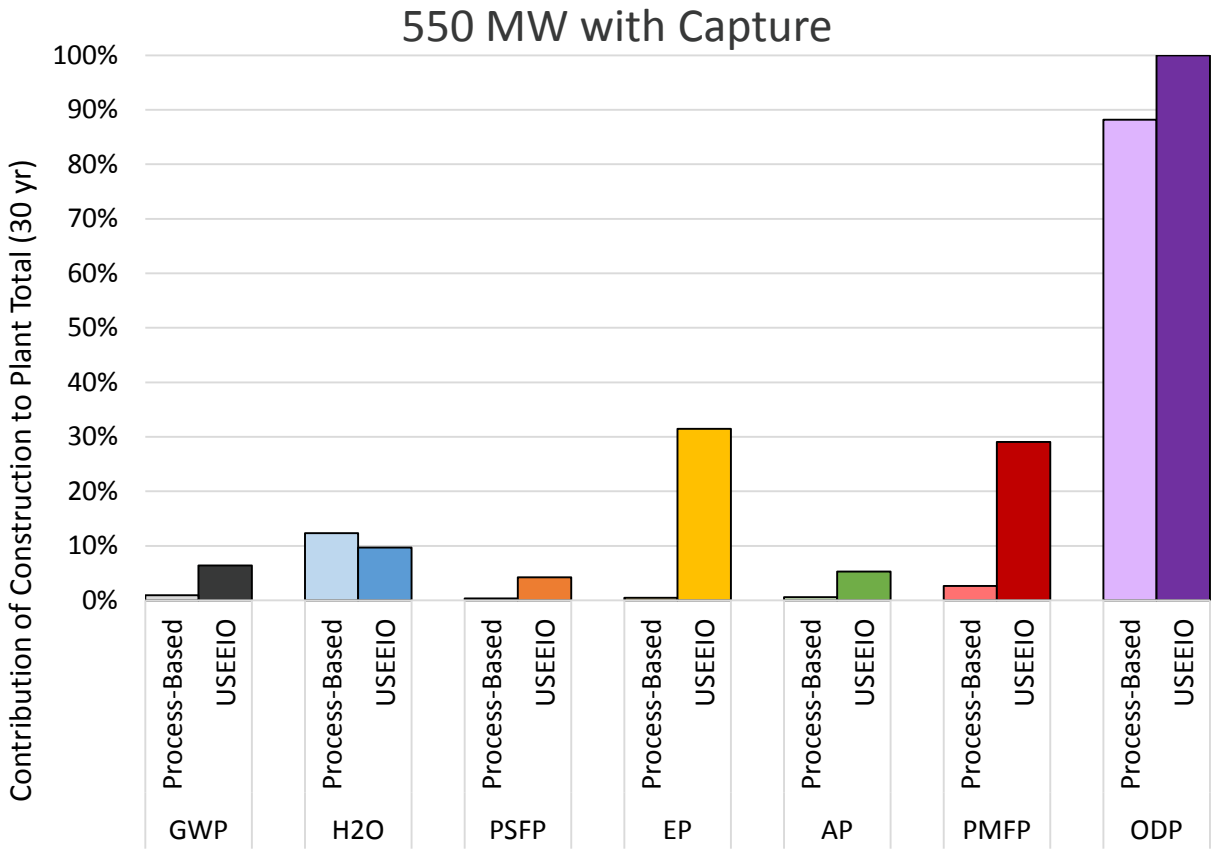


- These values are not normalized
  - NGCC Plant is slightly larger than PC Plants
- Adding carbon capture increases the infrastructure impacts significantly
  - Even more important with reduced combustion emissions

Infrastructure Impacts - SCPC

Contribution of Construction to Life Cycle Impacts

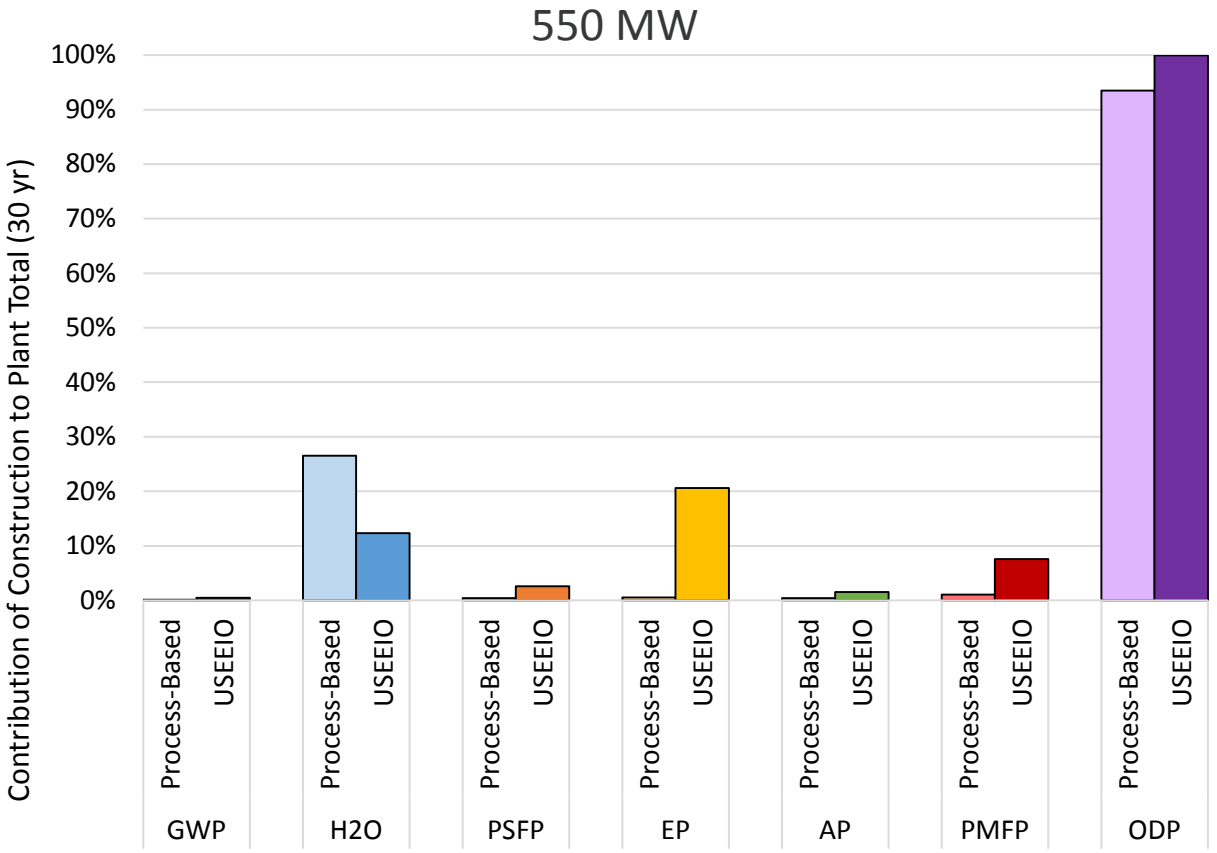


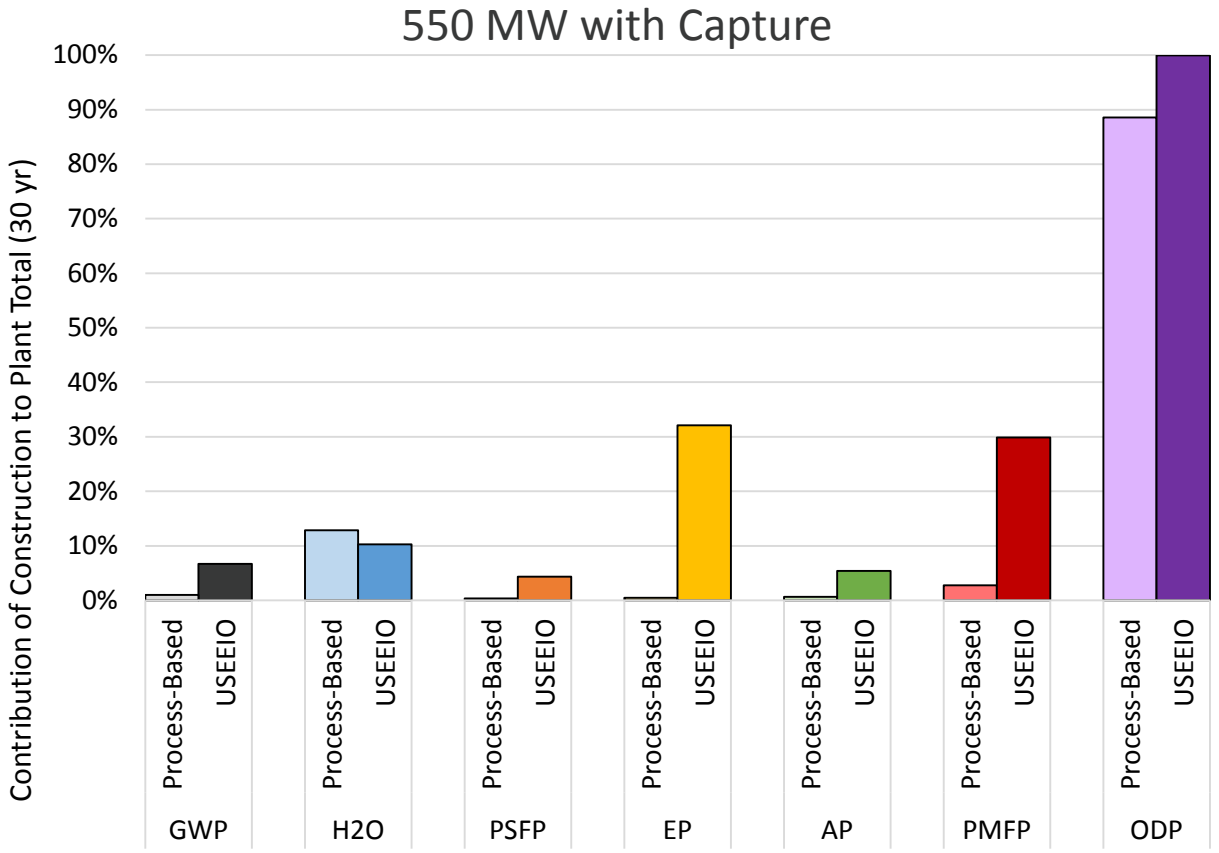


- USEEIO model shows additional EP and PMFP emissions, lower H_2O
- Addition of capture yields more infrastructure contributions to LC

Infrastructure Results - SubPC

Contribution of Construction to Life Cycle Impacts

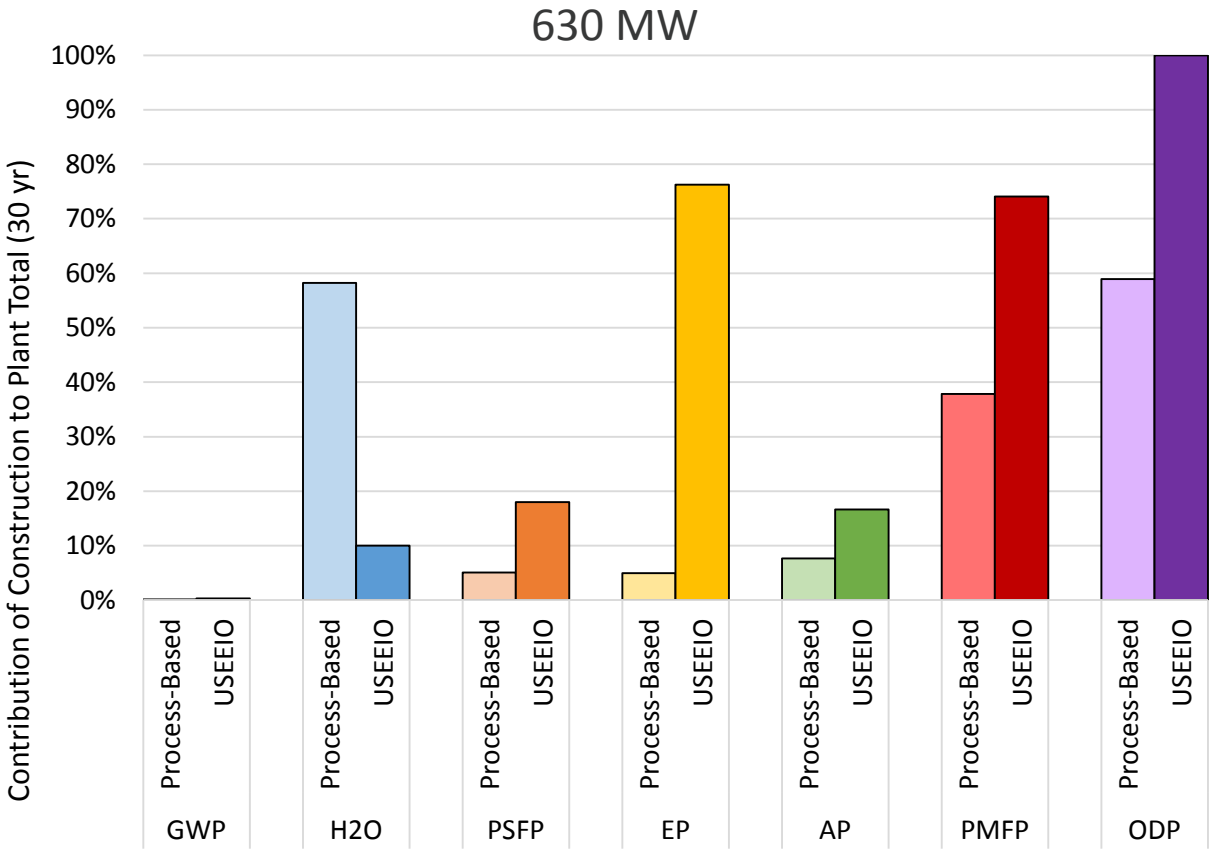


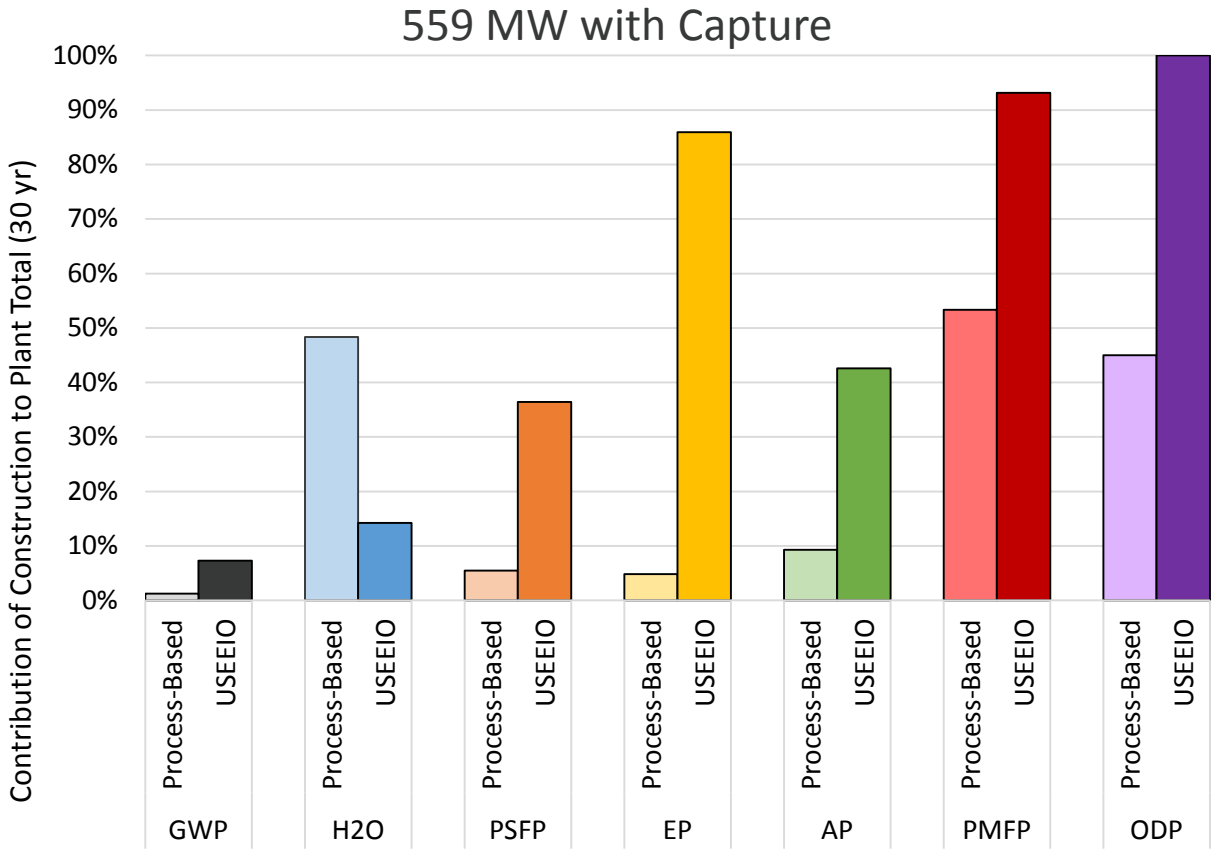


- USEEIO model shows additional EP and PMFP emissions, lower H_2O
- Addition of capture yields more infrastructure contributions to LC

Infrastructure Results - NGCC

Contribution of Construction to Life Cycle Impacts





- USEEIO model shows additional EP and PMFP emissions
- Addition of capture yields more infrastructure contributions to LC

SCPC 550 MW

Comparison of Select Releases: Process-Based Model vs. USEEIO for Construction

Select Releases	UP kg per Plant	USEEIO kg per plant	Ratio USEEIO to UP
Ammonia	145.2	28,994	200
Barium	1.7	0.71	0.42
Carbon Dioxide	1.10E+08	3.76E+08	3.4
Carbon Monoxide	1.10E+08	1.65E+06	0.02
Nitrogen Dioxide	1.20E+03	9.94E+05	828
Sulphur Dioxide	2.10E+05	5.44E+05	2.6
Organic Emissions to Air (Group VOC)	3.20E+05	5.55E+05	1.7
Methane	3.10E+05	1.41E+06	4.5
Particles to Air	1.30E+05	4.03E+05	3.1

- USEEIO shows higher gate-to-gate construction impacts across most releases than the simplified process-based model

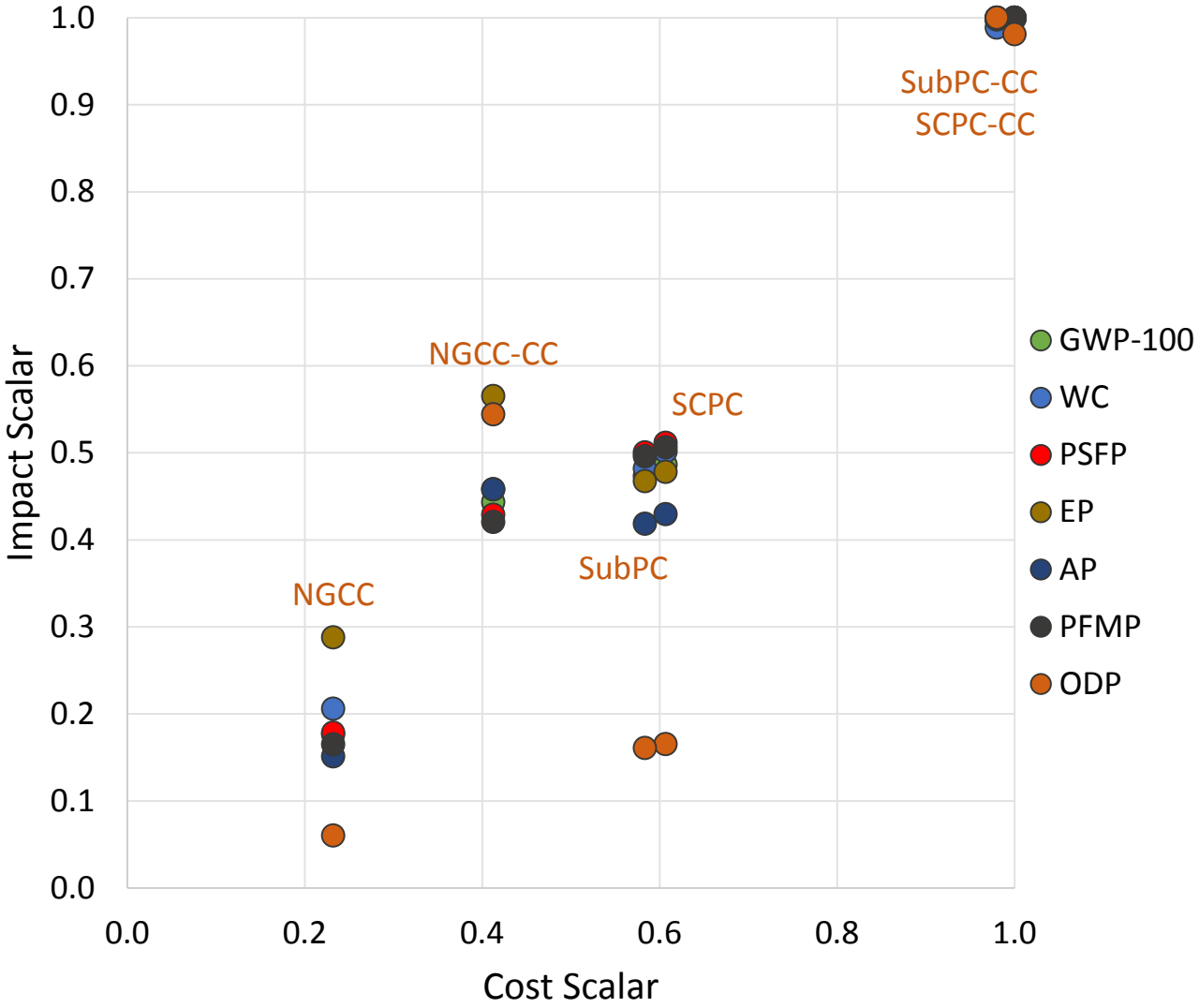
Contribution to Nitrogen Oxides Emissions

SCPC Infrastructure Life Cycle Emissions by Industry Sector

Industry	Contribution to NOx emissions
Truck transport	19%
Other nonresidential structures	16%
Cement	12%
Rail transport	8%
Unrefined oil and gas	8%
Electricity	8%
Clay and ceramic products	5%
Primary iron, steel, and ferroalloy products	4%
Water transport (boats, ships, ferries)	3%

- **USEEIO enables users to break down the life cycle emissions by sector**
- **Enables hot-spot analysis where process-based models can be used to create a hybrid analysis**

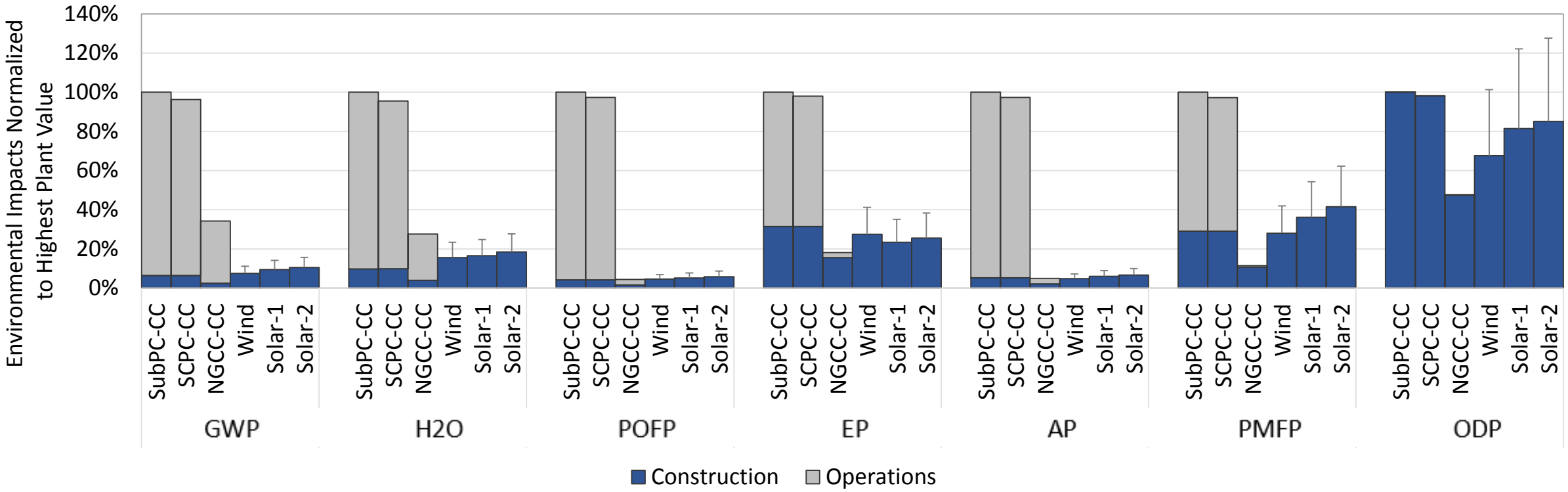
Impacts Across Plants (per Dollar)



Impact Category	Impact Category	Units	Impact per USD	R^2
Global Warming Potential (AR5, 100-yr)	GWP-100	kg CO_2 e	0.63	0.96
Water Consumption	WC	m^3	0.019	0.96
Photochemical Smog Formation Potential	POFP	kg O_3 e	0.037	0.98
Eutrophication Potential	EP	kg N e	9.40E-04	0.88
Acidification Potential	AP	kg SO_2 e	2.20E-03	0.93
Particulate matter Formation Potential	PMFP	kg $PM_{2.5}$ e	4.40E-04	0.98
Ozone Depletion Potential	ODP	kg CFC-11 e	4.40E-07	0.7

Contribution to Impacts per MWh

USEEIO modeling for construction impacts



- **Impacts of life cycle construction compared to the gate-to-gate emissions from power plant operations – normalized to the plant with the highest emissions per MWh**
  - Wind and Solar plants have no operations emissions
- **Uncaptured power plants are not shown as the construction impacts are <1%**

Discussion and Conclusions

- **This USEEIO based tool offers an easy and reliable method to estimate construction and infrastructure emissions for power plants and expand inventory**
  - Can also be used to point to hot-spots where process-based data can be used to make hybrid models
- **Construction and other services are important to the life cycle of the power plant**
  - Previous simplified process-based models were underestimating important emissions (e.g. CO_2 was underestimated by a factor of 3.4 for SCPC plants
- **Construction accounts for <1% of impacts for fossil power plants**
  - The addition of CCS with 90% capture increases the net and relative construction GHG emissions to 7-8% for fossil energy
- **Future work could focus on decommissioning impacts for power plants**

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