Coal Logistics System (COLS)

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The Coal Logistics System (COLS) is a comprehensive coal transportation and transshipment model that solves for coal flows on a network from supply nodes through transshipment nodes to steam and metallurgical demand nodes on the basis of systemwide cost minimization. The model is solved for a representative time period for the system of ports, and all decision variables are solved for simultaneously. COLS is a constrained optimization model formulated as a linear program with some integer variables. Its solution indicates the sources of the various types of coal, the routes and modes of transportation, and the locations, activity levels, and types of transshipment facilities that together minimize the systemwide costs. Effectively, the COLS model minimizes the cost per delivered British thermal unit of U.S. coal. COLS was designed specifically for the evaluation of coal flows in a competitive multiport framework. Coal can be routed from virtually any mining region by any feasible mode to any port and then to any demand node. Thus, ports need not be restricted by a predefined supply hinterland or a limited destination area. From one scenario to the next, a single destination can receive coal of a different quality from a different origin via a different mode through a different port. Cost reductions from one scenario to the next can thus include transport cost savings, change of origin or destination benefits (including lower coal purchase costs), and change of mode savings as well as port improvements and the use of new technologies.

The Coal Logistics System (COLS) is a comprehensive coal transportation and transshipment model that determines optimal coal flows on a network from supply nodes through transshipment nodes to steam and metallurgical demand nodes on the basis of systemwide cost minimization. The various types of nodes are connected by links consisting of several different transportation modes. The model is solved for a representative time period, and all decision variables are solved simultaneously. COLS is a constrained optimization model formulated as a linear program with some integer variables. Its solution indicates the sources of the various types of coal, the routes and modes of transportation, and the locations, activity levels, and types of transshipment facilities that together minimize the systemwide costs. Costs consist of four main categories: coal purchase, inland and ocean transportation, investment in transfer facilities (if any), and operation of facilities. Effectively, the COLS model minimizes the cost per delivered British thermal unit (Btu) of U.S. coal exports. This model can be used by planners to assess the impacts of port improvements such as the investment in new equipment and infrastructure and dredging. In addition, different technolo-

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gies—for example, midstream loading versus broad-beam ships—can be directly compared and evaluated.

The COLS model is described and the calibration of the model that was undertaken for the U.S. Corps of Engineers using 1985 data is discussed. Because of lack of space, the mathematical model is not reproduced here. It has been published in a number of different forms elsewhere (1–3).

BACKGROUND

COLS is one of several models of the U.S. coal industry available for planning purposes (4–9). Although most are built around a transportation component, each model focuses on a different aspect of the coal industry: mining, coal type differentiation, rail transport, inland waterway transport, transshipment, ocean transport, end use utilization, and so on. COLS includes all these considerations but is set apart from the others by its focus on transshipment and other port activities and on ocean transportation. This focus is the result of the initial model development for the Maritime Administration, U.S. Department of Transportation, and the subsequent model enhancement for the Institute of Water Resources of the U.S. Army Corps of Engineers (1–3, 10). While COLS is a comprehensive planning model covering the entire coal logistics system, it is especially well suited to analyzing port and infrastructure development.

DESCRIPTION OF THE MODEL

COLS incorporates most of the complicating factors in the coal industry. It is a network-based transportation and transshipment model with various transport modes defined on the network and with a detailed representation of port activities. Bituminous, subbituminous, and lignite coal are divided into a spectrum of nine different coal types on the basis of their Btu and sulfur characteristics. The cost of purchasing, shipping, and handling coal is by tonnage, but demand is based on the Btu content of the coal. Both steam and metallurgical coal demand are included. For steam coal demand, the analyst can set a sulfur limit for regions with strict environmental regulations. For metallurgical coal demand, the analyst can define the coal type (or types) that can be used to satisfy the needs of metallurgical buyers. COLS is designed to address the question of the effect of port deepening on coal flows and costs in a competitive, multiport setting. It is also equipped to evaluate the alternatives to dredging, such as topping-off and broad-beam ships.

Network Structure

COLS is, in a sense, two linked models, one nested in the other. In the "outer" model, coal is transported from supply nodes to demand nodes in a linear programming, transportation model formulation. However, the transportation pattern is dependent on the transshipment nodes that are selected as the location of handling facilities in the "inner" model. The inner model contains the operations and limitations of each port: the various sites within the port and their ability to accommodate the various transportation modes and facility types; the facility types and their ability to accommodate the various modes; and the investment and operating costs of coal handling for the chosen facility types. In most other coal industry models, this entire inner port model is replaced by a single transshipment link—with a cost per ton and a capacity—between incoming links by one mode and outgoing links by another. The main advantage of COLS is the way in which port operations are causally linked to the ocean vessel size that serves the port.

Figure 1 is a flowchart showing how coal moves through the various elements of COLS. From supply nodes, coal travels by land transport to either barge-loading ports, domestic demand nodes, or directly to Great Lakes or export ports. Barge coal can be delivered to steam and metallurgical domestic demand nodes, Great Lakes, or export ports. All ports—barge, Great Lakes, or export—are considered to be transshipment nodes that represent junction points at which transport links by certain transport modes terminate and links by other modes originate. Transshipment nodes (ports) are further subdivided in COLS into a number of potential sites, called subnodes. Figure 2 gives an example of a coal export port with three subnodes, each of which has a different channel depth. Each subnode can represent a separate terminal within the port for the location of coal-handling facilities. The types and sizes of such facilities that can be located at a subnode and the size of ship that can be accommodated at that subnode depend on the availability of land, rail connections, channel depths, and docking facilities.

From export ports, coal can be shipped to foreign steam or metallurgical demand nodes by ocean freighters of various sizes. The types of vessels that can be used on a link are uniquely determined by the channel depths specified for the
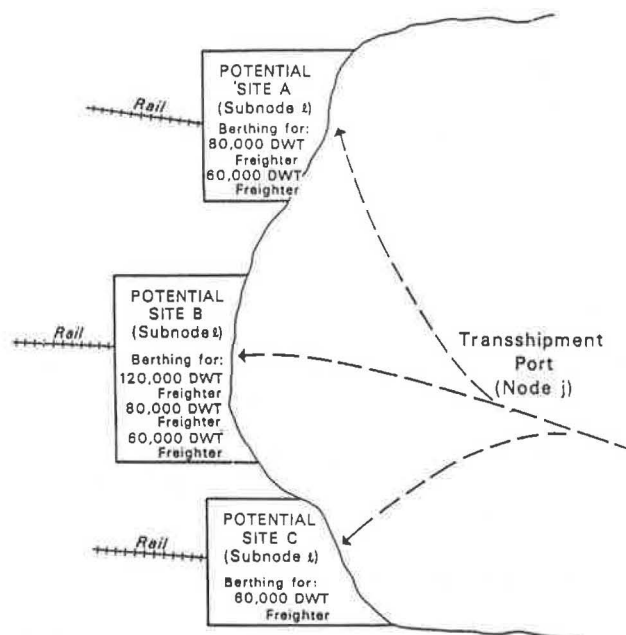
FIGURE 2   Example of coal harbor.

U.S. and foreign ports. If the model contains topping-off nodes, coal can be brought to the topping-off point by self-unloader and light-loaded supercollier and proceed from there by fully loaded supercollier.

Existing facilities are input to the model by stating in the data input tables that a particular type and size of facility is located at a particular transshipment node. Existing facilities are given an investment cost of zero dollars, and COLS does not have to decide whether to build them or not, because they already exist. Port scenarios can be run by changing the type of facility or depth of channel available at a port. Alternatively, COLS can be used at a more advanced level by making subnodes available for new construction and by giving COLS a choice of several configurations and sizes of handling facilities.

COLS has been designed specifically for the evaluation of coal flows in a competitive multiport framework. Coal can be routed from virtually any mining region by any feasible mode to any port and then to any demand node. Thus, ports need not be restricted by a predefined supply hinterland or a limited destination area. From one scenario to the next, a single destination can receive coal of a different quality from a different origin via a different mode through a different port. Cost reductions from one scenario to the next can thus include transport cost savings, change-of-origin or -destination benefits (including lower coal purchase costs), and change-of-mode savings.

Coal Type Differentiation

Coal is by no means a uniform commodity. Coal qualities vary widely both between and within the different regions of the United States. Some of the most important coal characteristics are heat content (Btu), sulfur, ash, volatility, and fixed carbon. There are major differences with respect to these characteristics not only between anthracite, bituminous, subbi-
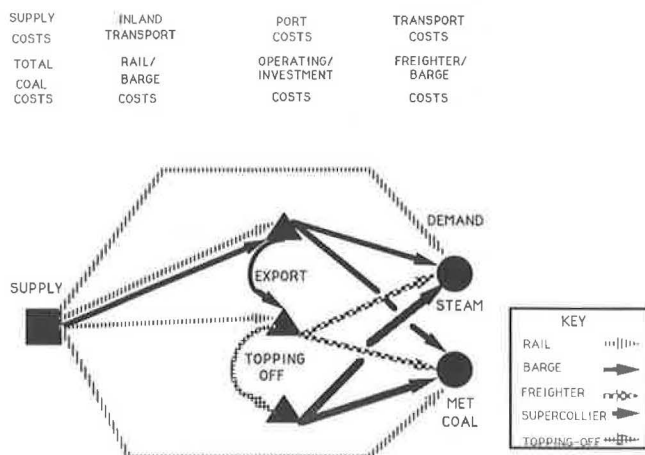
FIGURE 1   Flowchart of coal flows in COLS.

tuminous, and lignite coals, but also within the bituminous and subbituminous categories.

Although all of these coal quality characteristics are important to coal buyers (particularly metallurgical coal buyers), they cannot all be included in the model because it would cause a proliferation of coal types. COLS uses only Btu and sulfur content to characterize the coal types. The continuous gradations of Btu and sulfur content are subdivided into categories, and single representative Btu and sulfur values are selected for each category. For instance, all coal with between 21 million and 25 million Btus per ton and yielding less than 3.2 lb of sulfur dioxide per million Btus is designated as Type 5.

Btu and sulfur are used to define coal types because they are the most important criteria for both steam and metallurgical coal buyers. For steam coal, heat production is the main criterion although concern over acid precipitation has led to sulfur emissions limitations in several countries. Environmental regulations may become more strict in the future, which could lead to a shift in the balance of coal types and therefore supply regions and export ports.

For metallurgical coal, the important coal characteristics include ash and volatility in addition to Btu and sulfur. However, only bituminous coals have the proper coking properties that allow them to soften and solidify into a porous solid mass (coke) when heated to high temperatures in an oxygen-free environment. Sulfur and ash concentrations must be kept low because these impurities create inferior steel quality and because removal of impurities is expensive. The significance of the volatility characteristic is that a blend of volatilities is required, because high volatility coal produces a weaker coke, whereas low volatility coals added in excess can expand and damage the coke oven. All bituminous coals can be used to a certain extent in producing coke, but in practice the overwhelming majority of coking coal is produced in relatively few areas of the country and contains greater than 26 million Btus per ton and less than 1 percent sulfur. The National Coal Model, developed by the Department of Energy with a focus on end-use utilization, has been successful in defining metallurgical coal in terms of Btu and sulfur only, because most bituminous coal with the proper Btu and sulfur contents is generally acceptable for metallurgical use in terms of ash and volatility as well (8). The COLS model thus follows the National Coal Model in this respect.

Steam and Metallurgical Coal Demand

In COLS, the costs of purchasing, transporting, and trans-shipping coal are costs per ton; supply and handling capacities are also measured in tons. However, demand is not measured in tons because a single ton of low-Btu coal cannot substitute for one ton of high-Btu coal. Therefore, in the COLS model, tons are supplied and transported on the network but are converted to the equivalent amount of Btus for that coal type at the demand nodes. The requirements of the demand nodes are stated in terms of Btus rather than tons.

In satisfying steam coal demand, COLS allows different coal types to be blended. At demand nodes, the number of tons of each coal type is converted to an amount of Btus and sulfur dioxide based on the representative Btu and sulfur content of each coal type. These amounts are summed over all coal types at each node. Steam coal demand constraints require the total number of Btus to equal the requisite amount, whereas the sulfur dioxide production must not exceed the given environmental limitation.

Blending of coal types for metallurgical purposes is much more complicated and much less forgiving. Therefore, COLS can restrict the use of coal for metallurgical purposes to a subset of the coal types—anthracite, subbituminous, and lignite coal types can be prohibited entirely from being used for coke production. The remaining bituminous coal types can then be grouped into sets, with a given percentage of the metallurgical Btus coming from the various sets. For instance, the majority of metallurgical coal generally must be of the highest Btu and lowest sulfur quality, whereas a smaller proportion may be permitted from a slightly lower-quality group of coal types. Alternatively, the analyst can require all metallurgical coal to be of the highest quality.

USING COLS

There are four steps to using COLS: (a) data preparation and input, (b) generation of the mathematical model from the data input tables, (c) solution of the model, and (d) analysis of results. A flowchart of the steps in using COLS is shown in Figure 3.

Data Preparation and Input

The data for logistics planning scenarios to be analyzed with COLS are input to the model by the use of standardized data input tables called COLTABs. Each of the 14 COLTABs contains data on one component of the model. The data input tables cover the four basic components of the logistics system:

1. Coal supply characteristics
   a. Mine locations
   b. Mine capacities
   c. Coal types (sulfur and Btu per ton)
   d. Minehead prices
2. Transportation network characteristics
   a. Rail network
      (1) Rail links
      (2) Rail rates
   b. Water network
      (1) Inland water links
      (2) Barge transportation rates
      (3) Ocean water links
      (4) Ocean vessel sizes
      (5) Water transportation rates by vessel size
      (6) Light loading of vessels
   c. Port interface
      (1) Water linkages
      (2) Rail linkages
      (3) Coal transshipment sites
      (4) Depth of harbor
      (5) Dredging costs
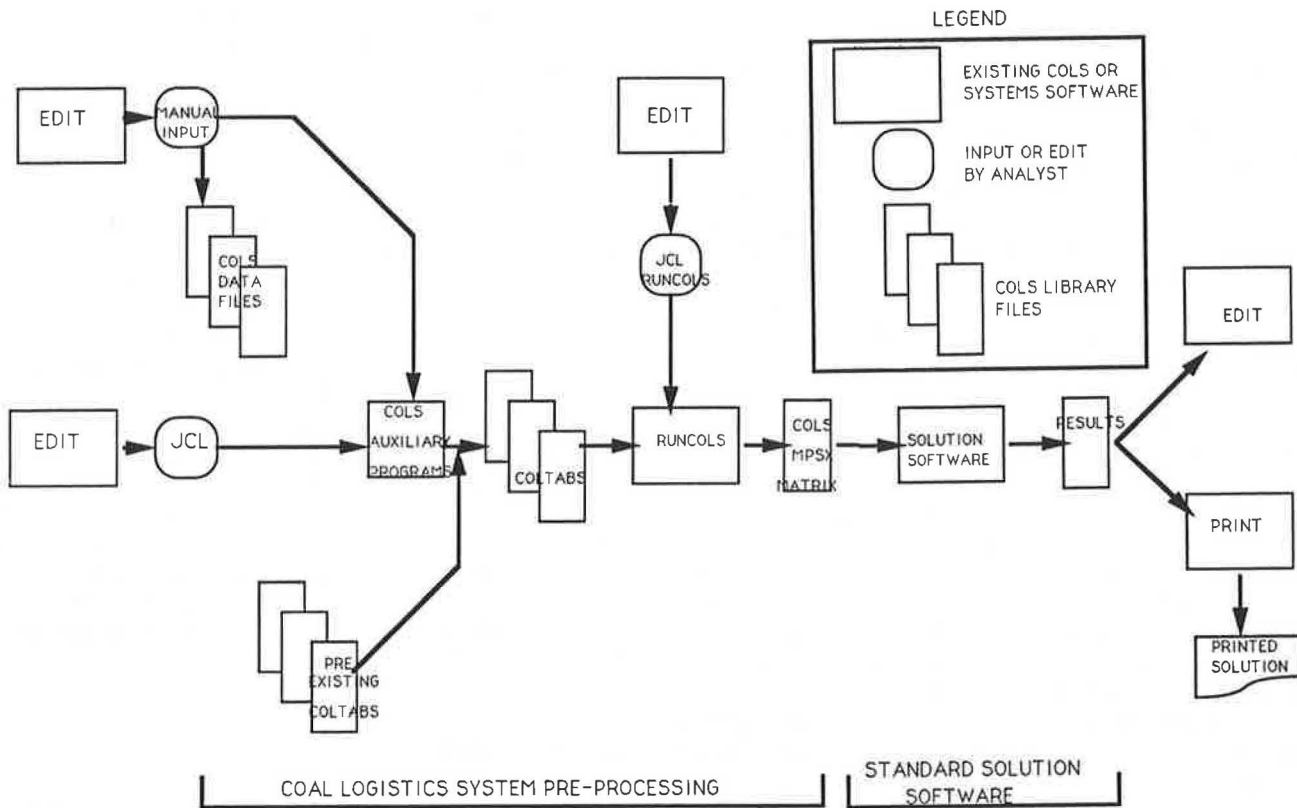   (6) Topping-off anchorages
      (7) Cost multipliers

FIGURE 3 Flowchart of steps in using COLS.

3. Coal-Handling characteristics
   a. Facility costs
      (1) Existing and new facilities
      (2) Fixed costs
      (3) Variable costs
   b. Facility capacities
      (1) Throughput
      (2) By mode
4. Coal demand characteristics
   a. Demand locations
   b. Transport linkages
   c. Steam coal demand
      (1) Btu requirements
      (2) Sulfur limitations
   d. Metallurgical coal demand (limited by coal type)

The data for the COLS model and the model itself are separate, independent entities. Users can provide their own data to be used in COLS as long as it is in the proper format, or they can use the data base developed for the Corps of Engineers for the coal export system as it existed in 1985.

Generation and Solution

After the data input tables have been created they are used to generate a mathematical model. The core of the COLS model consists of the matrix generating programs (COLS1 and COLS2) that convert input data on supplies, transportation rates and distances, transshipment, and demand into a mathematical programming model. The COLS matrix is generated in Mathematical Programming System (MPS) format—the industry standard—and can be used on any compatible solution software package such as Control Data Corporation's APEX or IBM's Mathematical Programming System Extended (MPSX). The solution output from COLS provides the user with comprehensive results from each scenario as follows:

- Purchase costs for coal by type;
- Routes, transport modes, and amounts of coal to be transported from mining regions to domestic demand nodes and ports of export;
- Cost of inland coal transportation;
- Number of tons transported through each port;
- Types of coal-handling facilities used to transfer coal between modes at transshipment sites;
- Costs of handling the coal at these sites;
- Degree to which existing capacity at transshipment sites is utilized;
- Amount and type of new transshipment capacity or infrastructure improvements (or both) that would make the transshipment and supply of coal more efficient (if the user chooses to ask this question);
- Investment costs associated with these new facilities and improvements;
- Routes, modes, and amounts of coal by type that is transported to foreign demand sites for steam and metallurgical purposes; and
- Costs associated with overseas transport.

Analysis

COLS was designed to facilitate the running of various scenarios. Once the COLTABs have been created, data elements on any table can be easily changed to generate a new scenario. For instance, the depth of a harbor can be changed by altering a single character on one COLTAB; for example, changing F3 to F5 would change the harbor depth for a port from 42 ft to 50 ft. Similarly, the transfer capacity of a terminal can be changed, ports or waterways can be added, or user fees can be assessed. The model is sensitive in varying degrees to all the input data, including harbor depths, transport rates, coal prices, coal supply, and demand.

CALIBRATION OF COLS TO 1985 HISTORICAL COAL FLOWS

The calibration stage of model building is especially crucial with large, complex systems such as the COLS model. A model must first prove that it can simulate the historical record before it can be trusted to answer what-if questions or to make future projections. Given a data set describing the system in a recent historical year, the model must generate results similar to what actually occurred in that year; otherwise, the model is not functioning as it should, which is as a simplified representation of reality that maintains the most essential interrelationships that determine the outcome of the system in question. In the case of COLS, the model should respond to data describing the demands, supplies, networks, transport costs and capacities, and any government regulations that existed in a given year in much the same way that the market responded, by routing coal through the same ports in roughly the same quantities.

In the project undertaken, the criterion set up in advance by the Corps of Engineers for evaluating the performance of COLS was that explanations be provided for any discrepancies for major ports where calibrated flows were not within a precision of ±15 percent of the flows for the representative year, 1985. The calibration results achieved by COLS in this study were within 10 percent of the historical flows except for the port of Los Angeles/Long Beach, which was the port that exported the smallest amount of coal in that year.

There are many reasons why a model might deviate from the anticipated results; "calibration" is the process of discovering and correcting these problems. First, it could be that the objective of the model—cost minimization—does not faithfully characterize the real world. Although recognizing that the real world tends toward an equilibrium, network-based cost-minimization models have a well-established history based in part on the idea that all individual coal buyers try to minimize their costs for the quality they require. Concomitantly, the buyer that saves the most costs by using a low-cost resource or advantageous port is able to bid the highest for it, and thus the allocations that accomplish overall systemwide minimization reflect bidding ability.

Second, with a complex system such as COLS, it is possible for mistakes and inconsistencies to slip into the data. The calibration runs performed caught several such problems.

But looking beyond mistakes, the most important role that calibration plays is in identifying weak areas in the data. The procedure followed by the authors was to run the model with the 1985 data base and then to compare the results to the corresponding historical results for 1985. When the results did not closely match, all components of the flows that did occur were carefully analyzed versus the flows that might have been expected, to check for a systematic error. [A complete discussion of data changes that were made in the calibration of COLS may be found elsewhere (3).]

Base-Case Results

Table 1 presents the results for the base-case run compared with historical results for 1985. The run was made using 1985 costs, capacities, channel depths, networks, supply, demand, and so on. The base case comes well within the contracted performance standards of 15 percent allowed deviation for each of the major ports. In fact, all major ports are within 10 percent, and three of the five are within 2 percent.

Figure 4 shows the model results in comparison with the historical data for 1985 in millions of tons per year for the five major ports plus Los Angeles/Stockton. For each port, the first bar shows the actual tonnage and the second shows the model results.

Cost Summary

The total system cost per day is $12,789,323. Based on a total export tonnage of 241,065 per day (87.99 million tons per

TABLE 1 COMPARISON OF BASE-CASE CALIBRATION RUN WITH HISTORICAL PORT LOADINGS FOR 1985

Port	COLS Node Code	Port Loadings (mtpa)		Model Results as Percentage of Historical
		Model	Historical	
Major				
Philadelphia	SC	3.24	3.6	90.2
Baltimore	SE	7.59	7.7	98.6
Norfolk	SH	43.47	43.1	100.9
Mobile	SO	9.89	9.0	109.9
New Orleans	SP	8.15	8.3	98.2
Minor				
Los Angeles/Long Beach	PK	0.04	1.0	46.0[a]
Stockton	PI	0.42	0.0	

NOTE: mtpa = million tons per annum.
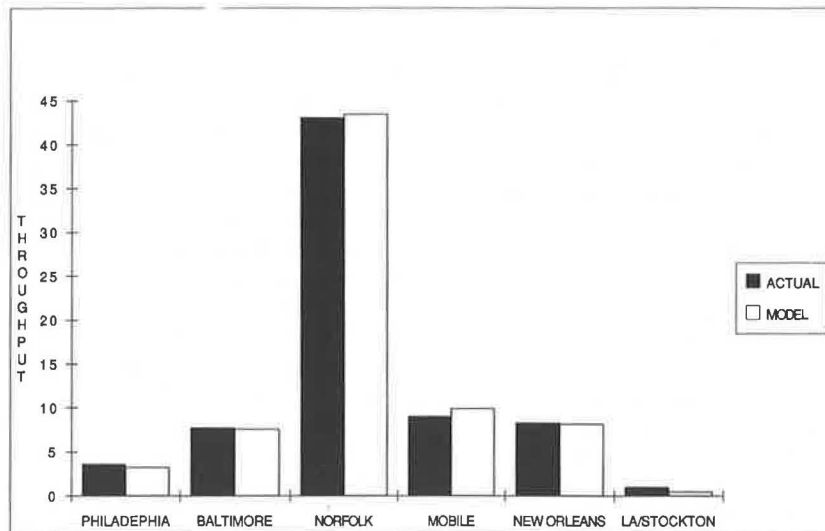[a] Combined total for California port loadings.

FIGURE 4 Comparison of model results with historical data (total coal throughput: actual = 72.70 mtpa; model = 72.81 mtpa.

TABLE 2 TOTAL COSTS IN BASE CASE BY COST CATEGORY

Type of Cost	Cost per Day ($)	Cost per Year ($)	Percent of Total
Coal purchase	7,567,577	2,762,165,605	59.17
Type 1	0	0	0.00
Type 2	0	0	0.00
Type 3	0	0	0.00
Type 4	0	0	0.00
Type 5	29,354	10,714,210	0.23
Type 6	33,819	12,343,935	0.26
Type 7	1,245,060	454,446,900	9.74
Type 8	703,264	256,691,360	5.50
Type 9	5,556,079	2,027,968,835	43.44
Coal transportation	4,770,289	1,741,155,485	37.29
Rail/truck	2,862,196	1,044,701,540	22.38
Barge	274,402	100,156,730	2.15
Laker (F1)	23,447	8,558,155	0.18
Panamax (F2)	954,694	348,463,310	7.46
42-ft (F3)	110,210	40,226,650	0.86
45-ft (F4)	544,744	198,831,560	4.26
Supercollier (F5)	595	217,175	0.01
Coal handling	451,021	164,622,665	3.53
Total	12,789,323	4,668,102,891	

year), the average delivered cost is $53.05 per ton. A summary of costs by cost category is provided in Table 2.

Coal purchase costs at the minehead make up 59 percent of the total system costs. This fact indicates the continuing dominance of the localization of the coal resource as the main determinant of export flows. A full 43 percent of the total is for purchasing Type 9 premium metallurgical quality coal only; this purchase accounts for 73 percent of the total minehead costs.

Coal transportation costs account for 37 percent of the total. Of the total transportation costs, 65.8 percent is for inland transportation (rail, truck, and barge), and 34.2 percent is by freighter for overseas and Canadian demand. Rail and truck accounts for over 91 percent of the inland costs, with barge accounting for less than 9 percent. Rail rates continue to

dominate the inland and the overall transportation structure. Overseas, 40-ft Panamax freighters and 45-ft freighters from Norfolk dominate the picture. Supercolliers account for less than 0.01 percent of the total cost, with a minimal amount of coal being shipped from Long Beach.

Coal-handling costs account for just 3.5 percent of the total system costs, despite the fact that some coal is handled twice— once at barge tippling points and once at export terminals.

Coal Origin Summary

Forty-nine different coal-producing nodes were active in the model results. All coal shipped to Philadelphia (COLS node code SC) originates in Pennsylvania except for a negligible amount originating in Ohio; it arrives by rail. The 3.2 million tons per year (mtpa) of Philadelphia-bound coal is high-Btu steam coal. The 7.5 mtpa shipped to Baltimore (SE) goes by rail from northern West Virginia and Maryland, mostly from DOE District 3, with smaller amounts from Districts 1 and 8. Baltimore's coal is predominantly high-Btu, high-sulfur steam coal, with smaller amounts of low-sulfur steam coal and metallurgical coal. Norfolk (SH) handles 43.4 mtpa of coal by rail, of which 39.8 mtpa (92 percent) is metallurgical coal. Norfolk draws coal from a four-state region: southern West Virginia, eastern Kentucky, northern Tennessee, and Virginia. Toledo (RH) draws all of its 15.1 mtpa of coal by rail from eastern Kentucky, split evenly between steam and metallurgical coal. In the base case, no coal is shipped to New York, to Atlantic Coast ports south of Norfolk, or to Great Lakes ports other than Toledo.

In comparison with the eastern and Great Lakes ports, the Gulf ports of Mobile (SO) and New Orleans (SP) receive all of their coal by barge. Mobile handles 9.9 mtpa from Alabama. Of this amount, 3.2 mtpa travels from Tennessee and one node in south central Kentucky through the Tennessee-Tombigbee Waterway. The remaining 6.7 mtpa of metallurgical Type 9 coal comes from central Alabama. New Orleans, on the other hand, receives steam and metallurgical coal via

the Mississippi River system. Half a million tons of metallurgical coal originates on the Arkansas system; 0.9 mtpa of high-sulfur/medium-Btu steam coal originates in western Kentucky and Indiana on the Ohio and Green rivers; 4.9 mtpa of metallurgical and high-sulfur/high-Btu steam coal originates in the Cincinnati-Wheeling-Charleston area of the Ohio and Kanawha rivers; and 2.2 mtpa of steam coal originates on the Allegheny and Monongahela rivers. None of the Texas Gulf ports are active in the base case, which parallels actual flows in 1985.

On the Pacific Coast, only Los Angeles-Long Beach (PK) and Stockton (PI) handle any coal in the model. Long Beach handles 38,000 tons per year of high-Btu/low-sulfur coal from southeast Colorado and northern New Mexico, whereas Stockton transships 0.4 mtpa of similar coal from central Colorado and southern Utah. In the West, as in the East, the model ships none of the four low-Btu coal types. This is generally true of the U.S. export business, because the low price of the low-Btu coal is more than offset by the higher transport cost per Btu. Twice as much of the low-Btu coal would have to be shipped to achieve the same heat value as high-Btu coal, which is why low-Btu coal generally is transported very short distances or used at mine-mouth power plants.

Foreign Demand Allocation Summary

Philadelphia ships only steam coal to Europe by 40-ft draft Panamax (F2) vessels. Because F2 is the largest vessel that the port of Philadelphia can handle, the largest share of Philadelphia's coal goes to Piraeus, Greece, which has a harbor only 40 ft deep. Baltimore ships mainly steam coal to Europe by 42-ft draft freighter (F3) whenever the foreign port can accommodate it, and otherwise by Panamax class. Norfolk ships a small amount to the Panama Canal and South America, but otherwise, like the other East Coast ports, ships exclusively to Europe. Norfolk ships mostly by 45-ft draft freighter (F4) and only ships by smaller vessels to metallurgical demand nodes, to which Philadelphia cannot ship because it handles no metallurgical coal.

All coal destined for Canada is shipped via Toledo and the Welland Canal (VB) by 27-ft Laker (F1). All coal from Mobile and New Orleans goes either through the Panama Canal (VA) to East Asia or to South or Central America by Panamax (F2). Long Beach and Stockton ship by their maximum vessel sizes to East Asia.

These routings are generally realistic, further confirming the fidelity of the model, because not only are the amounts loaded at each port realistic, but the origins and destinations are also fairly accurate.

Of the minor ports (ports with coal-loading capacity but shipping 1 mtpa or less in 1985), only Los Angeles and Stockton were active in the model results. The other minor ports that were not active in the model but were included in the network are New York, Morehead City, Charleston, and Savannah on the East Coast and Port Arthur and Corpus Christi on the Gulf Coast. Of all the minor ports, only Los Angeles actually shipped more than 100,000 tons of coal in 1985. Thus, the model was also accurate in not shipping coal through ports that shipped no coal in 1985.

The only major discrepancy was in West Coast shipments, where 1 million tons were actually shipped through Los Angeles-Long Beach (LA/LB) in 1985. In the model, a small amount was shipped through Los Angeles, and 400,000 tons was shipped through Stockton. A reasonable explanation for why Stockton was favored over LA/LB is as follows. Both ports are served by both the Santa Fe and Southern Pacific railroads, and the railroads may set discounts that encourage coal traffic to LA/ LB instead of to Stockton. Rail rates in COLS are set strictly by region of origin, distance, and number of interlines, so there is no mechanism for favoring LA/LB over Stockton. Furthermore, the port costs in the model for the two West Coast ports are nearly identical: $4.58 per ton for LA/LB and $4.78 for Stockton. In actuality, LA/LB was probably much less expensive than Stockton, but because LA/LB's average cost, $4.58, was used as the estimate for the smaller ports everywhere (including Stockton), it does not enjoy as significant a cost advantage over Stockton as perhaps it should. The lowest port cost estimate for the LA/LB port area was used ($4.58 at Long Beach).

The foregoing discussion explains the relative shares of LA/ LB and Stockton, but not why the total for the two West Coast ports is lower than the actual total for 1985. This discrepancy can most likely be traced to the methodology for estimating supply-node export production capacities. The methodology used works well except in areas where a very small percentage of coal is exported and where most of the export coal comes from a few high-quality counties. In the production capacity methodology for this model, the actual county production is multiplied by the percentage exported from that DOE district, plus a leeway factor of 10 percent. In the western DOE districts, the highest proportion exported from any district was 4.3 percent in Utah and 1.8 percent in Colorado. For example, the production in every Colorado county is multiplied by 0.018, and to that is added 10 percent—0.0018—for a total of 0.0198 multiplied by the total 1985 county production. However, in actuality, most of the export coal probably comes from one or two high-Btu counties in Colorado (e.g., Pitkin County, Type 9 coal), which probably export a much greater percentage of their coal than 1.98 percent, whereas the majority of Colorado counties export no coal at all. If the node capacities in the model for these high-Btu (Types 7 and 9) western nodes were larger, it would surely be expected that more western coal would be shipped out via LA/LB and Stockton.

The methodology for estimating the capacity of supply nodes for producing coal for export purposes works quite well in Appalachia and the Midwest, where export coal (generally high-Btu coal) is plentiful. However, in the western United States, where high-Btu coal is a localized phenomenon, the district average percent exported is too low for the few counties that do export and too high for the counties that have never exported any of their low-Btu coal. This entire problem, therefore, is isolated in the western United States, and, in a sense, is due to (a) a lack of export data at the county scale and (b) the author's unwillingness to abandon an unbiased methodology even in these few problem areas.

CONCLUSIONS

The COLS model calibration runs revealed the competitive aspect of the coal export system and confirmed that cost structure or capacity changes can lead to some very complicated

trade-offs between ports. In the example mentioned earlier, when the capacity of all supply nodes was increased by 4.54 percent (from leeway = 10 percent to leeway = 15 percent), the amount shipped via Mobile and New Orleans decreased, and the amount through Philadelphia, Baltimore, and Norfolk increased. This was because the most expensive mine-port combinations per Btu were being shipped via the two Gulf ports, and these were the first to drop out of the solution when replaced by greater shipments via the East Coast.

Using a more elaborate example in another scenario, a series of switches was prompted by a decrease in the short-haul rate from $1.80 to $1.60 per ton (base case is $1.80). At $1.60, supply nodes DF and DA (high-sulfur, high-Btu Ohio and Pennsylvania coal) were able to ship coal to New Orleans by barge and then through the Panama Canal. This flow replaced mines CT and CO (similar-quality Tennessee and Kentucky coal) that had been shipping to Mobile. This freed CT and CO to ship coal to Norfolk, replacing Types 7 and 8 coal going from various supply nodes to all three East Coast ports. In all, New Orleans was up by 1.52 mtpa, Norfolk was up 0.43 mtpa, and Mobile, Baltimore, and Philadelphia dropped by a combined total of 1.95 mtpa.

What is most interesting about this example is that it shows how a lowering of barge-related costs actually helped Norfolk at the expense of Mobile, which is the opposite of what was expected from a cost change that favors barge traffic. However, coal from Ohio/Pennsylvania shipped to Japan via New Orleans replaced coal from Pennsylvania and West Virginia to Europe via Philadelphia and Baltimore. This prompted a destination change of the Kentucky/Tennessee coal—to Europe via Norfolk instead of to Japan via Mobile. To put it another way, as the New Orleans hinterland extended up the Ohio River, the hinterlands of Baltimore and Philadelphia receded. This caused a corner of Kentucky and Tennessee to switch hinterland from Mobile to Norfolk. Moreover, the Kentucky/Tennessee coal changed modes from barge to rail.

There are numerous scenarios that the COLS model has been used to evaluate, including user fees, dredging, midstream transfers, and topping-off at Richards Bay, South Africa, to name a few. In these cases the model results appear reasonable and therefore provide the decision maker with a yard-stick by which to make policy analysis within a multiport framework.

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REFERENCES

1. J. Osleeb and S. Ratick. *Implications of World Coal Demands on U.S. Port Strategic Planning*, Vol. 1. Final Report. Maritime Administration, U.S. Department of Transportation, 1981. National Technical Information Service: PB-82-1360408.
2. J. Osleeb and S. Ratick. Implications of Coal Conversions on the Ports of New England. *Economic Geography*, Vol. 59, Jan. 1983.
3. Management Technology and Data Systems. *Coal Logistics System (COLS) Final Report*, Vol. 2. U.S. Corps of Engineers, Philadelphia District, Nov. 1987.
4. *McDuffie Terminals, Port of Mobile, Mobile, Alabama*. Alabama State Docks Department, 1981.
5. *Proceedings, Coal and Port Seminar* (Feb. 17–19, 1981, Mobile, Alabama). American Association of Port Authorities, 1981.
6. ICF, Inc. *The National Coal Model: Description and Documentation*. Federal Energy Administration, Oct. 1976.
7. *Coal Supply and Transportation Model: Model Description and Data Documentation*. DOE/EIA-0401. Energy Information Administration, U.S. Department of Energy, 1983.
8. *Documentation of Data Inputs to the National Coal Model*. DOE/EIA-11857-1. Energy Information Administration, U.S. Department of Energy, 1983.
9. *International Coal Trade Model: Executive Summary*. DOE/EIA-0444. Energy Information Administration, U.S. Department of Energy, 1984.
10. Management Technology and Data Systems, *Coal Logistics System (COLS) User's Manual*. System (COLS) User's Manual, Vol. 1. U.S. Corps of Engineers, Philadelphia District, August 1987.