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Environmental Implications of United States Coal Exports: A Comparative Life Cycle Assessment of Future Power System Scenarios

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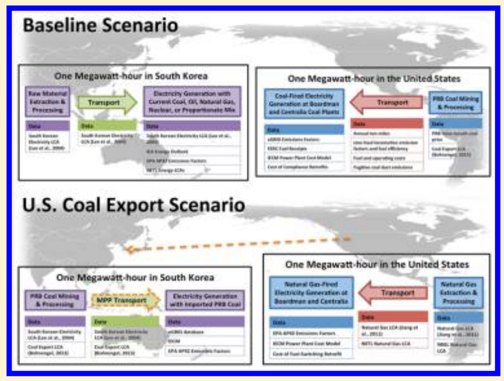
S *Supporting Information*

ABSTRACT: Stricter emissions requirements on coal-fired power plants together with low natural gas prices have contributed to a recent decline in the use of coal for electricity generation in the United States. Faced with a shrinking domestic market, many coal companies are taking advantage of a growing coal export market. As a result, U.S. coal exports hit an all-time high in 2012, fueled largely by demand in Asia. This paper presents a comparative life cycle assessment of two scenarios: a *baseline scenario* in which coal continues to be burned domestically for power generation, and an *export scenario* in which coal is exported to Asia. For the coal export scenario we focus on the Morrow Pacific export project being planned in Oregon by Ambre Energy that would ship 8.8 million tons of Powder River Basin (PRB) coal annually to Asian markets via rail, river barge, and ocean vessel. Air emissions (SO_x, NO_x, PM_{10} and CO_2e) results assuming that the exported coal is burned for electricity generation in South Korea are compared to those of a business as usual case in which Oregon and Washington's coal plants, Boardman and Centralia, are retrofitted to comply with EPA emissions standards and continue their coal consumption. Findings show that although the environmental impacts of shipping PRB coal to Asia are significant, the combination of superior energy efficiency among newer South Korean coal-fired power plants and lower emissions from U.S. replacement of coal with natural gas could lead to a greenhouse gas reduction of 21% in the case that imported PRB coal replaces other coal sources in this Asian country. If instead PRB coal were to replace natural gas or nuclear generation in South Korea, greenhouse gas emissions per unit of electricity generated would increase. Results are similar for other air emissions such as SO_x, NO_x and PM. This study provides a framework for comparing energy export scenarios and highlights the importance of complete life cycle assessment in determining net emissions effects resulting from energy export projects and related policy decisions.



■ INTRODUCTION

Background. Stricter emissions requirements on coal-fired generation resources and low natural gas prices have together contributed to a recent decline in the domestic use of coal for electricity generation in the United States. The share of electricity generated annually by coal combustion declined from 49% in 2007 to 37% in 2012,[1] a year in which coal was displaced by natural gas as the main source of American electricity for the first time in 29 years.[2] The U.S. Energy Information Administration estimates that coal's share of U.S. electricity generation was 39% in 2013.[3]

In the face of a declining domestic market, many coal producing companies have turned to a growing coal export market to fill the demand gap. American coal exports in 2011 totaled 107 million tons, the third most all time and a 30% increase over 2010.

Growth in U.S. coal exports has been driven largely by increased demand in Europe and Asia where coal consumption in the past decade has increased by 4% and 111% respectively.[4] The two regions received a combined 76% of all U.S. coal exports in 2011, and U.S. exports to Asia have more than tripled since 2009.[5] The three top importing countries, China, South Korea, and Japan, have experienced impressive demand growth of 150%, 74%, and 11%, respectively since 2001.[4]

A growing coal export market has sparked new business interest especially on the American west coast, where inexpensive and low-sulfur Powder River Basin (PRB) coal from Montana and Wyoming can be shipped to Asian markets.

The surface-mined, shallow coal deposits of the PRB produced 42% of all U.S. coal in 2011. Wyoming leads all U.S. states in annual coal production by a significant margin.[6]

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In 2011, Wyoming originated 438 million tons, or 40%, of all coal produced in the U.S. The two next highest producing states in 2011 were West Virginia and Kentucky, producing 12% and 9.9%, respectively.[6]

However, Wyoming trails eastern states in production bound for foreign shores. In 2011, the state produced only 4% of total coal exports, while states east of the Mississippi River accounted for 79% of the total.[6] As one would expect, many enterprising firms are showing interest in developing new trade routes to deliver America's cheapest and lowest sulfur coal to its fastest growing market.[7]

There are currently three coal export projects actively planned for Oregon and Washington alone.[7] One of these projects is the Morrow Pacific Project (MPP) proposed by Ambre Energy.[8] The coal-focused Australian energy developer has made significant investments in Wyoming coal mines and now plans to develop infrastructure to ship 8.8 million tons of PRB coal annually to Asia through two Columbia River ports in Oregon.[8]

The MPP takes advantage of existing rail routes historically used to transport PRB coal to the 585 MW Boardman coal plant in Boardman, Oregon, and the 1340 MW Centralia Coal Plant in Centralia, Washington. The two plants are the only existing coal-fired power plants in Oregon and Washington, and both are being closed by 2025 to avoid expensive upgrades required as part of stricter emissions regulations. In 2009, Boardman and Centralia together burned roughly 90% of the coal the MPP will ship at full capacity.[9]

The first leg of the MPP export route would trace the same BNSF and Union Pacific railroad routes historically used to ship PRB coal to the Boardman coal plant. But at full capacity, the MPP would bring four times the amount of coal to the City of Boardman than is currently shipped to the Columbia River port city to supply the aging coal plant. MPP coal would then leave Boardman's port via a series of water vessels likely bound for Japan, Taiwan, China, or South Korea.

The MPP proposal is welcomed by some in the region concerned with unemployment and economic opportunity, but it has also prompted criticism from environmental groups and citizens fearing that impacts from its development and operation will far outweigh associated economic benefits, endanger natural resources, and emit unprecedented levels of air pollution.[10]

Among the environmental questions surrounding energy export proposals, an important consideration is whether closures of U.S. coal plants in response to stricter emissions policies will have the effect of reducing global greenhouse gas (GHG) and other air pollutant emissions if coal that would otherwise be burned domestically is exported instead. In the case of the MPP, impending closure of the only two coal plants in the northwestern U.S. creates the conditions for a useful case study on the net emissions flux following a shift from domestic coal consumption to coal export.

This study explores the difference in air emissions (SO_x, NO_x, PM_{10}, CO_2e) resulting from exporting PRB coal as in the MPP and burning the coal domestically at the Boardman and Centralia coal plants. Comparing the life cycle emissions of burning U.S. coal domestically with those of burning it abroad is naturally complicated by uncertainty with regard to a number of factors, including destination of exported coal, amounts of exported coal, uses for exported coal (steam versus metallurgical), and foreign power plant technology and emissions factors. To address this uncertainty, wherever data is lacking and an assumption needs to be made we have determined both low and high estimates of air emissions corresponding to realistically (e.g., informed by literature values and actual operating data) conservative and optimistic assumptions. For example, a conservative assumption for the annual average heat rate at the Centralia power plant would be 10 878 Btu/kWh as reported for year 2008, whereas an optimistic assumption would be 10 502 Btu/kWh as reported for year 2012. The uncertainty in the estimates at each life cycle stage is propagated through the calculations so that final air emission estimates for each scenario are reported as ranges with both upper (pessimistic) and lower (optimistic) theoretical limits.

Morrow Pacific Project. The MPP would involve shipping coal in three phases: rail, barge, and ocean-going vessel (OGV). Coal first travels via rail approximately 1000 miles from the PRB in Wyoming to Boardman, Oregon, a small port city in eastern Oregon at Columbia River Mile 268. At the Port of Morrow in Boardman, coal is unloaded from trains into a negative-pressure, air-scrubbing storage facility. Coal is then loaded via a closed conveyor system from the storage facility onto covered Columbia River barges roughly 90-feet in length. Barges are then escorted in pairs by assist tugboats 218 miles down the Columbia River (through locks on three Lower Columbia dams unable to accommodate large OGVs) to Port Westward in St. Helens, Oregon. In St. Helens, coal is transferred directly from barges onto Panamax-sized OGVs roughly 150 feet in length using a stationary dry bulk ship loader. OGVs will then travel the remaining 85 river-miles of the Columbia River before entering Pacific waters near Astoria, Oregon. See Supporting Information Figure S1 for a schematic of the transportation phases of the MPP.

As planned, the MPP will operate at partial capacity of roughly 3.9 million tons of coal per year in the first two years of operation. At full capacity, the project is expected to ship 8.8 million tons of coal annually, requiring up to two open top 125-car trains per day, two barges per day, and two OGVs per week.[11] The MPP is currently under review by the Army Corps of Engineers for an operating permit.

Previous Studies. Ambre Energy has commissioned two studies of the MPP from regional consulting firms: an environmental review[12] and an economic impact study.[13] The environmental review considers only impacts related to construction and operation of the storage and conveying terminal at the Port of Morrow in Boardman. The economic impact study considers economic impacts within Oregon borders only.

The objective of this study is to estimate the direct and indirect air emissions of the MPP using a hybrid economic input−output environmental LCA approach, and then to use these estimates to complete a comparative LCA of coal-fired electricity generation in coal export and business as usual scenarios.

■ METHOD

To provide context for the assessment of the environmental impacts of the MPP, this study will compare the conventional air pollutant (CAP) emissions and global warming potential of two different scenarios.

The first scenario represents a baseline where the MPP does not occur and Boardman and Centralia continue operating as coal-fired power plants (following required retrofits to comply with EPA and State rules beyond their scheduled closure dates; we do not consider carbon capture and storage (CCS)

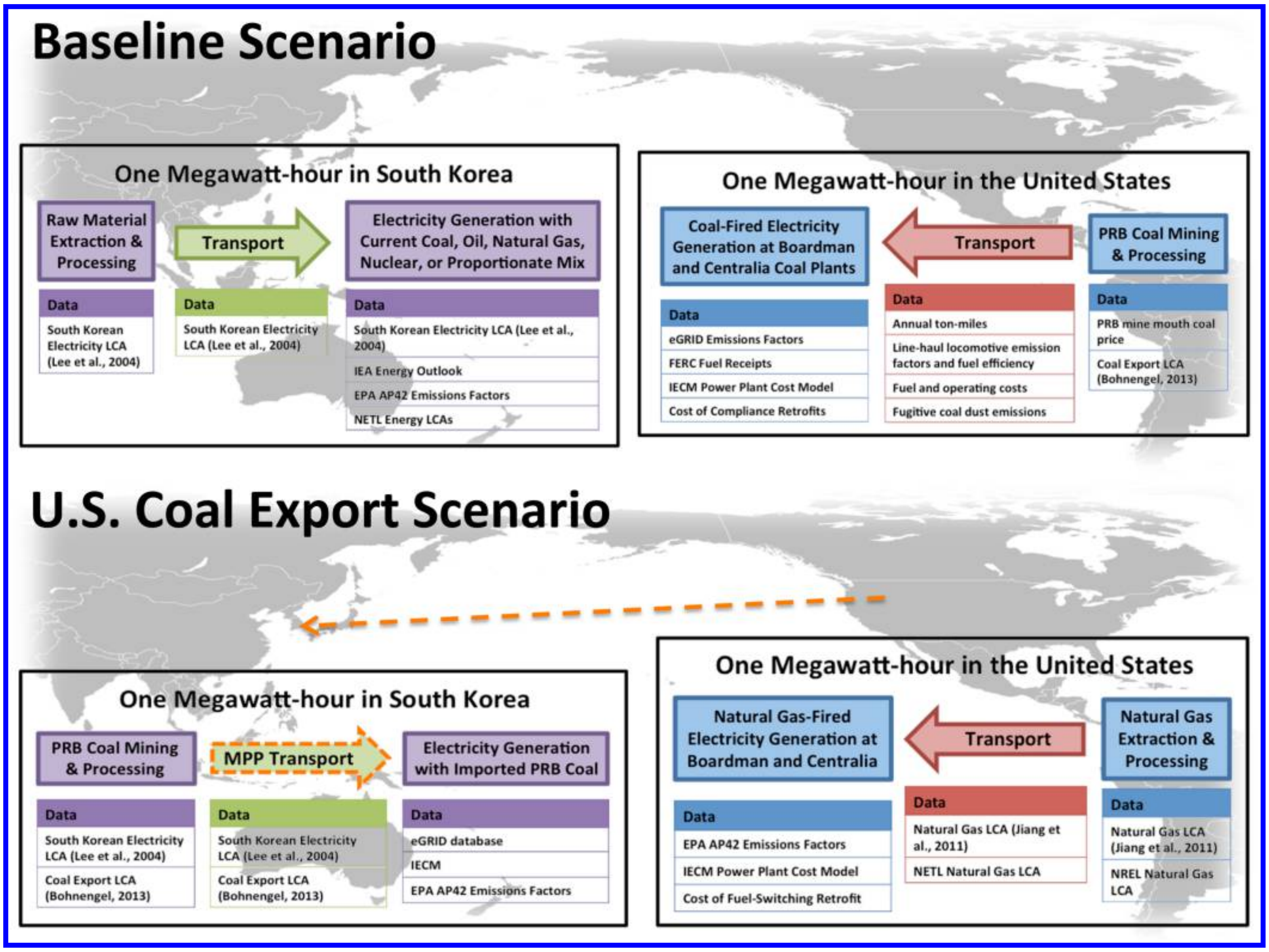

Figure 1. Life cycle boundaries, data sources, and LCA method used for analysis of Baseline Scenario (Scenario 1) and MPP Export Scenario (Scenario 2). Scenario 1 considers life cycle emissions from extraction, processing, transportation, and combustion of PRB coal in the U.S. at Boardman and Centralia coal plants. Indirect emissions associated with the construction phase of the emissions controls installed in order to continue burning coal at these two plants are also included. The South Korean component of this scenario considers displacement of various fuels in South Korea by imported PRB coal and then estimates the resulting emissions per MWh of electricity generated considering extraction and processing of different fuel sources for electricity generation in addition to transport and utilization. Scenario 2 considers the emissions from extraction, processing, transportation, and combustion of natural gas burned in new gas-fired units at Boardman and Centralia, as well as emissions from the construction of new NGCC plants at Boardman and Centralia. The South Korean component of this scenario includes the emissions from extracting and transporting PRB coal to South Korea and from utilizing it at existing coal-fired power plants.

equipment in this study, though CCS could be included as a future assessment). In this scenario, South Korean power plants also continue operations as usual with no additional PRB coal from the U.S.

The MPP export scenario assumes that the U.S. coal-fired power plants at Boardman and Centralia are shut down and replaced with natural gas combined cycle power plants of equal nameplate capacity. It is assumed that the natural gas burned at these plants comes from shale gas. Under this scenario, PRB coal is exported to South Korea and burned at existing coal-fired power plants.

Data and Assumptions. Most data for the MPP was obtained from Ambre Energy project brochures,[14] the environmental review by Anderson Perry & Associates,[12] the economic impact study by ECONorthwest,[13] and through personal communications with a spokesperson for the MPP.[15] Section 2 in the Supporting Information discusses all assumptions in detail. Data on direct and indirect emissions from electricity generation in South Korea and the U.S. is obtained from peer-reviewed literature or reports from U.S. federal agencies and laboratories as explained below.

Hybrid Input–Output Environmental Life Cycle Assessment Model. This study uses a hybrid life cycle assessment (LCA) approach that borrows from both the traditional Society of Environmental Toxicology and Chemistry/Environmental Protection Agency (SETAC/EPA) process-based approach and the economic input–output life cycle assessment (EIOLCA) model developed at Carnegie Mellon University's Green Design Institute.[16] Similar hybrid LCA models have been used to calculate the life cycle economic and environmental impacts associated with coal energy transportation via rail, wire transmission, and gas pipeline,[17] various sources of electricity generation,[18] and electric vehicles.[19] The hybrid LCA approach herein captures the relative advantages of both the SETAC and EIOLCA methods, and combines them in such a way that offsets each method's disadvantages. See further information on hybrid LCA methods in the Supporting Information.

Boundary and Scope Definition. For both scenarios we calculate the emissions resulting from the generation of 1 megawatt-hour (MWh) of electricity in the U.S. at Boardman and Centralia, and the generation of 1 MWh of electricity generated in South Korea. This functional unit is chosen to be consistent with other LCA comparative studies as well as to account for important efficiency differences between South Korean and U.S. power plants.

Figure 1 shows the process flow diagram of the Baseline and MPP scenarios along with the boundaries of this study. In the Baseline scenario, electricity at Boardman and Centralia is generated with PRB coal; and electricity in South Korea is generated using traditional fuel sources. In the MPP export scenario, electricity at Boardman and Centralia is generated by burning natural gas in new replacement NGCC power plants, while PRB coal is exported to South Korea where it displaces some of the fuel previously used for electricity generation in the country.

Baseline Scenario. For the United States component of the Baseline (Figure 1), we consider the impacts of mining coal in the PRB, delivery of coal to Boardman and Centralia, and subsequent combustion at these two existing plants. In this hypothetical Baseline scenario, Boardman would need to be retrofitted with air emissions controls in order to comply with EPA's Mercury and Air Toxics Standards (MATS), the CAIR/CSPR replacement rule, and state air emissions regulations. Therefore, the life cycle air emissions estimates for this scenario include the emissions from building the necessary retrofit controls, as well as the reductions achieved from the operation of these controls (below that of the existing plants). For the South Korean component, we consider the life cycle emissions of existing coal-fired electricity generation in South Korea, including the extraction and processing of coal, transportation, and use in South Korean power plants. To deal with uncertainty regarding the type and amount of fuel that is displaced in South Korea when PRB is imported, we consider five fuel displacement subscenarios: Baseline scenarios 1a through 1d assume that a given MWh in South Korea is generated with coal, oil, natural gas, and nuclear fuel, respectively, and scenario 1e assumes that a given MWh in South Korea is generated with a combination of these fuels proportional to its participation in the current South Korean electricity mix. This partition of the Baseline scenario into subscenarios is necessary to have a more accurate representation of the plausible range of LCA air emissions per MWh of electricity generated in South Korea since numerous studies demonstrate that direct fuel use (of oil, gas, coal) tends to contribute the largest proportion of emissions in the electricity life cycle (see e.g., ref 20).

MPP Export Scenario. Under the MPP export scenario the power plants at Boardman and Centralia no longer burn PRB coal and instead this fuel is shipped to South Korea for electricity generation. For the United States component of the MPP export scenario (Figure 1), we include the emissions of constructing the natural gas combined cycle plants that will replace Boardman and Centralia, as well as the emissions from extracting, transporting, and combusting shale gas for electricity generation. This assumption is consistent with current regional discussions surrounding the replacement of Boardman and Centralia capacity with natural gas-fired plants. For the South Korean component of the MPP export scenario, we consider the impacts of mining PRB coal, delivery to port in Busan, rail transportation to South Korean coal plants, and subsequent combustion for electricity generation.

To fully account for emissions associated with transportation of PRB coal from Wyoming to South Korea under the MPP export scenario, we include in the project scope impacts from construction of conveying and storage facilities, construction of ship-unloading equipment, construction of OGVs, construction of barges, construction of tugboats, fuel production, rail transportation, barge transportation, marine transportation, maintenance of vessels, buildings, and equipment, and combustion at a South Korean coal plant (see Supporting Information section 2 for more information on assumptions and sources used to account for these transport emissions).

Emissions from Construction and Maintenance of Equipment. For this analysis, the EIOLCA model was used to determine sector-specific life cycle environmental impacts from the construction and maintenance of different equipment. In the MPP scenario, this includes the construction and maintenance of vessels, buildings, and equipment, operation of the storage and conveying systems, and construction of the new natural gas power plants replacing Boardman and Centralia. EIOLCA was also used to calculate emissions from coal mining and from fuel production for the three transportation phases (rail, barge, and OGV) of the MPP, as well as emissions from construction of boats, barges, and the facilities themselves. The GREET model and a Chalmers University study were used to validate the fuel production estimates (see Supporting Information section 3). To determine inputs to the EIOLCA model, annual project capital and operating expenditures from the MP scenario were extrapolated to a 20-year pro forma income statement detailing project volumes and fixed and variable costs (See Supporting Information section 2).

In the Baseline scenario, the EIOLCA model is used to estimate the emissions from retrofitting Boardman to continue operation as a coal plant, and for estimating the indirect emissions of the transportation of coal to Boardman and Centralia. Cost estimates of power plant construction and retrofit in the U.S. were obtained from the integrated environmental control model (IECM)[21] (see Supporting Information section 3).

The price of PRB coal was used to estimate impacts from coal mining and related upstream activities within EIOLCA. Fuel costs were used to estimate impacts from fuel refining (e.g., diesel used in OGV) and related upstream activities. Storage and transloading costs were used to estimate impacts from the operation of storage and conveying activities at the MPP ports. Transportation operational costs were used to determine indirect (upstream) impacts from the operation of OGVs, barge, and rail product transport (see Supporting Information Table 1).

The EIOLCA sectors used for each operating and capital cost category are presented in the SI (Table S1). Dollar values were converted to 2002 dollars and used as inputs to the 2002 producer price model of EIOLCA to estimate emissions of GHGs and CAPs.[22]

Emissions from Transportation and Combustion of Coal and Shale Gas in the United States. To incorporate available project specific data, the SETAC/EPA method was used in determining direct emissions during the three transportation phases of the MPP. This includes direct emissions from combustible fuel during rail, barge, and OGV transportation, as well as particulate matter emissions from

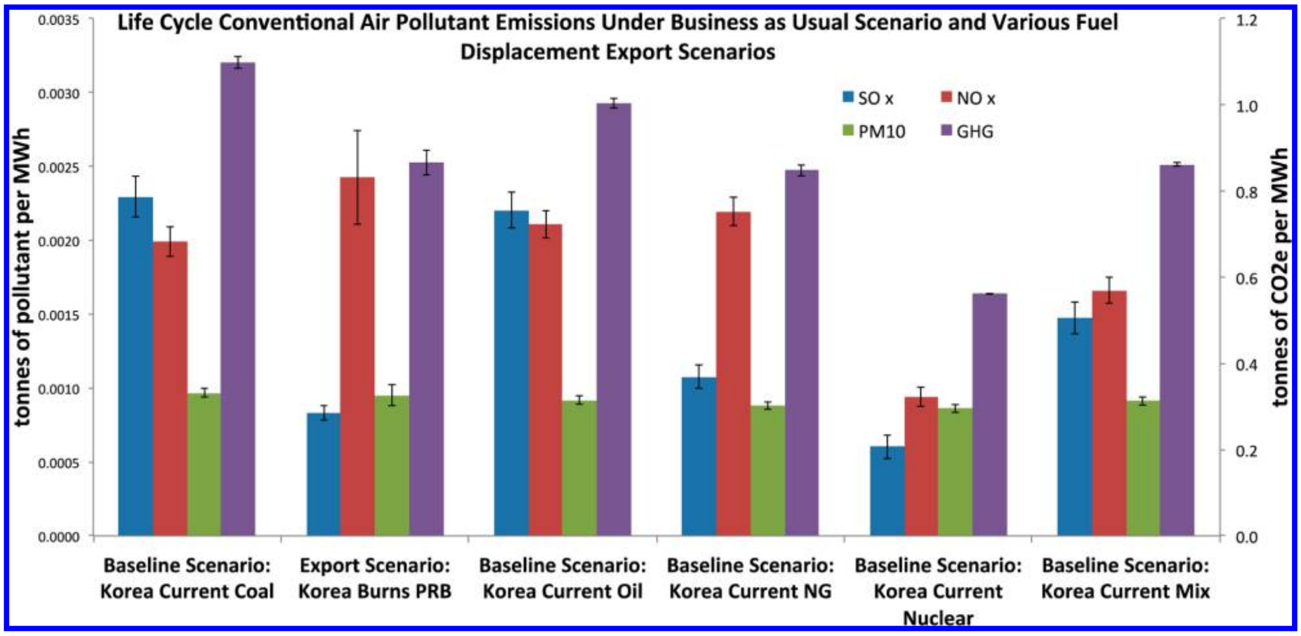

Figure 2. Life cycle conventional air pollutant and GHG emissions under baseline scenarios and MPP export scenario with various fuel displacement assumptions. These results show the average emissions per MWh within the boundary of analysis. For example, in the first Baseline scenario, the emissions estimate per MWh from the coal plants in the US is averaged with the emissions estimate from coal-fired power generation in Korea. Error bars denote low and high estimates of life cycle emissions under the reasonably optimistic and conservative assumptions summarized in the Supporting Information section 4. The GHG emissions represent CO_2 (93%−98% of GWP), CH4 (1%−4% of GWP), and N_2O (0.2%−0.5% of GWP). For GHG over a 20-yr horizon see Supporting Information section 6.

open top coal cars during the rail transport phase. As in Bergerson et al. (2005)[17] these direct emissions were then added to the aforementioned indirect emissions from the three transportation phases, as well as the emissions during construction, maintenance, and storage and conveying activities—all determined using the EIOLCA model.

In determining direct emissions during transportation phases, NREL LCI database emissions estimates for specific mobile combustion sources used in product transport (diesel-powered rail; diesel-powered barge; and residual fuel oil-powered ocean freighter) were used to quantify GHG emissions (CO_2, CH_4, and N_2O) and CAP emissions (SO*x*, NO*x*, and PM10) from operating the trains, barges, and OGVs of the MPP.[23] Fuel emissions factors were validated using EPA sector-specific (locomotive, tug and push boats, and OGV) emissions inventory studies,[24−26] a ship emissions model developed at the National Technical University of Athens Laboratory for Maritime Transport,[27] and industry-level estimates developed by Maersk Lines.[28] Estimates of fugitive coal dust and embedded PM10 from open top rail cars in the MPP were taken from Doctor et al. (2001),[29] and validated using an industry report by Connell Hatch.[30]

Ambre Energy has not been specific with regard to the destinations of the proposed MPP coal shipments. It has mentioned three possible destinations in several project documents: South Korea, Japan, and Taiwan. To date, no specific ports or allocated amounts have been given. This analysis assumes all coal is shipped to the Port of Busan in South Korea, roughly 5500 miles by Panamax vessel from St. Helens, Oregon. Additional rail transportation from Busan to destination South Korean coal plants is assumed in this study to be in the range of 100−300 miles.

GHG emissions from extracting and transporting shale gas in the U.S. (to be used at the new natural gas plants replacing Boardman and Centralia under the export scenario) are obtained from Webber and Clavin,[31] and a meta-analysis of LCA studies of U.S. shale gas are obtained from refs 32−37. SO*x* and NO*x* emissions from natural gas are from Jaramillo et al.[18] Air emissions from combusting PRB coal at Boardman and Centralia are estimated from historical data contained in eGrid.[9] Air emissions that would result from combusting natural gas at the new NGCC plants are estimated using IECM.[21]

Upstream and Direct Emissions from South Korean Electricity Generation. Upstream and direct emissions from existing South Korean power plants burning fuels other than PRB coal are obtained primarily from a study by Lee et al.,[38] which is the most recent SETAC/EPA based estimation of the life cycle emissions inventory of South Korea's electricity resources published in English.

Upstream and direct GHG emissions resulting from South Korean electricity generation not reported in Lee et al. (CH_4, and N_2O) are obtained from EPA AP42 emissions factors[39] and DOE-NETL data for fossil fuels,[40] and a report by the Intergovernmental Panel on Climate Change for hydropower.[41] To complement Lee et al.'s seemingly low-point estimate of direct emissions from coal, oil, and natural gas-fired generation we found a high estimate corresponding to coal plants that have a net heat rate 8% higher (see Supporting Information, section 4).

■ RESULTS

This study estimates and compares the total life cycle emissions of GHGs and CAPs that would occur in both the U.S. and South Korea, when 1 MWh of electricity is generated in each country under Baseline and MPP Export scenarios. Results suggest that exporting PRB coal to South Korea causes significant GHG and CAPs emissions during the transport phase, but that these emissions (with the exception of NO*x*)

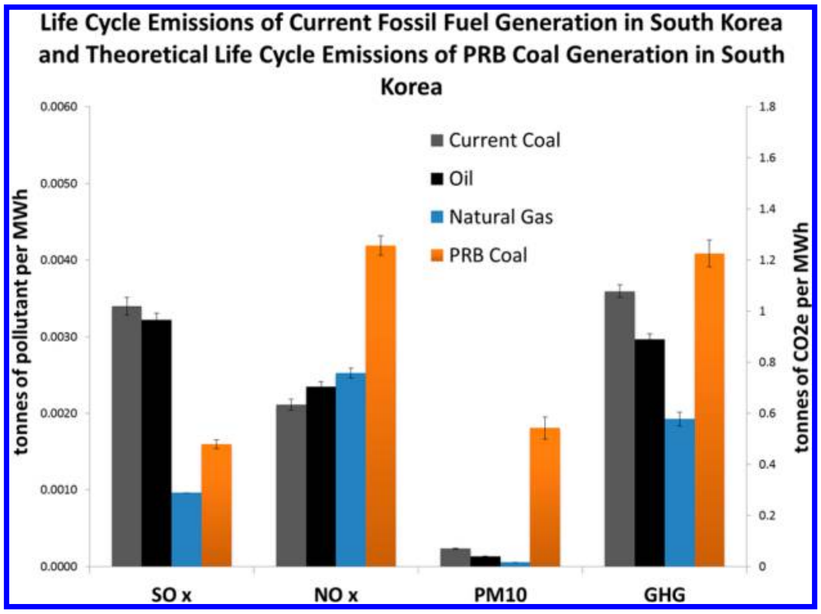

Figure 3. Life cycle emissions of current fossil fuel generation in south korea and theoretical life cycle emissions of PRB coal generation in South Korea. Error bars for PRB coal denote low and high estimates of life cycle emissions under reasonably optimistic and conservative assumptions.

are mostly offset through efficiency gains resulting from the generation of more electricity per ton of PRB coal in South Korea than in the U.S. Only in the case when we assume that an equivalent portion of nuclear power is replaced with PRB coal do we find that the export scenario significantly increases global GHG emissions.

Figure 2 shows that, even after accounting for uncertainty (see Supporting Information section 4), the baseline scenarios have higher or about the same life cycle emissions of sulfur oxides, PM10, and GHG per MWh than the MPP scenario (with the exception of the baseline scenario with nuclear power). The underlying reason for this finding is the major efficiency advantage South Korean coal plants have over the Boardman and Centralia coal plants. Coal is generally burned at much lower heat rates in South Korea than at Boardman and Centralia, and this superior generation efficiency (along with the emissions reductions in the U.S. from coal-to-gas switching) more than makes up for the pollution added during the three transport phases of the MPP. (For a breakdown of emissions by life cycle stage see Supporting Information section 6).

A comparison of emissions scenarios from the perspective of South Korea alone offers a different conclusion. Figure 3 shows a comparison of life cycle emissions of CAPs across scenarios and 100-yr CO_2 equivalent on a per MWh basis across all fossil fuels available in South Korea assuming that the PRB coal is exported to South Korea from the U.S.

From Figure 3, it is clear that if the MPP scenario materializes, PRB coal will be the dirtiest fossil fuel available to South Korean power generators in every emissions category except sulfur oxides. These higher emissions are mostly a result of the emissions associated with the transportation phases, but also a consequence of the increased NO*x*, PM, and CO_2 emissions of PRB relative to the higher rank bituminous coal that constitutes 92% of coal currently used in South Korea. To put the transportation emissions in context, it is worth considering that transporting (not transporting *and* burning) the coal to South Korea to generate electricity as in the MPP export scenario will create 19%−26% of the SO*x* emissions, 117%−140% of the NO*x* emissions, 85%−107% of the PM emissions, and 9.7%−10.2% of the CO_2e emissions that currently result from the entire life cycle of coal mined, transported, and combusted domestically at Boardman and Centralia.

For a similar analysis comparing the emissions scenario from the perspective of the U.S. alone see Supporting Information section 5.

■ DISCUSSION

At full capacity, the MPP would ship 8.8 million tons of coal annually. This level of coal export would represent a 7% increase in current U.S. coal exports and would satisfy roughly 3% of South Korea's total energy needs. The MPP project considered in isolation (just the additional transport of coal from Boardman to S. Korea) would increase the total annual U.S. GHG footprint by 0.033% (see Supporting Information section 7). For context, the average annual growth in U.S. GHG emissions from 1990−2010 reported by the United Nations is 0.4%.[42]

When the MPP project is considered in a broader context that includes coal combustion in Korea, natural gas combustion in the U.S., the amount of electricity produced, and a comparison of an export scenario with a domestic consumption scenario, results take on more meaning. On an emissions per MWh basis, burning PRB coal in South Korea results in about 10% more CO_2e than burning it in the United States. But export of PRB coal actually becomes favorable when widening the boundary of the study to include the rest of South Korea's energy mix and coal-to-gas fuel replacement in the U.S.; the result of capturing these additional considerations in the project scope is that depending on the type of fuel displaced in South Korea, exporting PRB coal as in the MPP can result in as much as a 21% overall reduction in global CO_2e emissions per MWh. These contradictory findings underscore the importance of boundary definitions when conducting LCAs.

Since combustion is the most impact-heavy phase in the life cycle of PRB coal considered here, the efficiency of South Korean coal plants relative to Boardman and Centralia is the main determinant behind the MPP export scenario's advantage in reducing air emissions per unit of electricity generated. If instead of estimating emissions per MWh we had chosen to look at emissions per tonne of PRB coal combusted, the MPP export scenario would not be advantageous (as shown Figure S3 in the Supporting Information). In this case, combusting a tonne of PRB coal in South Korea creates 29%−36% more CO_2e emissions than burning the same tonne in the U.S. As discussed above, this is because combusting 1 tonne of PRB coal in South Korea implies incurring high air emissions from the various transportation phases. But this view would fail to account for the fact that one tonne of coal can be more efficiently converted to electricity in South Korea than in the Boardman and Centralia Plants, and that ultimately the final use of coal in this context is for electricity generation. As the U.S. substitutes coal for shale gas in its electricity generation, the best choice to reduce air emissions would of course be to leave the unused U.S. coal in the ground. But operating under the assumption that in a global market, fuels will flow wherever there is demand, this study suggests that a global citizen concerned about GHG and SO*x*, NO*x*, and PM emissions would prefer a scenario in which PRB coal is combusted in more efficient plants than currently used in the Northwestern U.S.

The significant difference in the impact of the MPP when considered in isolation and as part of a larger system that involves fuel replacement in the U.S. and South Korea highlights the importance of expanding the boundary in a LCA study and the need for analyzing domestic energy policies in the context of the global systems they affect. The difference in conclusions when we look at emissions per tonne of coal instead of emissions per MWh or electricity generation illustrates the importance of the functional unit choice in an LCA study.

In addition to potential overall air emissions benefits, results from the EIOLCA model demonstrate that the MPP export project could bring total direct and indirect economic activity in the United States of more than $25 billion. It would also directly or indirectly create nearly $6 billion in total employee compensation (an average of 3750 $80,000 FTE on an annual basis), $742 million in new tax revenue, and roughly $4.7 billion in profits for all sectors involved (see Supporting Information section 5).

While this study focuses only on air emissions, there are potentially other significant impacts associated with the MPP including water use and quality (ballast water, water used in locks and dams during transport, water used in coal mining, water use and risks from extraction and wastewater disposal from shale gas activities in the U.S.), land use (Port of Morrow facility construction), fish and wildlife (construction on or near water, barging effects on sensitive Columbia River salmon populations), noise, and traffic (rail and river barge). All of these areas are deserving of further research. Also, results presented here have added all the conventional pollutant emissions per MWh as if they were all emitted in the same geographical region. Studies looking at where each of the emissions occur could shed light on the local impacts on air quality, human and ecosystem health in both countries, and in the ocean that serves as a means of transport for the exported coal.

The functional unit emissions inventory provided in this study serves as a basis for comparison with other energy export projects. The MPP, though not complete in its publicly available operational details, is, in the opinion of the authors, currently the most transparent of all Northwest coal export projects being planned. As details develop on additional coal export projects, this study design can be replicated to explore and compare the environmental impacts of all coal export alternatives, all potential coal destinations, and can even be used in an additive sense to explore the impacts of shipping PRB coal to multiple destination countries. In addition, the functional unit chosen for this study can be helpful when looking at other forms of energy export currently being considered, such as liquefied natural gas (LNG) export projects. A consequential approach to LCA[43] may also be appropriate to capture some of the system dynamics resulting from these projects better than an EIOLCA model is able to do.

This analysis could also be expanded to answer policy questions surrounding the strategic use of domestic resources. An expanded study could conduct a comparative LCA of coal and natural gas to explore the question of whether it is environmentally favorable to export coal and burn natural gas domestically, or to export natural gas and burn coal domestically.

Results presented here are limited in precision due to the fact that the MPP is currently in a permitting stage, and therefore many of its operational and financial details are unknown. Results are also limited by the use of EIOLCA, which although supplemented with SETAC-based methods wherever possible, introduces imprecision resulting from the consolidation of the U.S. economy into 428 sectors. As more project specific information is released, the calculations presented here can be updated to form a clearer picture of the impact of this transition on the U.S. energy system and global environmental conditions.

■ ASSOCIATED CONTENT

Supporting Information

Additional tables, figures, data, and assumptions as described in the text. This material is available free of charge via the Internet at http://pubs.acs.org.

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The authors declare no competing financial interest.

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