Should We Transport Coal, Gas, or Electricity: Cost, Efficiency, and Environmental Implications

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We examine the life cycle costs, environmental discharges, and deaths of moving coal via rail, coal gas via pipeline, and electricity via wire from the Powder River Basin (PRB) in Wyoming to Texas. Which method has least social cost depends on how much additional investment in rail line, transmission, or pipeline infrastructure is required, as well as how much and how far energy is transported. If the existing rail lines have unused capacity, coal by rail is the cheapest method (up to 200 miles of additional track could be added). If no infrastructure exists, greater distances and larger amounts of energy favor coal by rail and gasified coal by pipeline over electricity transmission. For 1,000 miles and 9 gigawatts of power, a gas pipeline is cheapest, has less environmental discharges, uses less land, and is least obtrusive.

1. Introduction

1.1. Background. The United States mines over 1 billion tons of coal each year (*1*) to produce 51% (*2*) of its electricity supply. Coal shipments represent more than one half trillion ton-miles each year, since coal deposits are distant from population and demand. This transport requires large amounts of energy, generates pollution emissions, and results in the death of about 400 people each year at rail crossings (calculated from ref *3*). Rail systems are costly to build and maintain; shipping coal by rail constitutes the majority of the cost of delivered Powder River Basin (PRB) coal.

Here, we explore the economic and environmental impacts of alternative options for delivering electricity to demand centers. We examine the implications of shipping energy equivalent to 3.9 million tons a year from the PRB 1000 miles to Dallas.

Several studies have investigated the environmental impacts of power generation systems (*4*, *5*), transmission systems (*6*−*8*), the tradeoffs between alternating current (AC) and direct current (DC) power (*9*, *10*), and the costs and feasibility of new transmission development (*11*, *12*). Amphlett et al. (*13*) investigated the environmental tradeoffs between transmission and rail but did not consider costs. Spath et al. (*14*) include a minemouth generation case in an evaluation of the life cycle impacts of coal-fired power production. However, the study does not include transmission line losses.

We compare four options to provide 6.5 billion kWh of electricity in Dallas from PRB coal: (1) a pulverized coal power plant in Texas, fueled by PRB coal transported by unit trains; (2) a pulverized coal power plant in Wyoming close to the mine, with transmission lines carrying the electricity to Texas; (3) a gasifier and methanation process converts the coal to synthetic natural gas in Wyoming, and the gas is transported to Dallas by pipeline to generate electricity in a combined cycle power plant; or (4) a gasifier, methanation, and combined cycle power plant at the mine to generate electricity, sending the electricity to Texas via transmission lines. Options that were considered but not included in the analysis were a coal slurry pipeline and other clean coal technologies (see Supporting Information for details).

We assume that new generation plants, transmission lines, rail lines, and gas pipelines can be built, despite siting problems. The base case assumes that no infrastructure exists and therefore must be built for all four options considered. This assumption was tested in the sensitivity analysis and is discussed further in this paper. We also assume that all plants satisfy stringent emissions regulations and that the location of the plants does not affect either costs or emissions. Transporting coal requires diesel fuel, while transporting electricity or gas requires additional capacity and coal to make up for transmission and gas pipeline losses. Although the plants are identical (whether located in Wyoming or Texas), the public health implications are quite different, since many more people are exposed to the generation plant located in Dallas.

1.2. Method. We use a hybrid life cycle comparative analysis (LCA) framework to assess the economic and environmental impacts associated with every stage of the production of electricity, from extraction of ore to final disposal of unwanted residuals. This method combines the benefits of the EIOLCA (economic input−output life cycle assessment) (*15*) method with those of the traditional Society of Environmental Toxicology and Chemistry (SETAC)/U.S. Environmental Protection Agency (EPA) approach (*16*). We use the cost and environmental impact data available at a national, aggregated level (by industrial sector) in conjunction with a product analysis of more specific electricity generation options.

We estimate the capital (amortized over the life of the investment), operating and maintenance costs and the social costs of the alternatives. These annualized capital and operating costs were apportioned to the appropriate economic sectors and input into the eiolca.net model (*17*) to determine the "indirect" environmental emissions; these were added to the direct emissions to estimate the life cycle emissions from these four options.

We estimate the discharges and costs from the generation phase of each alternative using the integrated environmental control model (IECM) (*18*). By use of this model, a power plant can be built "virtually" to specifications such as the fuel type, control technologies, and boiler type (for more detail, see Supporting Information).

1.3. Powder River Basin Coal to Dallas: Alternatives. Coal from the Powder River Basin (PRB) is in high demand due to its low sulfur content (<0.4%) (*19*) and low cost. Although the heat content of PRB subbituminous coal is lower (8340 btu/lb on an as-received basis) (*18*) than for bituminous coal, it occurs in massive shallow formations that are inexpensive to extract by surface mining; over 30% (*20*) of U.S. coal is mined in the PRB. In 2000, 27 states received 330 million tons of Wyoming coal, with Texas receiving 50 million tons (*21*). The 67 billion tons (*22*) of extractable coal in

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TABLE 1. General Assumptions for Four Options

parameter	base case assumptions
coal	powder river basin (PRB) subbituminous
distance (PRB to Dallas)	1000 miles
energy content of the coal	8340 Btu/lb
total electricity delivered to Dallas	6.5 BkWh
cost of capital	8%
plant capacity factor	75%
amortization period	30 years
pipeline losses	3%
transmission line losses ($\pm$408 kV HVDC line)	7%

Wyoming is 200 times the current extraction rate.

Wyoming exports 70% of the electricity it generates and 95% (*23*) of the coal it produces. The price of coal at the mouth of a PRB mine is approximately \$7/ton (\$0.42/million BTU) (*24*); the delivered price in Texas is \$17−\$29/ton (\$1.00−\$1.70/million BTU) (*25*).

Table 1 summarizes the general assumptions of the four options considered in this study.

The base case assumes that no infrastructure exists and so 1000 miles of rail, transmission lines (including converter stations), or gas pipeline must be built. The economies of scale in these systems would lower the costs if the transport systems were built and used to capacity, especially for rail and gas pipelines. This is less relevant for the transmission line, since increasing the power flows increases the losses and costs. This assumption is relaxed and discussed later in this text.

An HVDC line was chosen for transmission due to lower losses than the corresponding HVAC system. This is discussed in more detail later in this text.

Table 2 summarizes the specific assumptions for each option. The gross plant capacity is different for each option due to the plant characteristics and the additional power required to compensate for losses. The IECM software used to model the pulverized coal plant assumed it meets new source performance standards and has an efficiency (higher heating value, HHV) of 34%. The overall efficiency of coal by rail is overstated since it does not include the 10 milion gallons of diesel fuel required for transport. The gasification and methanation process is modeled after the Lurgi gasifier and methanation process currently in operation in North Dakota. This fixed-bed gasifier operates under conditions that make it better equipped to handle the high (and variable) ash and moisture content in the PRB coal than a Texaco gasifier. An efficiency (HHV) of 69% was assumed for the methanation process (see Supporting Information). The IECM software models the natural gas combined cycle (NGCC) unit and calculates an efficiency (HHV) of 49%.

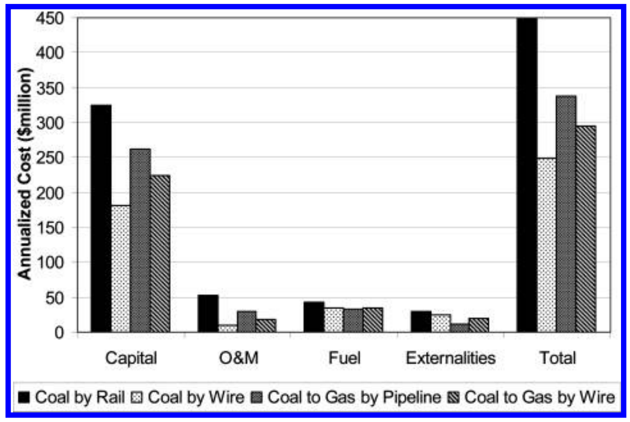

FIGURE 1. Summary of costs for the four methods of transporting energy from the PRB to Dallas, with the assumption of new infrastructure required for each option in the base case.

Other alternatives were considered for this analysis including, coal slurry pipelines, barge, other clean coal technologies, and other transmission technologies (see Supporting Information).

2. Results Section

2.1. Economic Results. Figure 1 summarizes the costs of each option. We present the capital cost of both the plant and the transport infrastructure as an annualized capital cost. Fuel includes the fuel used to transport the energy, either diesel fuel or coal. The externality costs include pollution and CO_2 emissions as well as death and injuries in transportation.

The annualized cost of the capital investments dominates the costs for each option. The coal-by-rail option is the most costly of the four options in the base case. The two transmission options are slightly cheaper than the pipeline option due to slightly lower construction and operating costs. However, these options do not use the full capacity of the new infrastructure: much more coal could be shipped on the rail system, the right of way could accommodate more transmission, and the pipeline could handle much more gas. In each case, spreading the capital costs over more shipments would decrease unit costs. However, increasing throughput would lead, eventually, to congestion with higher costs and losses.

U.S. rail shipments kill about 1000 people each year (*3*). We estimate that coal transport in the coal-by-rail option of the base case would result in 1.4 fatalities per year based on the proportion of freight to passenger travel, percentage of ton-miles of coal shipped in this analysis relative to the total ton-miles of freight transport. Other externality costs include injuries and lost work days due to nonfatal collisions. We found that these unfortunate events did not affect the conclusions from the analysis.

TABLE 2. Assumptions for Each Option for Transporting Energy from Wyoming to Texas

	coal by rail	coal by wire	coal to gas by pipeline	coal to gas by wire
power plant	subcritical pulverized coal	subcritical pulverized coal	gasifier + CC[a]	gasifier + CC[a]
gross plant capacity (MW)	1077	1153	1038	1114
overall efficiency (HHV, %)	34.1	31.7	32.8	31.3
coal required (million tons)	3.9	4.2	4.1	4.3
natural gas produced (Bcuft/yr)	N/A	N/A	48	50
net annual output (BkWh)	6.5	7.0	6.5	7.0
environmental controls[b]	NO_x, particulate matter, SO_2	NO_x, particulate matter, SO_2	sulfur control	sulfur control

[a] Lurgi gasifier and a Natural Gas Combined Cycle Unit. [b] NO_x requires in-furnace controls and hot-side SCR; particulate matter requires a fabric filter; SO_2 requires a lime spray dryer.

TABLE 3. Summary of Annual Fuel Consumption of Transport for Each Option

	fuel		energy			CO_2 eq emissions (million tons)		fuel cost
	add'l coal (million tons)	diesel (million gallons)	coal (trillion BTU)	diesel (trillion BTU)	total (trillion BTU)	CO_2 emissions from fuel only	total CO_2 equiv (million tons)	spent on fuel (million dollars)
coal by rail		10		1.4	1.4	0.13	0.25	15.0
coal by wire	0.28		4.7		4.7	0.51	0.55	2.0
coal to gas by pipeline	0.15		2.5		2.5	0.23	0.30	1.1
coal to gas by wire	0.33		5.5		5.5	0.54	0.57	2.3

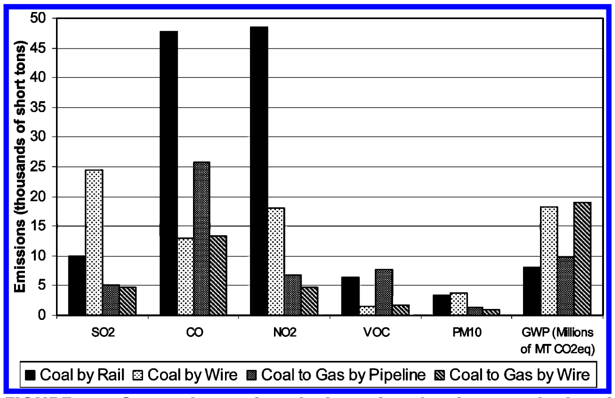

FIGURE 2. Comparison of emissions for the four methods of transporting energy from the PRB to Dallas over 30 years.

The externality costs from air pollution emissions were important but did not affect the conclusion.

2.2. Fuel Consumption. Table 3 shows various aspects of the energy consumed during the transport phase. This includes the diesel fuel consumed by the locomotives as well as the additional coal combustion to compensate for losses. The coal-by-rail option in the base case uses 10 million gallons of diesel fuel, while the other three options use 280 000, 150 000, and 330 000 tons of coal in order to deliver the stipulated amount of electricity to Dallas. At \$11/million BTU, diesel fuel is more than 26 times more expensive than coal at \$0.42/million BTU.

Emissions of CO_2 are shown for the fuel consumed in transport (diesel fuel and additional coal) as well as the total life cycle CO_2 emissions of the options considered. (Note: this includes any additional coal combustion and mining as well as upstream emissions from construction and operation of infrastructure but does not include the base 3.9 million tons of coal that are burned in all four options). The coal by rail option has the smallest CO_2 emissions and has the smallest fraction of the emissions generated during the transport phase of the life cycle.

2.3. Environmental Analysis. Figure 2 shows emissions from each of the options, excluding the emissions from the base electricity generation of 3.9 million tons of coal. These are cumulative emissions for construction of infrastructure and 30 years of operation for all four options. The results for the base case are mixed. For NO_2, volatile organic compounds (VOC), and particulate matter less than 10 microns in diameter the coal-to-gas-by wire option has less emissions; for CO the coal-by-rail option has the lowest emissions followed closely by coal-to-gas-by-wire; for global warming potential (GWP) coal-by-wire option has the lowest, followed closely by the coal-to-gas-by-pipeline. The GWP for coal-by-wire options use the most energy due to the additional generation required to compensate for line losses. A superconducting transmission line or a higher voltage HVDC line with losses less than 4.5% could have lower GWP emissions than coal-by-rail.

These new plants would have to purchase SO_2 allowances each year (\$140/ton was used in this analysis, but the price has recently risen). We translate pollution emissions into dollars using estimates of the social cost of air emissions (*27*). These pollution externality costs are substantial, as shown in Figure 1: The coal-by-rail and coal-by-wire transmission options have externality costs of \$17 and \$20 million per year, respectively. Gasifying the coal and then burning it in a NGCC unit would have lower externality costs.

Between 17 000 and 24 000 acres would be cleared and used for the transmission towers and lines, but much of this land could be used for other purposes (e.g., farming or ranching). Pipelines require less land and are virtually unobtrusive when buried. Rail road bed would be the most obtrusive because of the pollution, noise, and impediment to traffic. We have not quantified the environmental disruption and other land-use impacts.

In addition to accounting for the combustion of diesel fuel, we consider the life cycle impacts of producing the diesel fuel (*15*).

3. Generalization within PRB to Dallas

3.1. Break-Even Distances and Volumes. The U.S. rail infrastructure, particularly from the PRB to Texas, is extensive. Carrying 3.9 million tons of PRB coal to Texas requires just over one unit train per day, adding little congestion. If there are bottlenecks, tripled or quadrupled track could be added. We estimate that at most perhaps 100 miles of new track would have to be added. Thus, considering the existing infrastructure, coal by rail would be cheapest. However, if more than 200 miles of rail bed had to be added, building the transmission system would be cheaper. The environmental emissions would be less affected by the amount of new rail capacity that was added since the emissions are dominated by the amount of diesel fuel that is burned during the transport phase.

If there is not infrastructure in place, the cost of the rail infrastructure in this analysis decreases when it is spread over a greater number of shipments. Figure 3 shows that, to deliver more than 3000 MW, coal-to-gas-by-pipeline is the cheapest alternative. Coal-to-gas-by-wire is not competitive. In the competition between coal-by-rail and coal-by-wire, the latter is cheaper up to 9000 MW. This analysis assumes that all of the rail shipments could fit on one dedicated rail bed, that a new transmission line would be needed for each additional 1000 MW (a transmission corridor could handle multiple lines), and that one pipeline could transport enough gas for 12 000 MW.

Transmission line losses for a 1000 mile system can be large, but the capital costs of the lines are more important than the cost of the lost energy. Figure 4 shows a comparison of the annualized costs of the options as the distance changes, assuming that all new infrastructure is needed. The HVDC line is a ±408 kV line with 7.0% line losses (including the conversion station losses), whereas the HVAC line is a 500 kV line with 9.3% losses. For distances greater than 600 miles, the HVDC line is better, since the line losses more than compensate for the DC converter stations. At a length less than 500 miles, the HVAC line is better, since the line losses are too small to pay for the DC converter stations. Between

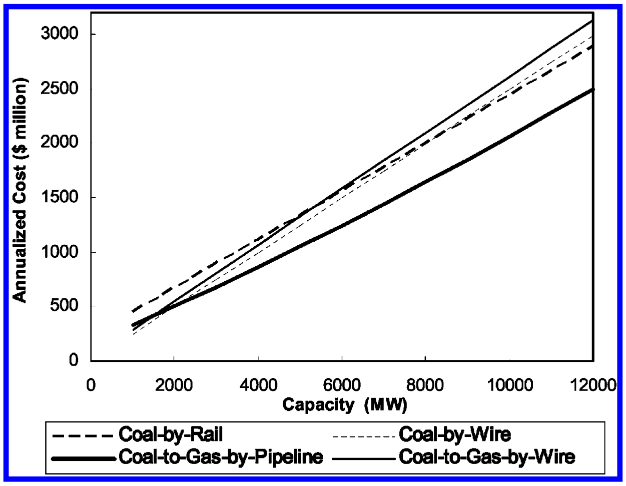

FIGURE 3. Annualized costs with varying amounts of electricity delivered.

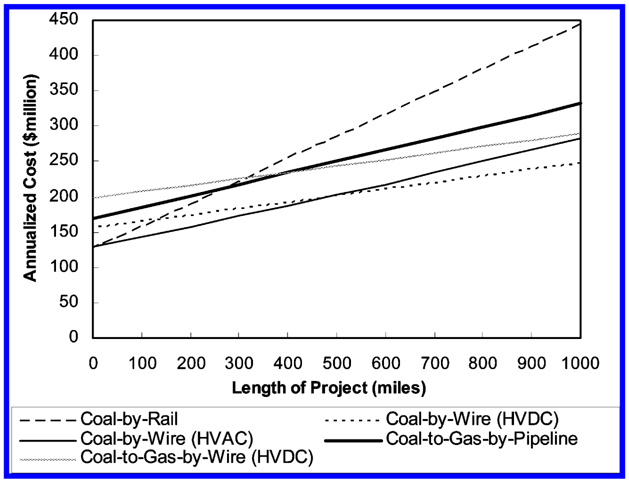

FIGURE 4. Break-even distances for all options.

500 and 600 miles, the choice is unclear. This breakeven distance is higher than a previous analysis (300−400 miles) since the losses assumed in that analysis were almost double those assumed here (*9*). These results are also sensitive to the line loading. Both the HVAC and HVDC lines were assumed to have a capacity of 2000 MW but were loaded at 1000 MW. The higher the loading above this level, the more the HVDC would be favored. While the cost of converting coal to gas remains more costly than the coal-by-wire options, below approximately 400 miles, shipping the energy through a pipeline is more economically attractive than shipping it as electricity.

3.2. Sensitivity Analysis. If petroleum prices increase, the cost of using unit trains would increase. However, the price of diesel would have to increase from $1.5/gallon to at least $4.0/gallon before shipping coal by rail would be more expensive than shipping electricity, assuming that only 100 miles of new track capacity would have to be built.

The social cost of CO_2 that was used in the base case analysis was $14/ton. It is possible that this value could increase in the future, for example, with the introduction of a carbon tax. If 1000 miles of rail were required, a carbon tax as high as $400/ton is required to make the rail option the economically preferred option.

One way to decrease the number of fatalities due to rail traffic is to have the train go over or under the highway at each rail crossing. At roughly $9 million to upgrade each crossing, if more than 11% of the over 600 crossings between Wyoming and Texas had to be upgraded, transmitting electricity would be cheaper, assuming that only 100 miles of new roadbed were required. It is acknowledged that this estimate is an upper bound since the area between Wyoming and Texas is less densely populated than the average and there could be less costly methods of increasing safety at the crossings (e.g., signals, gates, etc.)

3.2. Water. Water consumption for either of the power plants considered in this analysis will be on the order of tens to hundreds of billions of gallons of water annually if direct cooling is used. This can be reduced by switching to either indirect or hybrid cooling systems; however, there are cost and efficiency penalties. In general, gasification plants consumed less than pulverized coal plants by 4−10 times (see Supporting Information for more details). While this analysis does not consider siting constraints, they would be different in each location and water scarcity would play a role. However, since there are technical solutions to this problem and power plants have recently been proposed in both locations, it is considered possible to site a plant in either location.

3.3. Coal to Gas Options. While converting coal to synthetic natural gas is not a commonly discussed option, the results of this analysis show that it is a competitive alternative. Gasifying PRB coal by use of a Lurgi gasifier requires development. Transporting the gas by pipeline is attractive since the compressors consume only 3% of the gas in contrast to the 7% electricity line losses. The costs for this option would fall if the separated byproducts of the syngas were sold, including CO_2, fertilizers, phenol, cresylic acid, krypton, xenon, naphtha, and liquid nitrogen. Sale of byproducts represented more than 30% of Dakota Gasification Company's (company operating the current Lurgi gasifier in North Dakota) total gross revenue in 2000 (*28*). This option produces the second smallest greenhouse gas emissions and these could be reduced further by capturing and sequestering the CO_2 as is the current practice at the North Dakota plant.

4. Applicability of These Results for the United States

Getting energy from coal mine to the customer is a major problem throughout the United States. Distance between the mine and customer is important, as well as the ruggedness of the terrain in determining the best method to deliver the energy. The quality of the coal is important since 50% more lignite would have to be shipped than bituminous coal because of the ash and moisture content, implying that lignite would not be shipped far.

Siting power plants or rail beds, transmission towers, or gas pipelines is difficult. Pipelines are less obtrusive and may be the only feasible alternative if there is opposition to transmission towers or railroads.

Building a power plant in one location to serve customers in a different location can be problematic. Should Wyoming (and surrounding states) suffer the environmental impacts of generating electricity for Texas? A power plant in Wyoming would expose far fewer people than one near Dallas. However, Wyoming residents would ask why they are bearing the burdens for distant people. Wyoming would benefit from additional jobs, but it is unclear whether they would welcome the environmental degradation, crowding, and noise.

Several other options were investigated to replace the shipment of coal by rail. One option is the gasification of the coal for consumption in a Texaco integrated gasification/combined cycle (IGCC) plant either at the minemouth or by transporting the syngas by pipeline (*18*). However, the gasification of PRB coal is not favored in such a plant as the ash and moisture contents reduce the efficiency (HHV) of the IGCC plant from 37% (for Appalachian coal) to roughly 31%. Producing hydrogen in this plant is also possible to use in fuel cells; however, the cost and efficiency of such a system is not currently attractive. (For more details, see Supporting Information.)

4.1. Uncertainty. This analysis deals with a comparison of hypothetical power plants. The data used in this analysis combined theoretical data with data specific to currently operating systems. As such, there is a high degree of uncertainty associated with the input values. We have laid out the problem and suggested how it can be used for other applications. However, the cost and environmental impacts of the rail, transmission, or pipeline infrastructure will vary for each application. A sensitivity analysis revealed that the most important factors for the economic analysis include the amount of infrastructure required and the cost of that infrastructure. The transmission losses and emission factors for the combustion of diesel fuel are the most important for the environmental emission results.

5. Discussion

The best way to get a small amount of additional energy from the PRB to Dallas is to add it to the 50 million tons a year of Wyoming coal already being shipped to Texas by rail. Before new rail capacity is added, congestion can be relieved by, for example, double- and triple-tracking the existing lines. Up to 200 miles of additional capacity could be added before this option becomes more expensive than the other three base case options.

If PRB coal were to be used for supplying an additional 6.5 BkWh electricity to a location 1000 miles away that did not already have rail capacity, a generator at the mine and transmission line would be the cheapest alternative, with gasifying the coal and shipping the gas by transmission line a close competitor. Gasifying the coal and generating the electricity in a combined cycle plant has similar costs to a pulverized coal plant and has important environmental advantages.

If much greater amounts of electricity were needed by the distant customers, the new infrastructure would be used more intensively, reducing the cost. For sufficiently high demand (more than 9 GW), it would be cheaper to build a new rail line than to construct multiple transmission lines. Gasifying the coal and shipping it via pipeline might be an even more competitive alternative.

Finally, the answer to the question of shipping coal, gas, or electricity depends on the distance, the amount of spare capacity in infrastructure already in place, and the amount of energy to be shipped. Longer distances and greater amounts of energy favor rail and pipelines over transmission. Since the capital costs are the largest part of total costs, not having to build a large part of the infrastructure by relying on existing rail, transmission lines, or pipelines is likely to be the cheapest alternative.

While the social costs of rail deaths and emissions do not change the recommendation, internalizing the externalities associated with emissions serves to strengthen the case for rail over transmission. Burning additional coal to make up for transmission losses leads to larger pollution emissions than from the diesel locomotives. Accounting for these social costs strengthens the argument for gasifying the coal and using a combined cycle plant.

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Supporting Information Available

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

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