A Method for a Comparison of Bulk Energy Transport Systems

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We model alternatives for moving bulk energy, including both private costs and accounting for environmental externalities by requiring the transport system to satisfy environment, health, and safety standards. In particular, we focus on the cost and environmental trade-offs between “coal by wire,” mine-mouth generation with electricity transmission, and transporting the primary energy resources with generation near the customer. Having the bulk energy transport model satisfy standards avoids the controversy associated with estimating dollar costs for constrained visibility, noise, and 50/60 Hz electromagnetic fields. A sensitivity analysis examines implications of a range of carbon-dioxide discharge charges.

1. Introduction

Table 1 shows alternatives for moving the energy from source to load and transforming it to electricity. The way primary energy resources are moved to power plants and then electricity to load centers depends upon the nature of the resource, amount of energy to be moved, haul distance, capital and operating costs of the transport and power generation systems, existing infrastructure, etc. Additional factors affecting a selection are linked to the externality cost which is related to the environmental and social consequences of bulk energy transportation as well as those related to generation.

Previous research has modeled different bulk energy transport systems. A simple framework for environmental life-cycle assessment was presented in ref 1 and applied to a comparison of long distance energy transport systems including wire, pipelines, inland waterways, roads, and rail transport systems. An overview of existing HVDC technologies for long-distance bulk electric energy transmission is provided by ref 2. It highlights the economic superiority of HVDC over shipping primary energy resources by rail. Studies (3, 4) compared capital and operating costs of electric transmission lines (HVDC and HVAC) and gas pipelines coupled with a local generation and ref 5 extended this analysis to include LNG transport. AEP (6) assessed various considerations of electric transmission grid expansion versus local sitting of new generation types with coal transport by rail. Study (7) examined life cycle costs and environmental discharges of moving coal by rail, coal to syngas by pipeline, and electricity by wire. Study (8) introduced an engineering-based, bottom-up mathematical optimization model designed to show how to plan a large energy system at the least cost under a specific condition; they did not account for construction of new energy transportation routes.

These studies did not fully evaluate environmental and social “externalities,” undesired byproducts of energy transport and generation that have become important for evaluating competing bulk energy transport options. Examples include air pollution emissions, injuries, noise, visual effect, electro-magnetic field (EMF), etc. The Bergerson and Lave (7) study provides a launching point for this analysis.

This paper presents a bulk energy transport model (BET) for assessing technologies used or proposed to move fossil-fuel-based electricity from source to customer. In particular, it compares underground electricity transmission, overhead transmission and methods of primary energy resources transport coupled with local generation. To deal with unresolved issues such as placing a dollar value on impaired visibility, noise, and exposure to 50/60 Hz electromagnetic fields, the BET model uses health, safety and environmental standards to prevent significant externalities. To assess the alternatives under carbon emissions restrictions, the model evaluates the alternatives assuming a range of cost $0–1000 per ton of carbon-dioxide emitted.

2. Bulk Energy Transport Model

The first major decision is whether to transport fuel for generation near the consumer or to transmit electricity. Transmission is shown in the left-upper part of the figure while transporting fuel is shown in the left-lower portion of the Figure 1.

The total social cost of each transport option is the sum of capital, operating and externality costs. The private sector would select an option on the basis of the first two costs, excluding externality costs. Both the capital and operating costs include costs of power plant, transport infrastructure and rolling-stock (Supporting Information (SI) Tables S1 and S3).

2.1. Externality Cost. Externality cost is the environmental and social consequences of bulk energy transport and power generation that is not borne by the owner. If environmental regulations removed all externalities, these costs would be zero. However, the most socially beneficial standard is set at the level where the declining marginal social benefit of abatement is just equal to the increasing marginal cost of abatement. A more stringent standard would impose costs greater than benefits. Even assuming that environmental regulations are properly set, the remaining externalities influence which option has least social cost, e.g., an underground cable for transmission rather than overhead lines.

In this paper we consider air pollution emissions, safety hazard, audible noise, visual and EMF impacts of energy transport infrastructure and power generation as major “building blocks” of the externality cost.

2.1.1. Air Pollution Emissions. Air pollution caused by power generation and energy transport includes pollutants emitted by combustion of primary energy resources at the power plant, by rolling-stock engines, as well as pollutants.
related to combustion of extra primary energy resources to cover electric transmission losses. We have considered the following air pollutants: CO$_2$ for global climate change, NO$_x$, SO$_2$ for acid rains and aerosols, and suspended particulate matters. We also account for different air emission capturing capabilities of power plants and rolling-stocks. The total air emission externality cost aggregates the individual pollution emissions by weighting each by society’s damage due to the emissions. For example, the annual externality cost of CO$_2$ emission in the case of coal-fired power generation is calculated from the following parameters (eq 1):

$$\text{external cost}_{\text{CO}_2} = EM_{\text{CO}_2} \times \left(1 - \frac{\text{CAP}_{\text{CO}_2}}{100}\right) \times \text{Coal}_\text{cons} \times \text{TAX}_{\text{CO}_2} \quad (1)$$

Where $EM_{\text{CO}_2}$, emission factor in tons of CO$_2$ per ton of combusted coal; $\text{CAP}_{\text{CO}_2}$, emission reduction efficiency of coal-fired power plant in percent (influences capital and operating costs; higher emission reduction causes higher capital and operating costs); $\text{Coal}_\text{cons}$, consumption rate of coal in tons per year at the power plant required to supply the contracted power; and $\text{TAX}_{\text{CO}_2}$, estimated emission tax per ton of CO$_2$ over the year.

The air emission taxes reflect the health and ecosystem impacts monetized by a variety of methods (9–13). Since CO$_2$ emission has a global effect on the environment, $\text{TAX}_{\text{CO}_2}$ does not depend on the geographic location of a power plant and transport infrastructure. However, the other pollutants have more regional than global environmental impact. Therefore, we have introduced different air emission tax levels in the regions relatively close to the densely populated areas (DPA) associated with large electric load centers and in the remote regions with a sparse population.

2.1.2. Safety Hazard. Public safety is important for transport systems. Railroad transport of coal has the highest number of fatalities and injuries. Other human health related issues such as the audible noise and EMF are addressed in section 2.1.3.

The collisions result in compensation payments calculated from the following parameters (eq 2):

$$\text{external cost}_{\text{safety}} = (\text{FAT} \times \text{FAT}_\text{comp} + \text{INJ} \times \text{INJ}_\text{comp}) \times \text{BET}_\text{D} \times \text{Coal}_\text{prod} \quad (2)$$

Where $\text{FAT}$ and $\text{INJ}$, fatality and injure rates per year per billion ton*km of shipped primary energy resources (14); $\text{FAT}_\text{comp}$ and $\text{INJ}_\text{comp}$, estimated compensation payments per fatality/injury. We used the “value of a statistical life” (15) not a court determined compensation payment; $\text{Coal}_\text{prod}$, production rate of primary energy resources at their location in tons per year; and $\text{BET}_\text{D}$, a distance from mine to generator in kilometers.

2.1.3. Land Use. Each bulk energy transport option requires land where other activities are prohibited or restricted due to security and health risks. The land used is called the default right of way (RoW) corridor and its cost is included into capital cost and operating cost. However, impacts imposed by transport infrastructure and power

<table>
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<th>primary energy resource</th>
<th>electrons by</th>
<th>rail</th>
<th>barge</th>
<th>vessel</th>
<th>pipeline</th>
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<td>LNG vessel</td>
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Table 1. Alternative Bulk Energy Transport Scenarios

![FIGURE 1. Bulk energy transport analysis framework (left) and main blocks of the BET model (right).]
generation on society may result in restrictions that stretch beyond the default RoW corridor due to stricter limits on audible noise, visual effect and EMF impact. In these circumstances we assume that external cost corresponds to the cost of extending the default RoW corridor (purchasing more land and moving buildings and other structures outside of the extension) and will be added to the total cost in case of acceptance of stricter regulations. In the BET model the extension of the default RoW corridor is only applied to densely populated areas (DPA); we assumed that sparsely populated areas are not affected by new regulations. In addition we assumed that the expansion of the RoW corridor is a costly, but possible, regulatory option.

The width of the RoW is defined by the audible noise ($N_1$), visual effect, or EMF regulations ($N_2$). For example, SI Figure S1 illustrates a required extension of the default RoW corridor for several bulk energy transport options. This method is considered precise enough to estimate the land impacted by the energy transport system; the externality cost is the cost of the land needed to reduce noise, visual impact and EMF to meet the standards.

Extension characteristics for different types of bulk energy transport options are diverse. For example, railroad noise causes much greater impact than transmission line corona noise at the same distance (although installation of a noise wall barrier may substantially reduce or even avoid RoW extension) and the visual impact of a high voltage overhead transmission line is much greater than that of a railroad or pipeline. Equations 3 and 4 calculate the externality cost.

$$\text{external\_cost\_RoW} = 2 \times \text{DPA} \times \text{EXT} \times \text{TAX\_RoW} \times \text{CRF}$$  \hfill (3)

$$\text{EXT} = \max(\text{EXT\_noise, EXT\_visual, EXT\_emf})$$  \hfill (4)

Where DPA, percentage of densely populated area along energy transport route; EXT, required extension of the default RoW corridor (selected as a maximum value from extensions for audible noise, visual impact and EMF); TAX_RoW, estimated land price in the densely populated area; and CRF, capital recovery factor.

Required RoW extensions due to the noise, EMF and visual impact are calculated as following (eq 5–7):

$$\text{EXT\_noise} = e^{\alpha(N_1 - N_2)} - d_{\text{RoW}}$$  \hfill (5)

Where $d_{\text{RoW}}$ is the width of the default right of way corridor from one side of the bulk energy transport infrastructure. $N_1$ is the audible noise level at a distance of 1 m from the sound source, e.g., motion of unit train produces a sound level of 90 dB. However, if a whistle signal is required at road crossing, when leaving a tunnel or entering a bridge, the audible noise level of a train may climb above 100 dB. A HVAC 750 kV overhead line produces a sound level of 40–50 dB due to the corona effect in bad weather conditions. $N_2$ is the estimated future regulation standard, e.g., 40 dB is a typical noise level inside a sleeping room. $\alpha$ is the coefficient of sound reduction in open air. Sound is reduced by about 6 dB for each doubling of the distance from the source (19).

Audible noise reduction can be achieved by a noise-wall barrier. The noise level reduction depends on the separation distance and elevation difference between the receptor and the noise wall. The average unit cost of noise wall construction is $300 per m^2$ (including materials and installation). A typical 5 m noise wall on both sides of the track costs $3$ million per km (20). In the case of a high land cost an installation of a noise-wall barrier may become an economically attractive alternative. In this case $N_1$ is usually reduced by 10–15 dB. However, when blowing the whistle is required, the extension is much larger, even with a noise barrier.

The EMF around a HVAC transmission line is usually highest at the point of closest approach to the conductors. It falls rapidly with distance, as shown in eq 6 in the case of a single circuit three phase transmission line with a horizontal layout of phases (21).
HVDC underground cable which is assumed to be in the range of 10 to the observer and the object (house) in the residential area
houses in DPA. Relative visibility is used to regulate RoW width (Figure 2a). From the edge of the RoW, the infrastructure should not be higher than other objects, such as a building.

\[
EXT_{\text{emf}} = \left( \frac{\mu_0 V^2 I}{2\pi B} \right)^{1/2} - d_{\text{RoW}}
\]

Where \( I \) is the current carried by the transmission line, \( B \) is the estimated future regulation standard for EMF, e.g., 0.4 \( \mu T \) is the most prudent health regulation standard known today in Sweden and The Netherlands (22), \( s \) is the distance between phases in the horizontal layout, e.g., 15 meters for 750 kV transmission line, and \( \mu_0 \) is the magnetic permeability of air.

Relating visibility is used to regulate RoW width (Figure 2a). From the edge of the RoW, the infrastructure should not be higher than other objects, such as a building.

\[
EXT_{\text{visual}} = \left( \frac{H_0}{I V \times H_1} - 1 \right) - d_{\text{RoW}}
\]

Where \( H_0 \) is a height of the energy transport infrastructure, for example, the height of HVAC 750 kV transmission tower is 30–35 m and HVDC 600 kV is 20–25 m. In the case of HVDC underground cable \( H_0 \) is 0. \( d \) is a distance between the observer and the object (house) in the residential area which is assumed to be in the range of 10–20 m. \( rV \) is the assumed future regulation standard for a visual impact 0.25 or below, i.e., a projected transmission tower in the plane same with a house will not exceed 25% of the height of the house observed from a distance \( d \) (Figure 2c). Towers can be shorter with less visual impact but more towers will be needed to guarantee a minimum clearance distance between conductors and earth. This optimization is not included in calculations since we assume the common use transmission towers.

Finally, we may conclude that noise will be the dominant factor in determining width of RoW for railroad while for overhead lines it will be visibility and for AC overhead transmission lines it could be EMF. For underground transmission cables, no additional RoW is required.

3. Test Case
We examine a cost of supplying 1000 MW electric load center in Dallas, Texas using a coal from the Powder River Basin (PRB) in Wyoming, building on the analysis of Bergerson and Lave (7). This section illustrates results for the BAU (business as usual) case calculated with the BET model under typical land-based energy transport scenarios defined according to state of the art technology and typical land-based use. The BAU case serves as a reference for other cases. In the BAU case we do not include private utility costs for externalities abatement. Selected energy transport scenarios in the BAU case are related to a transportation of energy from a coal mine in PRB (low sulfur, subbituminous coal) to the Dallas electric load center via a generating plant and as following:

- Coal by wire (HVAC, HVDC, overhead lines and underground cables) coupled with a mine-mouth generation (pulverized coal-fired). Please note that coal to syngas to electricity, which is transmitted by wire (IGCC), is a more expensive technology and is not analyzed.
- Coal by rail (diesel unit trains) coupled with close to the load center generation (pulverized coal-fired).
- Coal to syngas (coal gasification) by pipeline coupled with close to the load center generation (combined cycle gas turbine).

Coal transport options that are not included in the test case analysis are barge, ocean vessel and coal slurry/logs pipelines. Superconducting transmission lines have been also excluded from the analysis, because we focus on existing and near-future (5 years horizon) technologies.

The functional unit of the analysis is the transport of 1000 MW electricity delivered to Dallas (transmission losses require additional generation). We assume that rail track, power transmission lines, and pipeline must be built. The route is through sparsely populated territory.

A selection of results (costs to the utility) is reported in SI Figure S2 and Figure 3. These costs include energy transport losses but do not include external costs. SI Figure S2 shows a summary of annual costs to the utility for different energy transport options in the BAU case. Figure 3 illustrates electricity cost to the utility at the electric load center including power generation and bulk energy transport.

Comparison of different energy transport scenarios in this specific BAU case leads us to the following observations:

- The capital cost is the largest component of energy transport and power generation costs.
- The operating cost component contributes most for the coal by rail option.
- The overhead HVDC transmission line offers the cheapest cost of electricity.
- The underground HVDC cable is the most costly of five options.

4. Sensitivity Analysis
The BAU case showed that overhead HVDC transmission option is more advantageous than transporting primary energy resources to the load center and generating electricity locally in the given example. In this section we analyze a sensitivity of the results to a variation of externality cost, bulk energy transport power, and distance.

SI Figure S3 shows that, to deliver up to 5000 MW (distance is fixed at 1600 km), coal by HVDC overhead transmission line is the cheapest solution. Coal by HVDC underground cable option is limited by 1100 MW, the highest rated capacity for a single cable and it is the most expensive options if there is no externality cost.

SI Figure S4 compares the cost of electricity at the load center vs a variation of the energy transport distance. The best way to get 1000 MW over a short distance is the overhead HVAC transmission line. Over longer distances the, higher investments for converter and switching stations of HVDC transmission are balanced by lower losses and line conductor costs. The so-called “break-even” distance for overhead HVDC transmission line with respect to overhead HVAC transmission line is about 300 km in the given example (depending on capital and operating costs it usually varies in the range of 200–700 km). For distances greater than 300 km, the overhead HVDC line is the more economic option.

The economic transmission distance for 1000 MW by HVDC 600 kV is limited by 3000 km (for longer distances a higher voltage level e.g. 800 kV is recommended to reduce transmission losses); for distances beyond 3000 km coal to syngas by pipeline is the most economic option in the given scenario followed by coal by rail.

We estimate the social costs, allowing the monetary value of external cost to be added to total cost and analyze how the various externality factors change the BAU case ranking of bulk energy transport options. We explore higher values for monetizing the externalities since society may value these externalities more highly in the future. In particular, the price of emitting a ton of CO₂ is likely to be higher in the future.

Figure 4 shows a variation of cost of electricity at the load center due to increasing the CO₂ emission tax in a scenario with no CO₂ capture. The left end of the graph shows the 0 tax scenario (identical to the BAU case discussed above, Figure 3). From here, the cost of electricity increases with
the CO₂ emission tax for all options. We assume emissions caused by combustion of coal/syngas at the power plant, by rolling-stock engines, as well as CO₂ emissions related to combustion of extra coal to cover electric transmission losses. Underground HVDC cable has the highest cost because of the higher amount of coal that must be fired to compensate electric transmission losses. Although coal by rail is more costly than HVDC overhead transmission line, the higher transmission losses make rail the cheapest option for high CO₂ taxes. The breakeven tax for HVDC is $150 per ton of CO₂. Present CO₂ emission taxes in Europe are in the range of $25–40 per ton of CO₂.

A high CO₂ emission tax makes CO₂ capture and deep geological sequestration economically attractive. When 80% of CO₂ emissions (this is an economically justifiable limit) are captured and sequestered, the breakeven CO₂ tax for transmission becomes much higher. The breakeven CO₂ taxes rise from $150 to more than $1000 per ton of CO₂ for HVDC OHL versus rail. Thus, the capture of CO₂ increases the competitiveness of “wire” technologies with coal by rail option (the costs of CO₂ transport/storage is not taken into account).

EMF created by overhead HVAC transmission lines is suspected of having a negative impact on human health (18, 19, 21). Therefore, imposing RoW extension for reducing EMF may have a serious impact on the competitiveness of overhead HVAC transmission option only. SI Figure S5 shows that when the stricter EMF standard of 0.4 µT (the most prudent health regulation standard known today in Sweden and The Netherlands (22),) is imposed, the overhead HVAC 750 kV transmission line may become more expensive than the HVDC underground cable, when 4.25% of the total energy transport distance BET_D is in a densely populated area. Obviously, the advantage of the underground HVDC cable option over overhead HVAC transmission line would grow as the portion of the densely populated area increase.

When the stricter audible noise standard (50 dB) is imposed in densely populated areas, the coal by rail option suffers the most since it generates noise significantly higher than the overhead HVAC transmission line (due to the corona effect). Noise generated by overhead HVDC transmission line, underground HVDC cable and syngas pipeline options can be neglected. As a result, reducing the audible noise level in the densely populated area will significantly increase the cost of electricity at the load center for the coal by rail option. At some noise standard (56 dB in case when 5% of the energy transport route is...
in the densely populated area), underground HVDC cable will become more economically attractive than coal by rail option (see SI Figure S6). Installation of the 5 m noise wall barrier may reduce a required extension of the default rail RoW corridor (10 m), although it will lead to higher capital cost. It is obvious that the higher land price or larger densely populated area will make underground cable economically more attractive even at higher noise level limit. SI Figure S7 shows a sensitivity of electricity cost to a variation in both land price and DPA.

A relative visibility of energy transport infrastructure is used to weight impacted land close to the energy transport route in the case its visual effect is considered as externality cost. It has an influence on the distance at which the energy transport infrastructure does not disturb an observer because of the much smaller height than other objects (e.g., houses, trees, etc.) close to the observer. The relative visibility decreases with the distance from the transport infrastructure. Overhead high voltage transmission lines create high visual impact, where HVAC option usually creates higher impact than HVDC at the same voltage level because of higher towers and more conductors. Coal by rail produces only a minor visual impact. Underground HVDC cable causes no visual impact at all (see SI Figure S8).

Figure 5 shows the delivered cost of electricity at the electric load center for each bulk energy transport mode at the assumed values for future noise, visibility, and EMF standards and CO₂ tax. In fact it refers to the costs of meeting the standards of all technologies. In this example noise is the dominant factor for rail, visual impact is most important for overhead HVAC and HVDC lines and in addition HVAC lines are affected by EMF. Cost of underground HVDC would not vary with these constraints.

The analysis underestates the difficulties of siting a new rail or overhead high voltage line. In the U.S. it is extremely difficult to site either. It may be that an underground line is the only option that can be sited, at least within the densely populated area.

SI Table S5 shows the assumptions that justify underground HVDC as a percent of bulk energy transport distance in densely populated area and a land price in this high value area in $/m². It illustrates when underground HVDC becomes the option of choice for specific restriction levels on audible noise, visual and EMF impact as well as capital and operating costs.

5. Discussion

This paper presents a bulk energy transport model for a technology assessment and comparative analysis of transporting large amounts of energy over long distances. The model estimates both private and social costs for a wide range of externality mitigation. Having the bulk energy transport model satisfy standards avoids the controversy associated with estimating dollar costs for constrained visibility, noise, and 50/60 Hz electro-magnetic fields.

We examined a set of long distance energy transport options related to the PRB coal to Dallas scenario, according to state of the art technology and typical use on the mainland and analyzed a sensitivity of the results to a variation in externality cost.

Taking into account possible stricter environmental and social regulations in the future (air emission, safety, noise, and EMF impact, etc.), early conversion of coal to electricity and transmission with HVDC technologies would demonstrate a significant improvement over the conventional land-based transport of primary energy resources by rail in the case when a new full length transmission line, rail double track, or pipeline must be built.

If people object strongly to overhead transmission lines underground HVDC transmission could become the dominant option, at least in densely populated areas.

As distances and other conditions changes, the preferred way of transporting the energy may change. Even here, the results are subject to uncertainty concerning the costs of the various options.

Supporting Information Available

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

Literature Cited

