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

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Table S1. Summary of GHG results—AR5 100-year GWP (kg CO_2e/MWh).

Process	Japan				Korea				Taiwan				Japan with Carbon Capture			
	PRB	AU	ID-Adaro	ID-Mulia	PRB	AU	ID-Adaro	ID-Mulia	PRB	AU	ID-Adaro	ID-Mulia	PRB	AU	ID-Adaro	ID-Mulia
Mining	6.78	27.00	17.38	21.99	6.78	27.00	17.38	21.99	6.78	27.00	17.38	21.99	9.45	36.84	24.22	31.18
Coal Cleaning	N/A	0.17	N/A	N/A	N/A	0.17	N/A	N/A	N/A	0.17	N/A	N/A	N/A	0.23	N/A	N/A
Truck Transport	N/A	N/A	2.02	2.56	N/A	N/A	2.02	2.56	N/A	N/A	2.02	2.56	N/A	N/A	2.82	3.63
Rail Transport	16.90	1.51	N/A	N/A	16.90	1.51	N/A	N/A	16.90	1.51	N/A	N/A	23.55	2.06	N/A	N/A
Barge Transport	N/A	N/A	1.87	2.36	N/A	N/A	1.87	2.36	N/A	N/A	1.87	2.36	N/A	N/A	2.60	3.35
Export Terminal	0.38	0.30	0.39	0.49	0.38	0.30	0.39	0.49	0.38	0.30	0.39	0.49	0.53	0.41	0.54	0.70
Ocean Transport	32.59	26.50	19.65	24.87	34.90	28.09	18.38	23.26	40.90	25.89	12.58	15.91	45.41	36.17	27.39	35.26
Import Terminal	0.38	0.30	0.39	0.49	0.38	0.30	0.39	0.49	0.38	0.30	0.39	0.49	0.53	0.41	0.54	0.70
Power Plant	807.34	778.57	812.64	842.39	807.34	778.57	812.64	842.39	807.34	778.57	812.64	842.39	125.24	118.96	125.52	132.11
Saline Aquifer Sequestration	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	14.36	16.65	14.49	15.24
Total	864.38	834.36	854.33	895.15	866.68	835.94	853.06	893.54	872.68	833.74	847.26	886.20	219.06	211.74	198.12	222.16

Table S2. Energy use for reference mine [1–3].

Energy Source	Equipment	Overburden Removal	Coal Extraction	Reclamation	Total	Units
Electricity	Dragline	7.04×10^{0}	0.00×10^{0}	0.00×10^{0}	7.04×10^{0}	kWh/ton
	Cable Shovel	2.34×10^{0}	5.85×10^{-1}	0.00×10^{0}	2.92×10^{0}	
	Rotary Drill	3.82×10^{-1}	9.55×10^{-2}	0.00×10^{0}	4.78×10^{-1}	
	Total	1.08×10^{-5}	7.50×10^{-7}	0.00×10^{0}	1.15×10^{-5}	MWh/kg
Diesel	Dump Trucks [1]	2.08×10^{4}	5.20×10^{3}	0.00×10^{0}	2.60×10^{4}	Btu/ton
	Bulldozer	9.44×10^{3}	0.00×10^{0}	2.36×10^{3}	1.18×10^{4}	
	Pick-up Trucks	1.24×10^{3}	4.97×10^{2}	1.24×10^{3}	2.98×10^{3}	
	Water Tankers	8.64×10^{2}	2.16×10^{2}	0.00×10^{0}	1.08×10^{3}	
	Pumps	2.77×10^{2}	1.11×10^{2}	2.77×10^{2}	6.65×10^{2}	
	Service Trucks	2.44×10^{2}	9.77×10^{1}	2.44×10^{2}	5.86×10^{2}	
	Bulk Trucks	4.69×10^{2}	1.17×10^{2}	0.00×10^{0}	5.86×10^{2}	
	Graders	4.16×10^{1}	1.04×10^{1}	0.00×10^{0}	5.20×10^{1}	
	Total	8.53×10^{-4}	1.60×10^{-4}	1.05×10^{-4}	1.12×10^{-3}	kg/kg

[1] Dump trucks are assumed to have engines greater than 750 horsepower (hp) [4]. When EPA Tier IV standards are applied in this model, dump trucks will have different emission profiles than diesel equipment with engines that are less than or equal to 750 hp.

Table S3. Diesel engine and fuel parameters.

	United States	Australia	Indonesia
U.S. EPA Title IV Phase—In Years For Mining Equipment			
50% Engine Conversion	2022–2027	2034–2039	N/A
100% Engine Conversion	2027–2050	2039–2050	N/A
U.S. EPA Title IV Phase—In Years For Line-Haul Locomotives			
50% Engine Conversion	2020–2025	2028–2033	N/A
100% Engine Conversion	2025–2050	2033–2050	N/A
Diesel Fuel Specifications For All Engines			
Sulfur Concentration (ppm) [1]	15	10	3500

[1] Sulfur content in diesel fuel impacts SO_x emissions. It is assumed that SO_x emissions from diesel fuel are in the form of SO_2, because the equation used only accounts for SO_2.

Table S4. Grid mix for electrically-powered equipment [1].

Power Source	PRB Region—Powder River Energy Corp. Mix	Australian National Mix
2020		
Coal	42.4%	63.8%
Natural Gas	22.0%	18.4%
Petroleum	0.4%	1.1%
Nuclear	20.4%	0.0%
Hydroelectric	7.4%	7.0%
Renewables	7.8%	8.6%
2040		
Coal	36.8%	64.5%
Natural Gas	26.5%	14.5%
Petroleum	0.3%	0.9%
Nuclear	18.4%	0.0%
Hydroelectric	6.5%	5.4%
Renewables	10.0%	13.0%

Note: [1] It is assumed that Indonesian coal mines are not connected to the electricity grid [5].

Table S5. Ocean transport distance (km).

Destination	PRB—Longview, WA	Australia—Newcastle	Indonesia—Tanjung Bara
Japan—Yokohama	7892	8075	4683
Korea—Pohang	8451	8558	4380
Taiwan—Keelung	9904	7888	2997

Table S6. NETL PPFM model output by coal source.

Parameter	U.S. PRB						Australia		Indonesia	
	Decker	Spring Creek	Black Thunder South	Black Thunder	Antelope	North Antelope/Rochelle Complex	Hunter Valley	Ensham [1]	Adaro	Mulia
Inputs (kg/MWh busbar)										
Coal	414	393	416	417	418	419	329	333	421	532
Ground Water In	532	531	531	531	531	531	527	526	532	538
Municipal Water In	532	531	531	531	531	531	527	526	532	538
Limestone	4.11	2.44	1.72	2.97	1.99	1.82	3.81	4.82	1.3	1.65
Ammonia	0.97	0.96	0.97	0.97	0.97	0.97	0.93	0.93	0.98	1.01
Activated Carbon	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07
Natural Gas	0.14	0.14	0.14	0.14	0.14	0.14	0.13	0.13	0.14	0.14
Outputs (kg/MWh busbar)										
CO_2	800	796	799	800	800	801	772	772	806	835
NO_x	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
SO_2	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
PM	0.03	0.02	0.02	0.03	0.02	0.02	0.05	0.05	0.01	0.02
Mercury	0	0	0	0	0	0	0	0	0	0
Wastewater	223	222	222	223	222	222	222	222	223	224
Ash	29	22	22	27	26	22	52	49	11	24
Plant Specifications										
Gross power (MW)	578	580	578	578	578	577	596	597	573	557
Net power (MW)	550	553	551	550	551	550	569	569	547	529
Net plant efficiency	39.9%	40.1%	40.0%	39.9%	39.9%	39.9%	41.2%	41.3%	39.6%	38.4%

Note: [1] Hunter Valley and Ensham coal have nearly identical specifications; thus only Hunter Valley is modeled for this analysis.

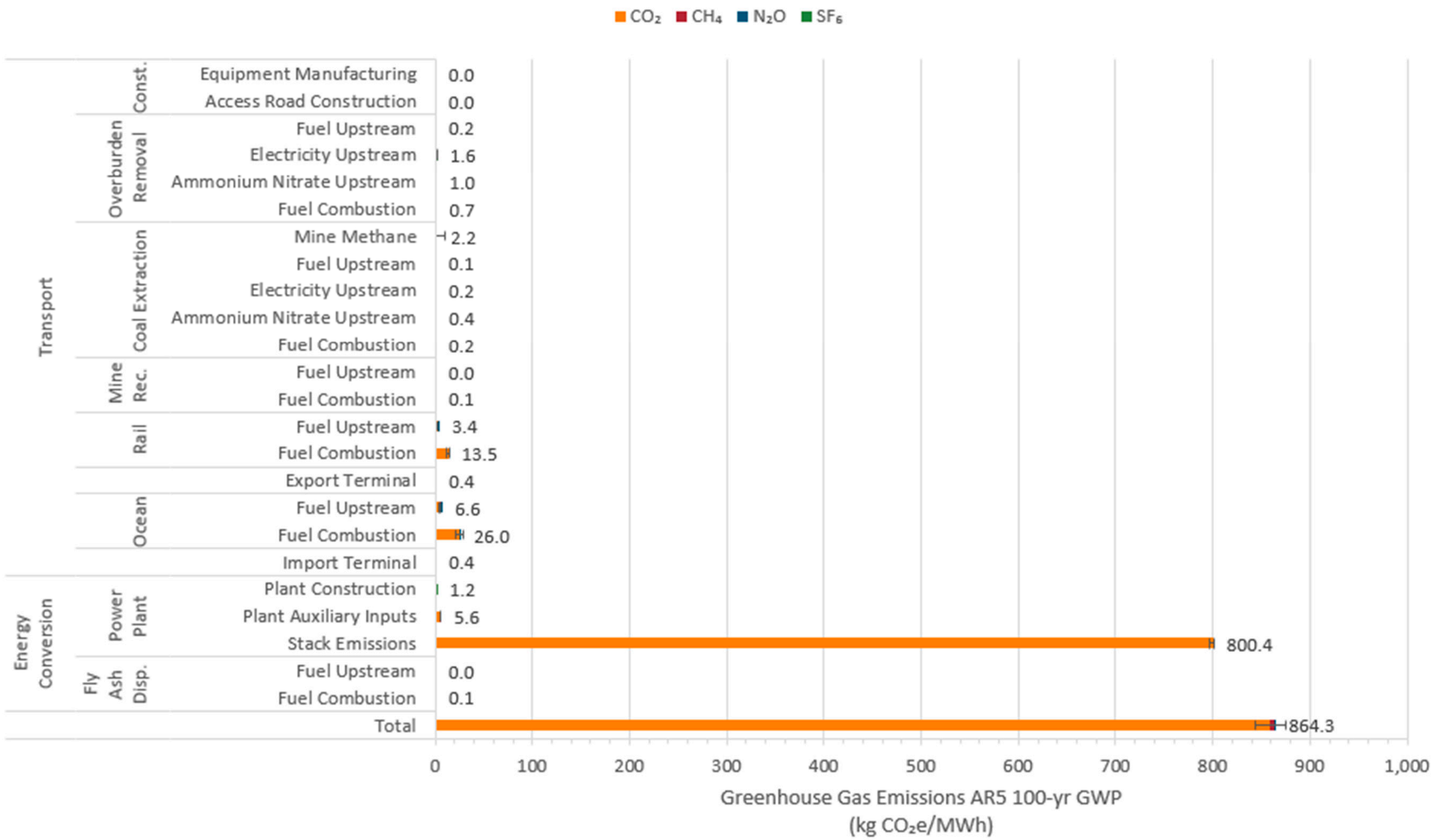

Figure S1. Cradle-to-busbar LCA results for PRB coal exported to Japan (Abbreviation Key: Fly Ash Disp.—Fly Ash Disposal, Mine Rec.—Mine Reclamation, and Const.—Construction).

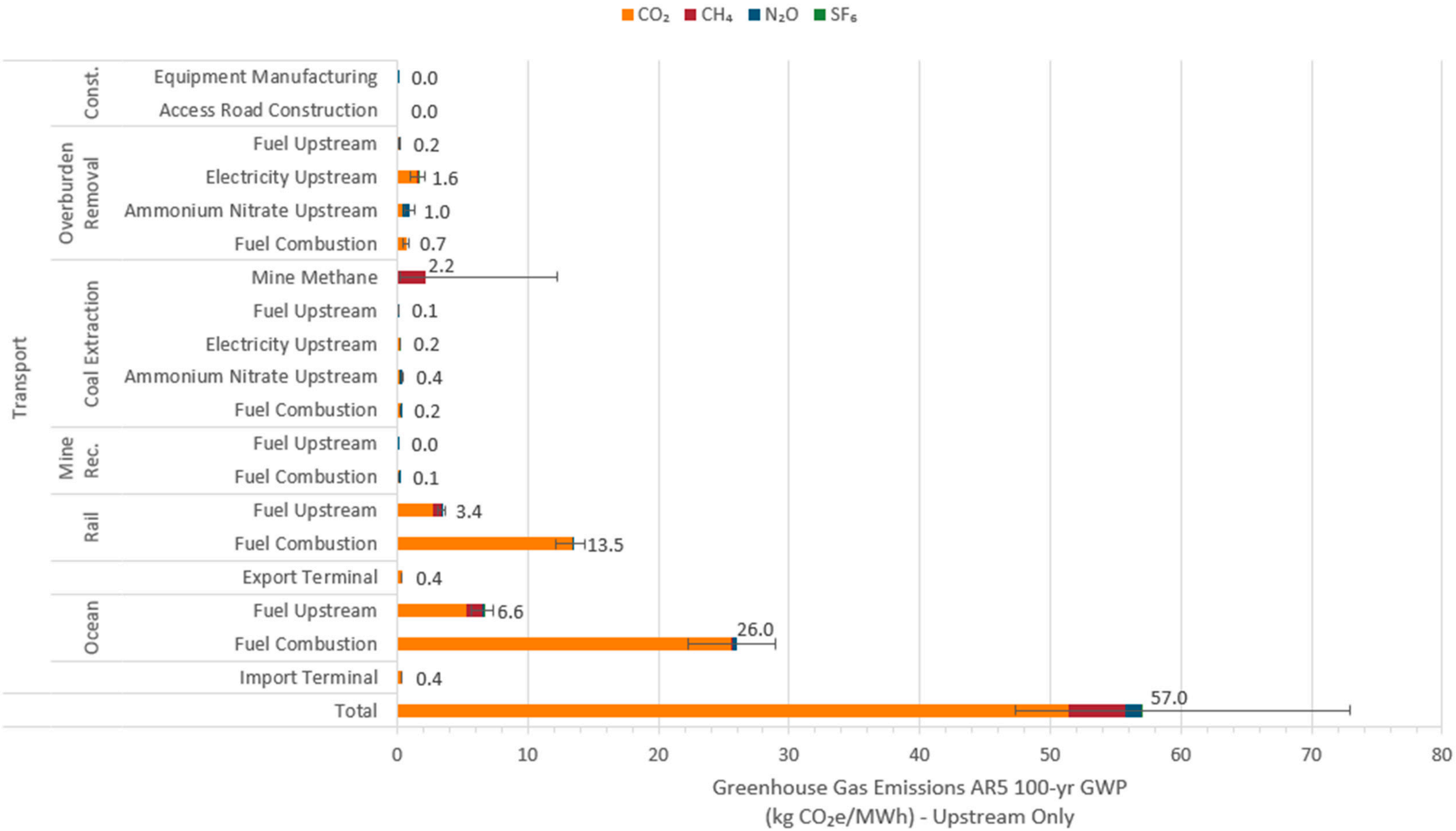

Figure S2. Cradle-to-busbar LCA results for PRB coal exported to Japan—upstream results only (Abbreviation Key: Mine Rec.—Mine Reclamation and Const.—Construction).

For the TRACI Acidification impact category (measured in SO_2 equivalents (SO_2e)), shown in Figure S3, 43 to 64 percent of the impacts come from SO_2 and 35 to 57 percent come from NOx. Power plant combustion accounts for 42 to 63 percent of the SO_2 emissions and rail transport accounts for 3 to 34 percent of NOx emissions (depending on Tier IV diesel engine standards implementation).

The acidification impacts are slightly higher for the Australian and Indonesian sources due to delayed or no implementation of Tier IV diesel engine standards. As a result of the higher strip ratios for Australian and Indonesian coal and higher diesel use for Indonesian extraction, the mining activities account for a larger percentage of the total acidification impacts at 13 percent and 17 to 23 percent, respectively.

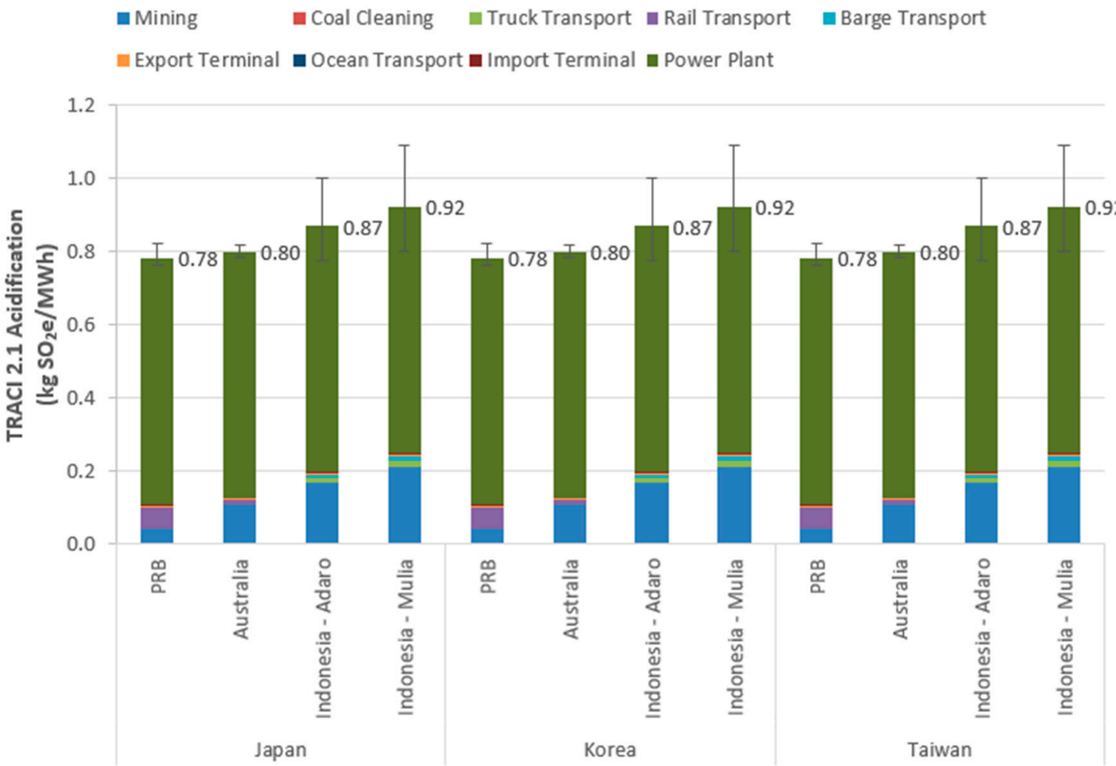

Figure S3. TRACI 2.1 acidification results with ocean transport removed.

The TRACI Human health particulates impact category (measured in PM2.5 equivalents (PM2.5e)) are shown in Figure S4. The majority of PM health impacts are caused by PM2.5 at 68 to 88 percent (Humbert, 2009). For PRB, 5 to 63 percent of particulate emissions come from transport and 27 to 72 percent comes from power plant combustion. For Australia, the majority of emissions are from power plant operations and for Indonesia, the majority of emissions come from mining.

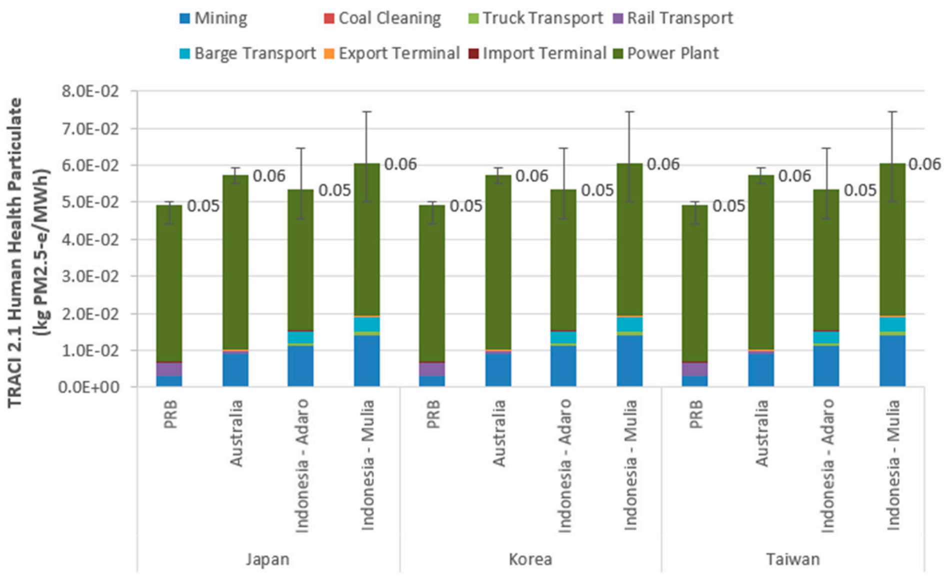

Figure S4. TRACI 2.1 Human Health particulate results with ocean transport removed.

For the TRACI Smog formation (ground-level ozone (O_3)) impact category (measured in O3 equivalents (O3e)), shown in Figure S5, 99 percent of the impacts come from emission of NO_x. For the PRB cases, rail transport accounts for 10 to 51 percent of the smog formation impacts, while power plant combustion accounts for 40 to 77 percent. As a result of the higher strip ratios for Australian and Indonesian coal and higher diesel use for Indonesian extraction, the mining activities account for a larger percentage of the total smog formation impacts at 24 percent and 29 to 34 percent, respectively.

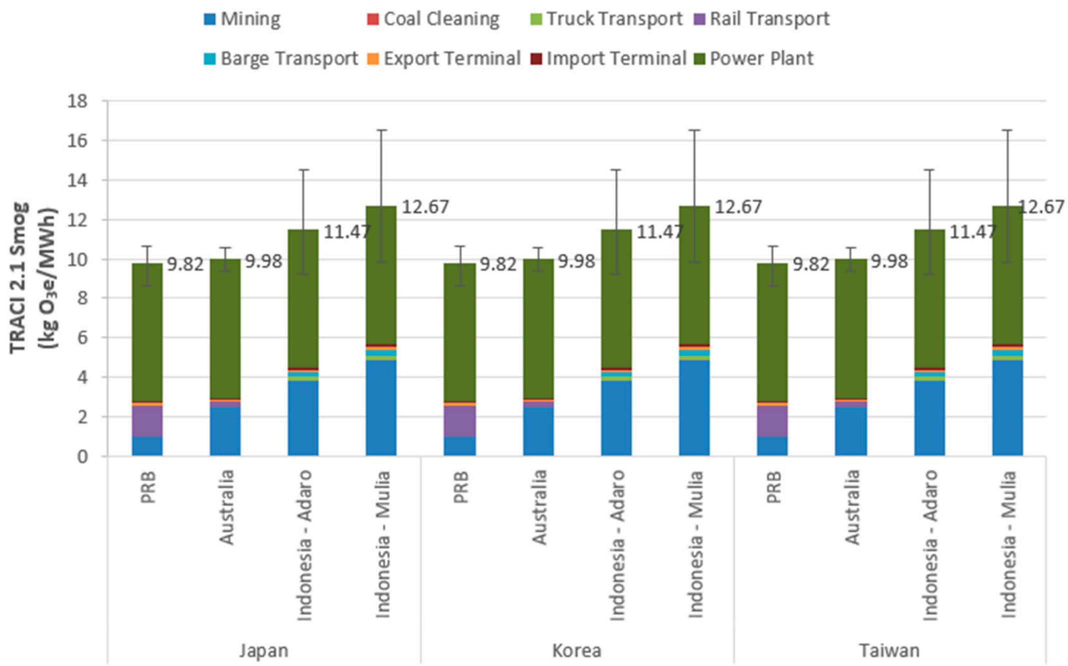

Figure S5. TRACI 2.1 Smog Formation results with ocean transport removed.

Percent hydrogen values for coal in Table 1, were calculated using the equation,

$$0.036C + 0.086(VM - (0.1A)) - 0.0035M^2(1 - 0.02M) \quad \text{(S1)}$$

where C is the percent of fixed carbon, VM is the percent of volatile matter, A is the percent ash, and M is the percent moisture in the coal [6].

The coal mine methane value described in Section 4.3 for Indonesia was calculated as follows:

$$[(4\ \text{mmt } CO_2e) \times (1\ \text{mmt } CH_4/21\ \text{mmt } CO_2e) \times (10^6\ \text{Mg } CH_4/1\ \text{mmt } CH_4) \times (2204.62\ \text{lb } CH_4/\text{Mg } CH_4) \times (1\ \text{scf } CH_4/0.042\ \text{lb } CH_4)]/(3.58 \times 10^8\ \text{st coal}) \quad \text{(S2)}$$

where 21 units of CO_2e is equivalent to one unit of CH_4 and the density of CH4 is 0.042 lb/scf [7,8]. It is assumed that all of the direct CO_2e emissions from surface mining is CH_4.

References

1. DOE. *Energy and Environmental Profile of the U.S. Mining Industry*; U.S. Department of Energy: Washington, DC, USA, 2002.
2. Maunder, D. *PRB Coal Extraction Operations*; National Energy Technology Laboratory: Pittsburgh, PA, USA, 2015.
3. USGS. *Estimates of Electricity Requirements for the Recovery of Mineral Commodities, with Examples Applied to Sub-Saharan Arica*; U.S. Geological Survey: Reston, VA, USA, 2011.
4. Miller, K. *Epa Tier IV Requirements and Equipment Engine Size*; Skone, T.J., Pickenpaugh, G., Cooney, G., Ed.; National Energy Technology Laboratory: Pittsburgh, PA, USA, 2015.
5. Mewing, M. *International Coal Specifications and Operations*; Cooney, G., Ed.; National Energy Technology Laboratory: Pittsburgh, PA, USA, 2015.
6. Research Gate. 1.3 Properties of Coal. Availble online: http://www.researchgate.net/publictopics.PublicPostFileLoader.html?id=55101748d5a3f291118b45de&key=099d2483-4e58-44f1-9f50-bd4206c0658f (accessed on 1 July 2015).
7. API. *Compendium of Greenhouse Gas Emissions for the Oil and Natural Gas Industry*; American Petroleum Institute: Washington, DC, USA, 2009.
8. EPA. *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2020*; U.S. Environmental Protection Agency: Washington, DC, USA, 2006.