WATER AND FIRE: WATER NEEDS OF FUTURE COAL DEVELOPMENT IN THE SOVIET UNION AND THE UNITED STATES

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FOREWORD

Efforts by IIASA scientists to assess medium- and long-term energy problems have led to the quantification of scenarios describing the possible role of alternative energy forms in meeting a growing energy demand in all major world regions.

Within a wide range of assumptions fossil energy is likely to supply most of human energy needs for the next 50 years and beyond, with coal assuming an increasing share in the global energy balance.

However, this coal is not evenly distributed throughout the world and may therefore have local impacts that were not immediately apparent when viewed on the global scale. It is informative therefore to disaggregate these global scenarios to the country level and to take a closer look at possible constraints to coal production.

Among these possible limitations is the supply of water for coal development. Accordingly, this report examines this potentially crucial constraint to the exploitation of this major global energy resource – coal.

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SUMMARY

This paper presents estimates of water requirements for future coal use in the USSR and the US. Future levels of coal use were based on scenarios presented by IIASA in Energy in a Finite World. *As a first step in the analysis, IIASA's coal scenarios were broken down from the scale of "world region" to the scale of coal-producing region. This exercise revealed that American and Soviet coal targets, which seem feasible when viewed on the "world-region" scale, may be difficult to attain on the coal-region scale due to insufficient coal reserves in some regions.*

In the next stage of the analysis, an analytical model was developed, which describes on the coal-region scale the quantity of water required during different stages of coal development from mining to its final conversion to useful energy. Application of this model to each of ten principal coal-producing regions of the US and USSR suggested that roughly 1–2 tons of water will be consumed for every ton-equivalent (tce) of coal-fuel delivered. However, these estimates assume a high degree of water conservation; with less emphasis on conservation, perhaps 50% more water will be required.

Water requirements for coal were then compared with competitive water uses in each US coal region, as well as estimates of surface water supply in these regions. It was found that the amount of water needed for coal is small relative to other projected water uses such as agriculture and industry. However, after accounting for competitive water uses, there will probably be little or no water available for coal use during dry years in the Southwest and Northwest regions. Unless significant quantities of water can be stored for these years, coal development will have to displace other water uses in these regions.

Intense water pressure will probably also occur in the Asian-USSR coal region of Ekibastuz, and possibly in Kuznetsk, Kansk-Achinsk, and Tungusska.

It is concluded, therefore, that an overall four- or fivefold expansion of coal use in the US and Soviet Union will probably be constrained to some degree by both limited coal reserves and lack of readily available water.

1 INTRODUCTION

From its prominence as the mineral that fueled the Industrial Revolution, coal fell into a lesser role this century behind the more versatile fuels–petroleum and natural gas. But now, once again coal is headed for an important position in the world's energy picture. According to one estimate, IIASA's High scenario in *Energy in a Finite World*, global coal production may increase by a factor of five in the next 50 years (Häfele 1981a).

But there are a number of economic, environmental, and other factors that may constrain the growth of coal production. High on this list is *water*, which is consumed in prodigious amounts during every step of coal development from the mine to the power plant. This report asks: Will there be sufficient water to fuel a significant expansion of coal production? and then examines the two nations that produce over 50% of the world's coal – the United States and the Soviet Union.

An introductory question might be: How much coal will these countries produce in the future? Referring again to the High scenario in *Energy in a Finite World*, it is expected that the regions* containing these two countries will continue to supply and consume the greater part of the world's coal in the year 2030. As Figure 1 notes, the IIASA scenarios show that by 2030, the US and Canada will have expanded their production by a factor of five, from 0.6 to 2.9 billion tons of coal equivalent (tce**) per year, and the Soviet Union and Eastern Europe by a factor of four, from 0.9 to 3.8 billion tce/yr. According to the IIASA study, the US will need this coal for electricity, coke, export, and especially for liquid fuels to make up for declining world oil production. Meanwhile, the Soviet Union will require large amounts of coal for both export and synfuels, as well as for uses not considered significant in the US, such as district heating and co-generation.

To evaluate how much water will be required to sustain these high levels of coal production, the methodology outlined in Figure 2 was used. This figure notes that the IIASA coal scenarios were used as a basis for estimating the future coal needs of the US and the Soviet Union. These scenarios also provided quantitative estimates for the amount and type of coal that will be produced in the year 2030***. The calculations are expressed in terms of a "Low" and a "High" scenario, which differ chiefly in anticipated world economic growth rates. The Low scenario assumes a growth rate of 1.7–3.6%/yr, and the High scenario, 2.7–4.7%/yr, depending on the year considered (Häfele 1981b). These two cases attempt to "bracket" the range of possible energy requirements for the globe in the year 2030. These figures are also close in some respects to numerical results of other studies. For example, IIASA's Low scenarios for coal requirements in North America and Soviet Union/Eastern Europe for the year 2030 are similar in magnitude to the World Coal Study projections for the same regions for the year 2000 (WOCOL 1980a).

*For computational purposes, the IIASA study divides the world into seven regions. Region I contains the US and Canada, Region II the USSR and Eastern Europe.

**Three types of coal units are used in the literature: short tons (t), metric tons (te), and metric tons of coal-equivalent (tce). A short ton is equal to 0.907 metric tons. A "coal-equivalent" is based on a typical heating value for good quality bituminous coal, 7000 kcal/kg. Ten metric tons of coal with a heating value of 3500 kcal/kg is equal to 5 metric tons of coal-equivalent [10 te × (3500/7000) = 5 tce].

***The usage of the year 2030 in IIASA's scenarios is intended to provide an estimate of what is to be expected in about 50 years. Considering the uncertainty of energy forecasting, one should not take this specific year too literally.

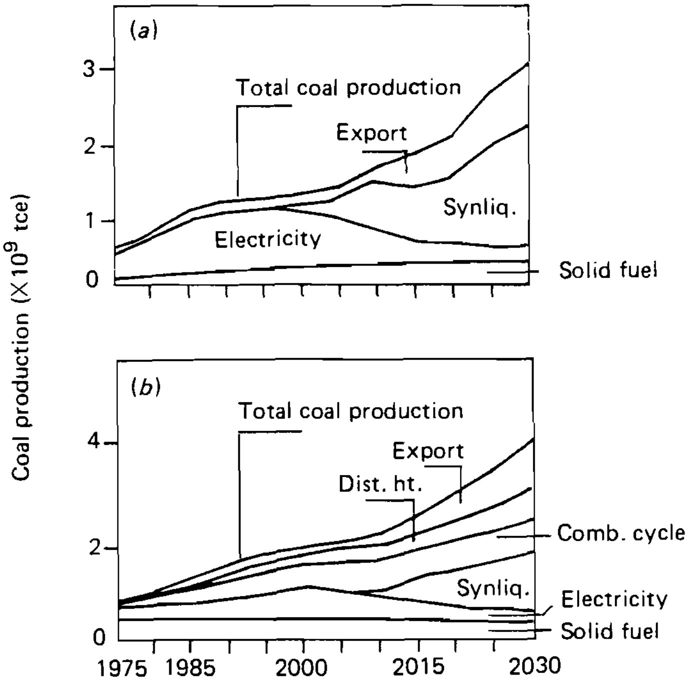

FIGURE 1 Projections of coal production for (*a*) North America (USA and Canada), and (*b*) the USSR and Eastern Europe, given in the IIASA High scenario (Häfele 1981a).

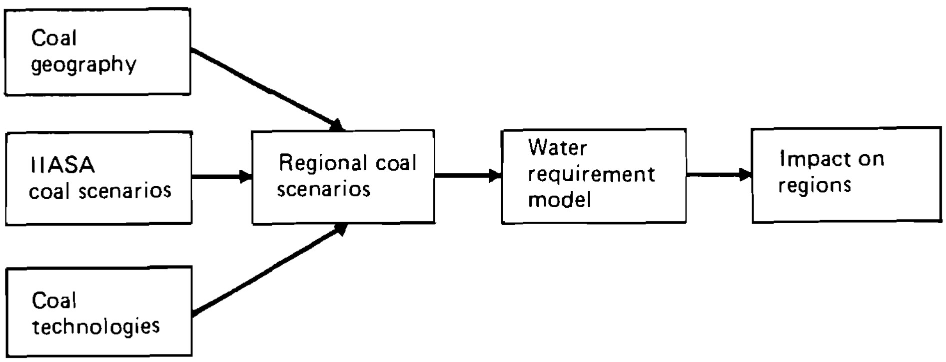

FIGURE 2 The systems approach to determining the impact of coal development on water resources.

Since IIASA's scenarios are presented for seven world regions, we must first disaggregate the coal production figures from roughly the continental scale down to the scale of coal-producing region. Figure 2 notes that knowledge of both coal geography and future coal technologies is used to construct these disaggregated regional scenarios.

An analytical tool or "model" is then developed and used to compute the water consumed in the different sectors of the coal industry. This model is used with the regional scenarios to estimate the water that will be needed for coal development within each coal-producing region. The final step in the analysis is to compare this water requirement with estimates of water available in each region.

2 FUTURE COAL TECHNOLOGIES

Obviously the water requirements of future coal development in the Soviet Union and the US will depend on the kind of technology that will be used in the future coal industry. Unfortunately, it is not so obvious what these technologies will be. It becomes easier to speculate once one realizes that the "lifetime" of a mine is on the order of 30 years or longer, as is the lifetime of a well designed and maintained power plant. It follows that much of the coal infrastructure that will exist in the year 2030 will have been designed, or even constructed, before the end of this century. With this in mind, it was decided to select only those technologies that are currently in use or are at an advanced stage of development. Technologies that are considered either technically or economically uncertain, such as fully automated mining, were not chosen.

Another important consideration in our selection of future coal technologies was to ensure that they were consistent with the type of coal uses cited in the IIASA scenarios. For example, the IIASA study incorporates coal liquefaction not gasification; in North America and the Soviet Union, therefore, liquefaction technologies had to be specified*. Another example is that the IIASA study assumes that much of the coal will be used for metallurgical purposes, so that coke preparation facilities also had to be included.

The result of this selection procedure is presented in Figure 3. In order to meet a "demand" on the right-hand side of this diagram coal must follow a path or "chain" through each of the six major coal sectors: (1) mining, (2) local transport, (3) processing, (4) regional transport, (5) conversion, and (6) demand. As Figure 3 notes, there are several possible technologies for each of these sectors.

(1) Two types of mining are distinguished: surface and underground. Underground mining is, in turn, subdivided into two categories, long-wall and room and pillar. The latter is by far the most common type of underground mining in the US, whereas long-wall is the predominant method used in Europe and the Soviet Union. Hydraulic mining is being discussed as an alternative to long-wall mining in the Soviet Union but its future share of total underground mining is still unclear (Gontov 1979, Astakhov 1979). It was assumed, therefore, that long-wall mining will continue to be the principal form of underground mining in the Soviet Union.

(2) "Local transport" refers to the movement of coal between mining and processing centers, which are often in close proximity. Two forms of local transport are included – truck and conveyor.

(3) Three alternatives are specified for coal processing: (*a*) enrichment facilities for low-grade coals destined for power plants; (*b*) cleaning and sizing facilities for higher-grade coals used in power plants or for residential or commerical heating; and (*c*) coke preparation for coking and other industrial coals.

*IIASA assumes that existing natural gas supplies in the US and Soviet Union are sufficient to meet their near-term gas demand.

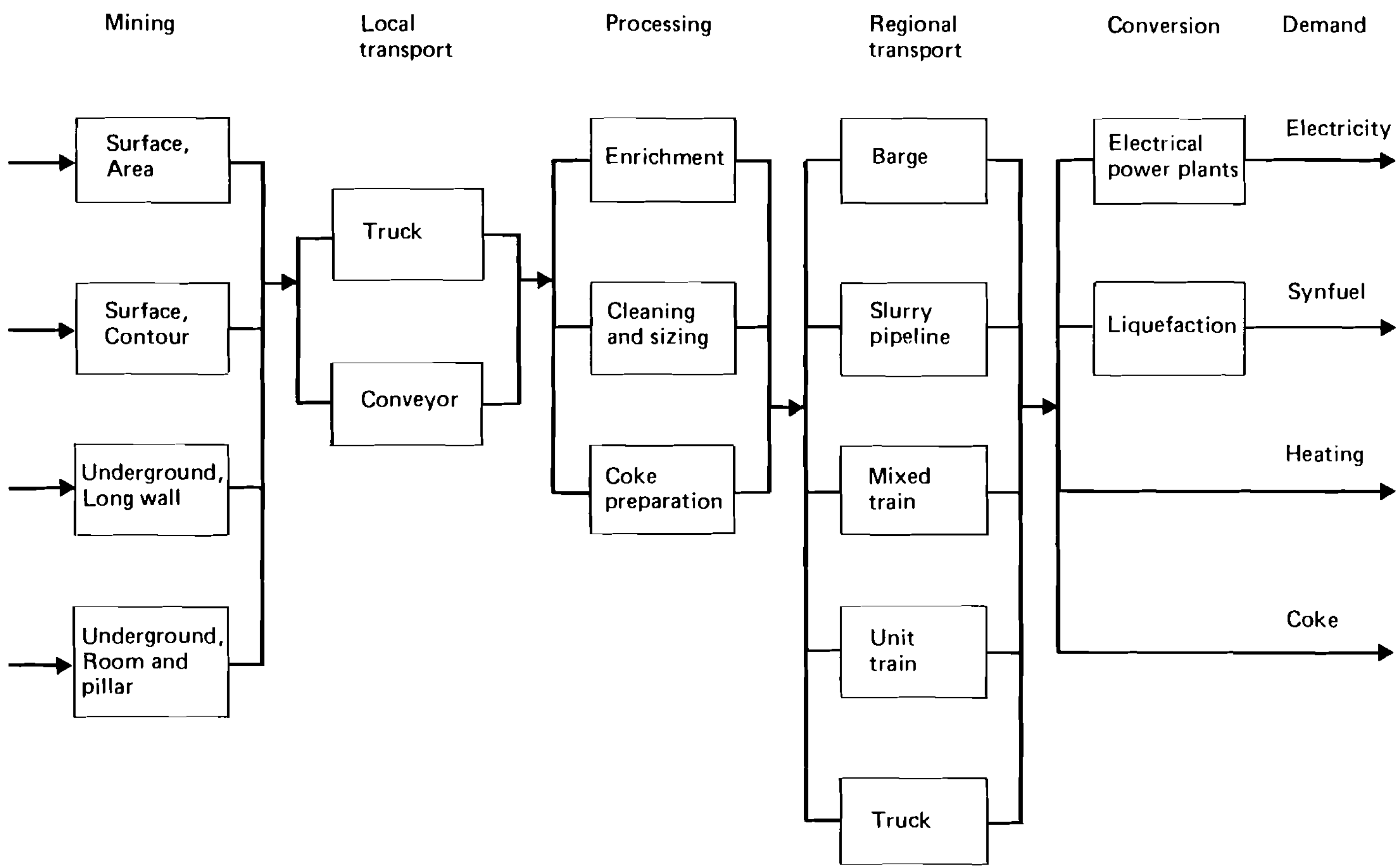

FIGURE 3 Selection of technologies for the coal industry in the future.

(4) "Regional transport" represents the distribution of coal from processing centers to either conversion facilities or demand centers. Five different transport modes were selected: barge, slurry pipeline, mixed train, unit train, and trucks. Barges are used in the Appalachian and Central coal regions of the US but not to the author's knowledge in the Soviet Union. Slurry pipelines are considered a future transportation alternative even though they are considered speculative by some. It seemed reasonable to include them in this model, however, because one is already in operation in the Four Corners coal region of the Southwestern US. Moreover, the US staff of the World Coal Study included slurry pipelines in their projections of future coal use in the US (WOCOL 1980a). There is also some discussion about their future use in the Soviet Union (Baibakov 1979), though in this paper no slurry pipeline transport was assumed for the Soviet Union. A mixed train refers to a train that carries non-coal cargo in addition to coal. A unit train carries only coal. Both types are currently used in the Soviet Union and the US. Trucks are currently used for short-distance haulage to conversion facilities or to other transportation modes in the Appalachian coalfields of the US.

(5) Figure 3 specifies two possibilities for coal conversion – electrical power plants and liquefaction. Power plants are assumed to be of the conventional combustion type. Liquefaction plants are assumed to use the synthoil process, which is used by Probstein and Gold (1978) to project water requirements of the future US synfuels industry. There are a few reasons for selecting synthoil as the future typical liquefaction process. First, it falls under the major category of liquefaction termed "hydrogenation", which is the category receiving significant research support in the US because of its possible technical feasibility (Schwaderer 1980, Predicasts, Inc. 1979). Secondly, according to Probstein and Gold (1978), synthoil consumes about the same amount of water as other feasible hydrogenation processes such as the so-called "SRC" and "H-coal" processes.

(6) The last sector, demand, specifies four possible forms of energy from coal – electricity, synfuel, heating (which includes electrical production via co-generation) and coke (which includes all industrial uses of coal, including feedstocks).

3 THE GEOGRAPHY OF COAL

To develop regional scenarios, one must understand the patterns and distribution of coal production and use in the Soviet Union and the US; in other words, understand the geography of coal.

3.1 The Soviet Union

A key feature of the Soviet Union's coal geography is the shift that is currently taking place in the location of coal production. Currently, over three-quarters of Soviet energy consumers live on one-quarter of its territory in the European part of the USSR (Styrikovich 1979). These energy consumers also use over three-quarters of the Soviet Union's total energy, and by the year 2000 it is unlikely that they will use less than 65–70% of the Soviet Union's energy (Styrikovich 1979). Much of this energy is provided by coal from a few European coal regions. By far the largest producer is the Donetsk, whose output overshadows all other coalfields in the USSR, as noted in Figure 4. High-quality coal from the Donetsk's underground mines satisfies much of the coking-coal needs of European-USSR

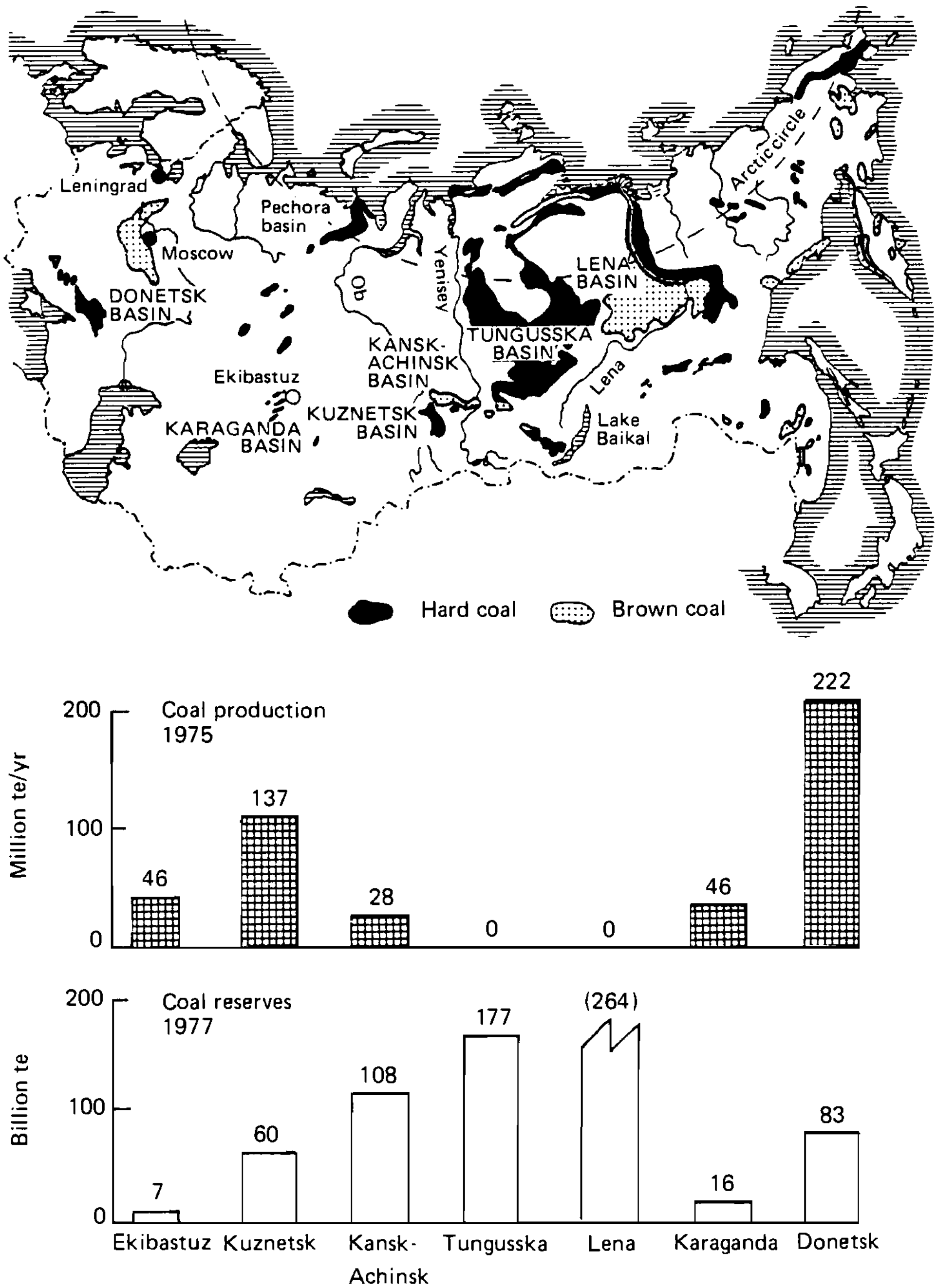

FIGURE 4 Coal production and reserves in the USSR. Sources: Coal production data from Shelest (1979). Coal reserves data are low estimates of known/identified reserves cited by Astakhov (1977). See text for explanation of estimates for Tungusska and Lena.

industry, as well as its heating and power production requirements. However, there are other important sources of high-quality coal, such as the Asian-USSR coalfields in Kuznetsk and Karaganda. In addition, lower-quality brown and hard coal is extracted cheaply from surface mines in other Asian fields such as Ekibastuz and the vast coalfields of Kansk-Achinsk. Unfortunately, the lower value of this coal makes it uneconomic to transport it to demand centers in the west of the country, so that it is therefore necessary to convert it to useful products. An example of this is the current plan to construct four huge electricity generating stations in Ekibastuz, each possessing eight power plants with a capacity of 500 MW (Styrikovich 1979). 40% of this electricity will be transmitted 2400 km to the European power grid.

Unfortunately for the Soviet coal industry, however, the mighty output of the Donetsk is stagnating, and may soon even decline. The root of the problem is the increasingly difficult mining conditions – one third of the mines are already worked down to depths of 1.2 km or deeper (Astakhov 1979) and they become 12 m deeper each year (Astakhov 1977). Deepening mines result in more difficult working conditions, as well as increasing technical problems. In addition, some entire coalfields in the Donetsk have been exhausted and few undeveloped fields remain. All this adds up to stagnating production and increasing costs.

If the Donetsk cannot meet the possible fourfold expansion in production, then where will this coal come from? It is clear from the diagram of coal reserves in the Soviet Union (Figure 4) that it will have to come mostly from the rich reserves of Soviet Asia, such as the Siberian fields of Lena and Tungusska, which are not only undeveloped but virtually unexplored. However, the reserve estimates for these fields shown in Figure 4 represent a possibly optimistic 10% of total resources*. But if this estimate is correct, then an enormous quantity of coal lies in these fields.

In summary, it is clear from Figure 4 that production by the year 2030 will have to shift to the eastern part of the USSR. Furthermore, much of this coal will probably be converted to useful products near the coal mines and then sent to the European part of the USSR.

3.2 The United States

A locational shift of the same magnitude is also occurring in US coal regions. Figure 5 shows that much of current US production originates in the Appalachian coalfields. High-quality coal from these fields is used in the industrial East, while Central region high-quality coals serve much of the industrial corridor in the vicinity of Detroit and Chicago (Figure 5). Production of the mostly lower-quality coal in the West is now substantially lower than the sum of Appalachian and Central coal production, but as Figure 5 notes, the reserves of US coal are largely in the West, where the coal can also be extracted rather easily in surface mines. Other constraints notwithstanding, it is likely that future production will shift from east to west in the US.

*10% is roughly the ratio of estimated reserves to resources for the Asian fields of Kuznetsk and Kansk-Achinsk presented by Astakhov (1977). Data provided by mining engineer Günter Fettweiss (1979), however, suggests that this may be an optimistic estimate for the remote fields of Lena and Tungusska.

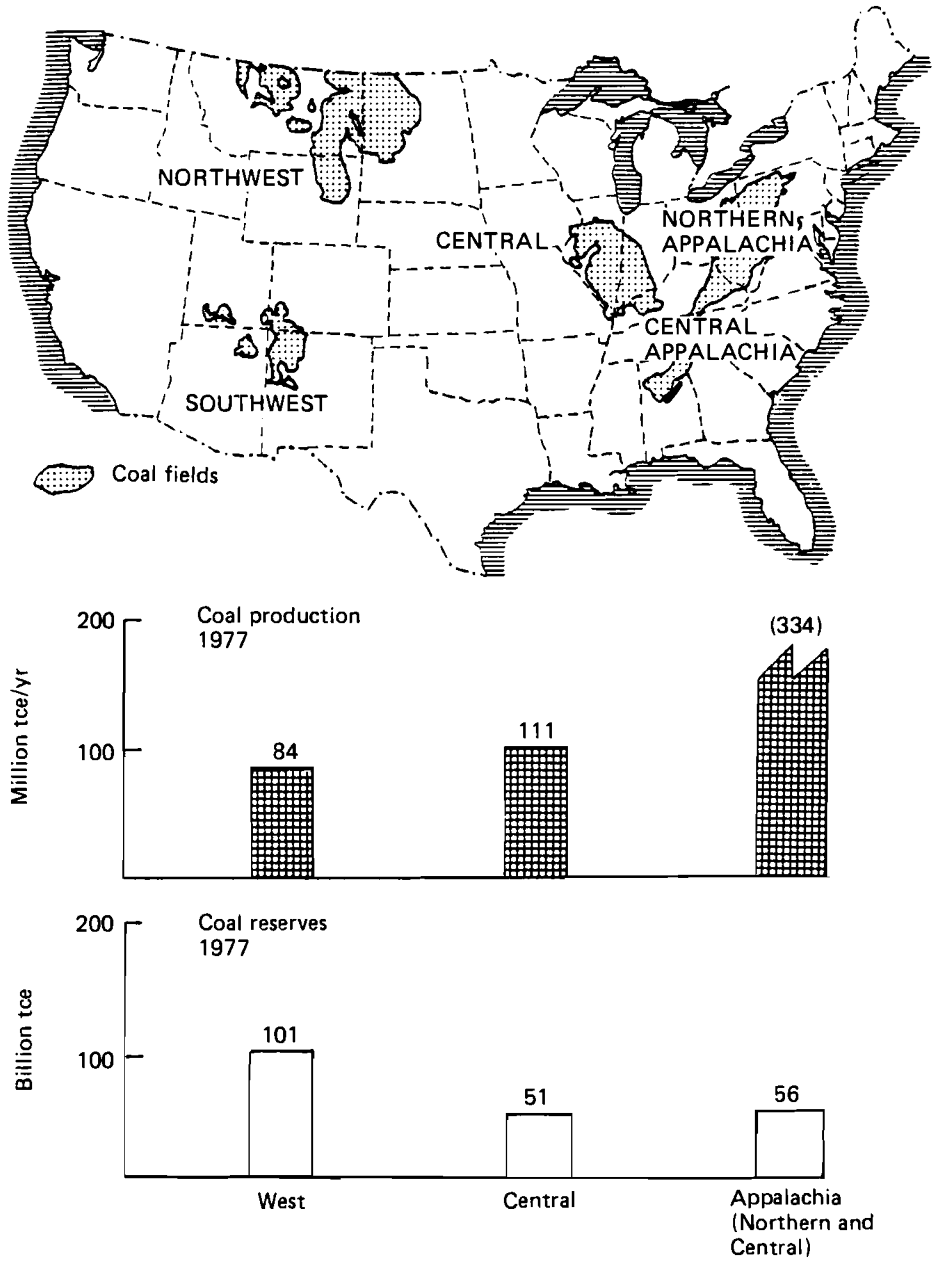

FIGURE 5 Coal production and reserves in the US. Sources: Coal production data adapted from OTA (1979) using average coal heat values from Hittman (1974). Coal reserves data from the US National Academy of Sciences (1974).

These major geographic shifts set the "tone" for future coal development in the Soviet Union and the US, and provide a departure point for the construction of the regional coal scenarios.

4 REGIONAL COAL SCENARIOS

Figure 2 notes that we should combine our knowledge of current and future coal geography with our selection of future coal technologies in order to devise regional scenarios for future coal development in the Soviet Union and the US. It is appropriate now to clarify the term "regional scenario": in this report each scenario consists of the following information for each coal-producing region:

- total coal production;
- quantity of different coal "products"*;
- type of coal technologies employed within each region**;
- coal characteristics.

The main guidelines used in constructing these scenarios were as follows. First, upper limits were set on total coal production in a region when this information was available. In addition, a rough upper limit of about 6%/yr was set on the rate of expansion of coal production for any one region. Recent expansion of coal production in Ekibastuz demonstrates that this is an achievable upper limit for at least a short period of time. Between 1975 and 1979 production was reported to have increased by 31%, which is equivalent to a 5.5%/yr expansion for that five-year period (Shabad 1980). But this rate of expansion has also been sustained over a much longer period of time in the Kuznetsk Basin, where production increased from 21 to 134 million te/yr between 1940 and 1975, an annual rate of expansion of 5.4%/yr (Astakhov 1977).

Secondly, the quality of coal in a particular coal region was matched with the "type" of coal products needed. For example, IIASA estimates in its Low scenario that the Soviet Union will produce 0.2 billion tce/yr of coking coal. Since the Kuznetsk possesses over 50% of the USSR's coking coal reserves (Lelyukhina 1973), this region was allocated most of the country's total coke production. The proximity of the coal region to potential consumers is also an important factor. In the case of Ekibastuz, for example, it would be uneconomic to transport low-quality coal thousands of kilometers to European demand centers for residential heating or industrial use, but it may be economic to convert it first to electricity, as is currently planned. Therefore a significant amount of the Soviet Union's future coal-electricity requirement was assigned to Ekibastuz.

The third guideline is that regional scenarios were based wherever possible, on existing authoritative forecasts. At least two such forecasts exist for the US, one from the World Coal Study (WOCOL 1980a) and the other from the Office of Technology Assessment (OTA), a research arm of the US Congress (OTA 1979), both of which estimate the same magnitude of future coal production in the US as IIASA's Low scenario. Calculations in this report were based on OTA figures because they were available on a state by state basis, whereas the WOCOL figures were regionally aggregated. Unfortunately, similar regional scenarios were unavailable for the Soviet Union.

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*Coal "products" include liquid fuels, electricity, heating, and industrial coals.

**For example, a particular coal region might use 50% surface mining and 50% underground mining.

TABLE 1 Low and High regional coal scenarios for the year 2030 (coal production in billion tce/yr).

Region	Low scenario	High scenario
Soviet Union[a]		
1. Ekibastuz	0.1	0.1
2. Kuznetsk	0.5	1.0
3. Kansk-Achinsk	0.4	1.0
4. Donetsk	0.2	0.2
5. Tungusska	0	1.0
United States[a]		
1. Southwest	0.15	0.27
2. Northwest	0.41	0.75
3. Central	0.23	0.43
4. Northern Appalachia	0.26	0.48
5. Central Appalachia	0.32	0.58

[a] See Figures 4 and 5 for locations of these regions. US regions are defined in Table A4.

Finally, current plans to expand coal production, such as those to construct four power plant complexes at Ekibastuz over the next 10 years, were incorporated into the scenarios.

Following these guidelines, the Low and High regional scenarios presented in Table 1 were constructed. The specific assumptions behind these results are presented in Appendix A.

An important question raised by these scenarios is: Do these regions have adequate reserves to reach such levels of production? Figure 6(*a*) shows a hypothetical scenario of coal production for a particular region, in this case Ekibastuz. If we assume an exponential growth in production from 1975 to 2030 we obtain curve A in this figure. The shaded area under this curve represents the total amount of coal that will be taken out of the ground in those years. We can then compare this cumulative production with the region's estimated reserves. This computation was performed for each region, and the results indicate that some regions would, in fact, consume much of their reserves. Regions with particular problems are noted in Figure 6(*b*). For the High scenario, Ekibastuz and Kuznetsk in the Soviet Union, and Appalachia in the US are expected to consume one-half or more of their reserves. It follows that coal mining will be very expensive in these regions by the year 2030. It is also important to note that reduced production levels in these areas would only shift the supply burden to the reserves of other regions.

Another important finding from these regional scenarios is that existing Soviet coalfields could probably meet the requirements of the Low scenario, but it may be necessary to open up entirely new coalfields in order to meet the production targets of the High scenario. In order to meet these additional requirements the choice seems to be between two largely undeveloped Siberian coalfields, the Lena and Tungusska. Tungusska was selected because it is located further south from the Arctic Circle than the Lena Basin, and may therefore have better climatic conditions, and also because it possesses higher-grade coal (Astakhov 1977).

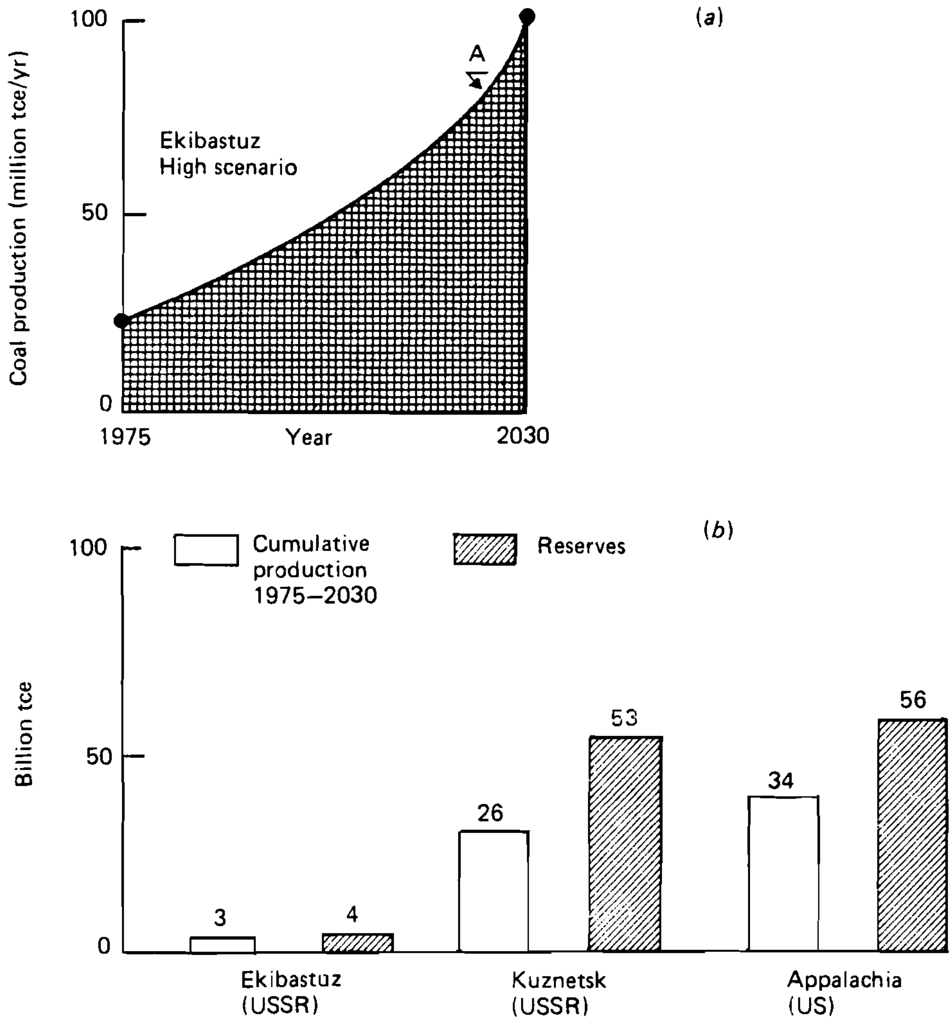

FIGURE 6 Comparison of cumulative coal production with current estimates of reserves. (*a*) Ekibastuz, High scenario, 1975–2030; (*b*) comparison of Ekibastuz, Kuznetsk, and Appalachian coal regions, cumulative production and reserves. Coal production data based on the High scenario figures given in this report.

5 A WATER-CONSCIOUS FUTURE

Now that we have estimated the quantity and location of future coal production and processing, and the methods by which this coal will be extracted, transported, and processed, we can proceed to compute the industry's water requirements.

Of paramount importance, this report assumes a "water-conscious" future in which planners will be aware of regional or local constraints on water use and will therefore have

TABLE 2 Water requirements of various stages of coal processing.

Mining
• Dust control
• Revegetation
Preparation
• Dust control
Transport
• Slurry water
Conversion (power plants, liquefaction)
• Process water
• Cooling water
• Pollution control
• Ash disposal
• Dust control

the economic and political incentive to maximize water conservation. It follows that all wastewater streams will be treated and recycled, and that other strict conservation measures will be taken in water-short areas. But is this an economically reasonable assumption? One set of investigators (Probstein and Gold 1978) maintain that the cost of water treatment to provide recycled water in a synthetic fuels complex will probably not exceed 5% of the final cost of the product. Maximum water conservation may therefore be affordable. This water-conscious future also influences the selection of power plant and liquefaction cooling techniques, which are among the most significant water consumers in the coal industry (Harte and El-Gasseir 1978). Assumptions relevant to cooling are discussed in Appendix C.

After assuming maximum water recycling, we are left with the list of ways in which water is consumed, as presented in Table 2. These include water lost by evaporation during dust control in mining, processing, and conversion facilities. Water is also evaporated during the cooling processes of liquefaction and power plants, and is the "basic ingredient" of pipeline slurry and various process streams in liquefaction plants. Theoretically it can be reclaimed from pipeline slurry, but this report assumes that it would be uneconomic to do so.

Water is lost in the disposal of sludges originating from ash residues of liquefaction plants and scrubber equipment of pollution control devices. As with the pipeline slurry, it is assumed that water associated with these sludges cannot be economically recovered. Water is also lost with the flow of "scrubbed" air in pollution control devices.

To compute the amount of water required for each of these uses, an analytical tool or "model" was developed. Equations in the model were based mostly on the work of Probstein and his colleagues at the Massachusetts Institute of Technology and Water Purification Associates (Probstein and Gold 1978, Gold *et al.* 1977). The model equations presented in Table 3 vary from the simple "black-box" type to more complex expressions containing several independent variables. For example, the equation used to compute water lost through power plant cooling (Table 3, eqn. 6) is of the "black-box" variety. A single value is assigned to the amount of water used per energy unit of coal combusted in a plant.

TABLE 3(*a*) Water requirement equations.

Surface mining	
$W_1 = b/e\,(y_{11}\,\alpha_{11} + y_{12}\,\alpha_{12})\,12.0$	(1)
Underground mining	
$W_2 = 0.067\,(y_{13}\,\alpha_{13} + y_{14}\,\alpha_{14})$	(2)
Cleaning and preparation	
$W_{32} = 0.0125\,y_{32}\,\alpha_{32}$	(3)
SRC	
$W_{34} = (1 + d)\,y_{34}\,\alpha_{34} + 0.75\,y_{34}\,a$	(4)
Slurry pipeline	
$W_{42} = f y_{42}$	(5)
Power plant cooling	
$W_{51a} = g X_{51}$	(6)
Power plant FGD unit	
$W_{51b} = (WF_1 + WF_2)\,y_{51}$	(7)
Liquefaction process and dust control	
$W_{52a} = j X_{52} + 0.01\,y_{52}$	(8)
Liquefaction cooling	
$W_{52b} = k X_{52}$	(9)
Liquefaction FGD unit	
$W_{52c} = (WF_1 + WF_2)\,y_{52}$	(10)
FGD – water loss	
$WF_1 = 1.07c + 0.4s + 2.51h - 0.33x - w$	(11)
FGD – ash disposal	
$WF_2 = 8.85\,s$	(12)

TABLE 3(*b*) Constants and variables in water requirement equations*.

a = wt. fraction, ash/coal (te/te)
b = potential evaporation rate (cm/yr)
c = wt. fraction, carbon/coal (te/te)
e = yield of coalfield (te/ha)
f = water:coal ratio in slurry pipeline (te water/te coal)
g = cooling water required for power plant ($m^3/10^{15}$ J input)
h = wt. fraction, hydrogen/coal (te/te)
j = process water required for liquefaction ($m^3/10^{15}$ J input)
k = cooling water required for liquefaction ($m^3/10^{15}$ J input)
s = wt. fraction, sulfur/coal (te/te)
w = moisture content of coal (te/te)
W = water requirements of coal process (m^3/yr)*
x = wt. fraction, oxygen/coal (te/te)
X = energy equivalent of coal input to process (10^{15} J)
y = coal input to process (te/yr)*
α = efficiency of coal process (fraction)*

*In developing equations for the water requirement model, the following convention was used to denote the variables: water requirement is assigned the variable W, the amount of coal input to a process y, and the energy equivalent of this coal x. A double-digit subscript is assigned to each variable; the first refers to the major coal development sectors noted in Figure 3, and the second to a particular process in one of these sectors. For example, in Figure 3, the first sector is mining and the first process in this sector is surface-area mining. Therefore, a variable referring to surface-area mining would have a subscript 11. The water requirement of a surface mine is thus denoted W_{11}.

This value is then multiplied by the total tonnage of coal combusted in power plants in a particular coal region to obtain the amount of water used. Note, however, that the selection of a value for water requirement per unit coal is based on water conservation considerations detailed in Appendix C.

An example of a more complex equation is the expression used to determine the amount of water consumed in pollution control equipment (Table 3, eqn. 11). This equation computes water loss as a function of the five principal chemical components of coal.

The development of these and other model equations is described in Appendix B. Inputs to the equations are fully discussed in Appendix C.

6 HOW MUCH WATER IS NEEDED?

Using the water requirement model with the prescribed inputs from each of the coal regions, we obtain the results presented in Table 4 for the Low and High regional scenarios. The amount of water consumed for various regions ranges from about 0.1 to 1.0 km^3/yr. For perspective, we can compare this range to average flows of major water delivery projects in the US and the Soviet Union. For example, in the Soviet Union the Volga–Moscow Canal transfers about 2.3 km^3/yr from the Volga River to the thirsty industrial and residential areas around Moscow, while the California Project in the US brings 4.2 km^3/yr of water from water-rich northern California to rapidly growing and arid southern California (Golubev and Vasiliev 1978). Since the projected requirement for water in coal-producing regions (0.1–1.0 km^3/yr) approaches the magnitude of these water projects, one may conclude that a significant water resource engineering effort will be necessary to meet these water requirements.

It is also instructive to look at the "water intensity" of coal development, i.e., the amount of water required to deliver a specific quantity of coal from mining to delivery of final fuels. This is obtained simply by dividing the total water requirement for the US and

TABLE 4 Water requirements of the High and Low regional scenarios for the year 2030, with pollution controls (in km^3/yr).

Region	Low scenario	High scenario
Soviet Union		
1. Ekibastuz	0.27	0.27
2. Kuznetsk	0.43	0.77
3. Kansk-Achinsk	0.69	0.84
4. Donetsk	0.07	0.07
5. Tungusska	–	0.58
United States		
1. Southwest	0.26	0.47
2. Northwest	0.65	1.01
3. Central	0.55	0.99
4. Northern Appalachia	0.46	0.51
5. Central Appalachia	0.63	0.62

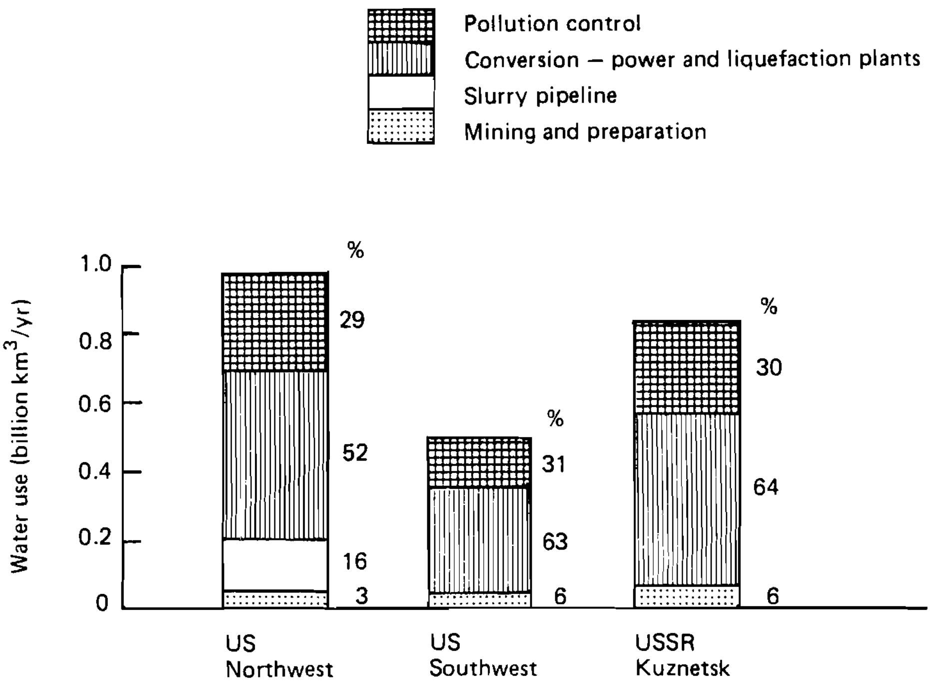

FIGURE 7 Breakdown of coal-related use of water, based on High scenario calculations.

the Soviet Union (in km^3/yr) by the amount of coal-fuel delivered (in billions of tce/yr). This calculation yields a water intensity for the two countries of about 1–2 km^3 water per billion tce coal. In other words, 1–2 tons of water are consumed for every ton-equivalent of coal-fuel delivered*.

It is important to recall, however, that these figures are based on the assumption of strict water conservation practices. A sensitivity analysis described in Appendix C notes that less water-conscious practices could use over 50% more water; i.e. 1.5–3.0 tons of water may be necessary for each ton-equivalent of coal-fuel delivered.

Also of interest is the breakdown of total water requirements according to the different sectors of coal development. Figure 7 shows, for instance, that water consumed by the flue gas desulfurization equipment necessary to control air pollution is about 30% of the total water requirement, while mining and processing use 6% or less. Figure 7 also notes that the slurries that are assumed to transport some of the coal in the Northwestern US consume over 15% of the total amount of water for the coal industry in that region.

*Since national figures were used for this computation, this "coal-fuel delivered" consists of a mix of coal for liquids, electricity, heating, co-generation, and industry.

7 IS THERE ENOUGH WATER?

Now that we have an idea how much water we will need for coal in the major coal-producing regions we can ask: Will there be enough water available to satisfy this need? We can begin to answer this question by comparing the water requirement for coal with the amount of surface runoff of the water basin in which the coal-producing region is located. This is an arbitrary yet reasonable judgement since it assumes that a coal region can draw more economically on surface water than on groundwater. It is an especially realistic assumption for the US because groundwater overdrafting is already a major problem throughout much of the country. It also implies that it is more economic to take advantage of topography and gravity and draw water from within a basin than from outside it. This approach has already been used in studies for the US government conducted by Harte and El-Gasseir (1978) and March (1974).

For the US, the demarcation of major drainage basins by the US Water Resources Council was used. Figure 8 notes the basins that are assumed to provide water for the coal-producing regions. Figure 9 compares the mean annual surface runoff in these basins (column 2) with computed water requirement for coal in the year 2030 from the High scenario case with pollution control (column 1). It is clear that there should be no *absolute* shortage of water for coal development, but this is, of course, a simplistic conclusion since this amount of water is not available each year. More reasonable measures of long-term

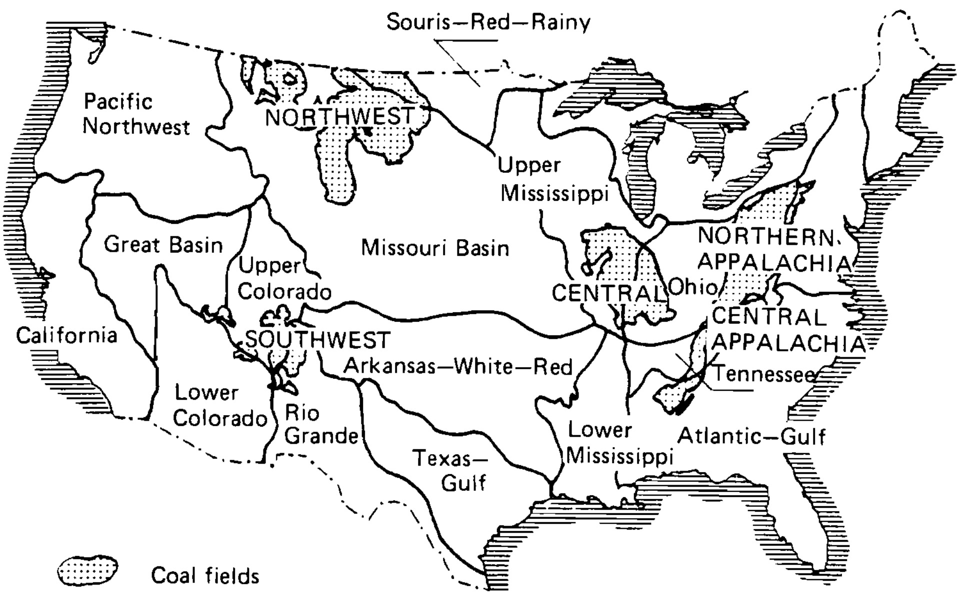

FIGURE 8 US coal regions and major drainage basins. Note that regions are matched with basins as follows: Northwest – Missouri basin; Southwest – Upper Colorado and Rio Grande basins; Central – Upper Mississippi basin; Northern Appalachia – Ohio basin; Central Appalachia – Tennessee and Atlantic Gulf basins. Source: details of water basins from US Water Resources Council (1978).

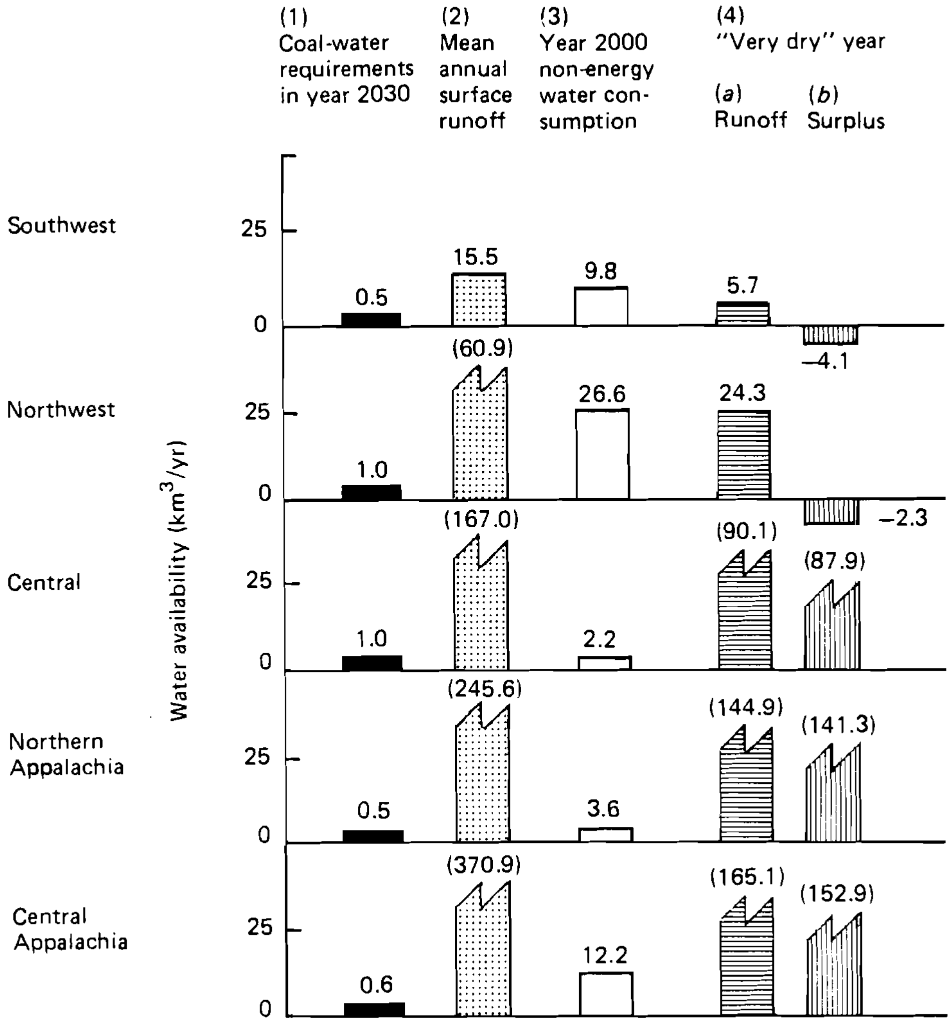

FIGURE 9 Future availability of water for coal production in the US. Column 4(*b*) gives the difference between dry-year runoff (column 4*a*), and non-energy water consumption (column 3). Sources: Water requirement for coal is computed elsewhere in this report and refers to the High scenario. Runoff data and non-energy water consumption have been taken from US Water Resources Council (1978a, b).

water reliability are the basins' drought flows presented in column 4(*a*). These are the annual flows of 95% exceedance, i.e., those flows that are exceeded in 95 out of 100 years and occur during "very dry years" (US Water Resources Council 1978b).

By comparing the coal water requirements (column 1) with these low flows (column 4*a*) we can see that there is still sufficient water for coal development, though in some cases coal requires a large fraction of this flow. For example, water needed for coal development in the Southwest is nearly 10% of the region's low flow.

But for a better grasp of the future availability of water we should also account for water uses that will compete with the coal industry. Column 3 in Figure 9 presents the projected water requirements for non-energy activities estimated by the US Water Resources Council (1978a, b) for the year 2000*. Column 4(*b*) gives the surplus water remaining after this non-energy water demand has been subtracted from the low flows. In the case of the Southwest and Northwest US, a water deficit is observed, which implies that the coal industry will displace other projected water needs, such as irrigation and municipal water supply during dry years in these regions. For the Central and Appalachian coal regions, Figure 9 suggests that ample water should be available for all uses, even during low flow years.

However, it is important to note that this analysis takes a somewhat conservative approach and may therefore underestimate the possible severity of the future water supply problem in a few significant ways. First, as discussed earlier, a good deal of water-consciousness has been assumed for the future coal industry. As also noted previously, water requirements could actually be 50% greater than this report assumes. Secondly, non-energy water requirements were probably underestimated because projections for the year 2000 instead of for 2030 were used. Since it is likely that water requirements will continue to increase beyond the year 2000, it is also likely that this report underestimates the non-energy water requirements of the year 2030.

Finally, "in-stream" water requirements were neglected. These "in-stream" requirements, which are necessary for both maintenance of fish and wildlife habitats, as well as navigation channels, may amount to *50% or more* of the *mean annual surface runoff* of these water basins (US Water Resources Council 1978a, b).

For the Soviet Union, the type of information used in the US analysis was unavailable in the published English literature. For example, the size of the drainage basins that would provide water for the coal-producing regions was unknown. But we can devise a crude estimate of water availability by assuming that the Soviet Union's drainage basins are of the same scale as those that provide water for coal in the US (roughly 50 000–200 000 km^2). Table 5 uses this rough estimate together with known values of mean annual surface runoff (in cm/yr) to compute average runoff values in Soviet coal regions. Low

TABLE 5 Estimates of water availability in Soviet coal regions.

Region	Coal-water requirement (km^3/yr)[a]	Mean annual surface runoff (km^3/yr)[b]	Low flow (km^3/yr)[c]
Ekibastuz	0.27	0.5–2.0	0.3–1.0
Kuznetsk	0.77	25–100	12.5–50
Kansk-Achinsk	0.84	10–40	5–20
Donetsk	0.07	5–20	2.5–10
Tungusska	0.58	7.5–30	3.8–15

[a] From this report, High scenario with pollution controls.
[b] Computed as the product of the mean annual surface runoff (cm/yr), from UNESCO (1978), and drainage area (50 000–200 000 km^2).
[c] Low flow = 50% mean annual surface runoff.

*The US Water Resources Council only provides estimates up to the year 2000.

flows in these regions are taken to be 50% of the mean flow. Although these figures are rough, they are nonetheless informative. For instance, they indicate that coal development in Ekibastuz may consume much of the region's available water; in Kansk-Achinsk and Tungusska it may deplete up to a quarter of the estimated low flows; and that Kuznetsk may also experience pressure for water. In addition, note that competitive water uses in these regions (for example, for agriculture or municipal water supply) were not accounted for.

A more direct comparison between coal-water requirements in the US and the Soviet Union is made in Table 6, which presents estimated drainage area sizes that will be needed to provide water for each coal region. As expected, the drier regions will require larger areas from which to draw water for their coal industry. Ekibastuz, the driest of the coal regions, with only about 1 cm/yr of surface runoff (UNESCO 1978), will need the runoff from about 27 000 km^2 during an average year to meet its coal-related water requirements. The arid Northwest and Southwest coal regions of the US, will need drainage areas of the same scale (on the order of a few thousand km^2) as three of the five Soviet coal regions: Kansk-Achinsk, Kuznetsk, and Tungusska. These numbers suggest that the level of effort needed to provide water for coal in the American West will be comparable with the effort needed in the Soviet Union's major coal regions.

TABLE 6 Drainage area required to satisfy coal-water requirements.

Coal region	Coal-water requirement (km^3/yr)[a]	Drainage area required (km^2)[b]
Soviet Union		
1. Ekibastuz	0.27	27 000
2. Kuznetsk	0.77	1540
3. Kansk-Achinsk	0.69	3450
4. Donetsk	0.07	700
5. Tungusska	0.58	3870
United States		
1. Southwest	0.47	1770
2. Northwest	1.01	2690
3. Central	0.99	780
4. Northern Appalachia	0.51	190
5. Central Appalachia	0.62	230

[a] From Table 4, High scenario.
[b] For the USSR, computed from

$$\frac{\text{coal-water requirement (km}^3\text{/yr)}}{\text{mean annual runoff (cm/yr)} \times 10^{-5}}$$

For the US, computed from

$$\frac{\text{coal-water requirement (km}^3\text{/yr)} \times \text{drainage area (km}^2\text{)}}{\text{mean annual runoff (km}^3\text{/yr)}}$$

Runoff and drainage areas for the US were obtained from US Water Resources Council (1978a, b). Runoff for USSR from UNESCO (1978). All values have been rounded.

8 CONCLUSIONS

The "order of magnitude" calculations presented in this report are informative despite the rough approximations they invoke. For example, by disaggregating IIASA's coal scenarios from the "world-region" scale down to the scale of "coal-producing" region, it was found that it will be difficult to meet implicit production targets for certain coal regions. In trying to attain IIASA's High scenario coal future, the US would probably deplete a significant proportion of its Appalachian coal reserves and the Soviet Union its Kuznetsk and Ekibastuz reserves. Furthermore, for this scenario it may be necessary for the USSR to develop an entirely new and remote Siberian coalfield, such as Tungusska.

It was also found that if we assume a water-conscious future in which the coal industry is motivated to conserve water, then about 1–2 tons of water will be required in both countries for each ton-equivalent of coal-fuel delivered. This figure might be 50% larger if the coal industry is less concerned about water conservation.

In addition, we found that the water requirement for coal in the US coal regions was relatively small compared with future non-energy water uses in these regions. However, if we subtract these non-coal water uses from the water available during low flow years in the Southwest and Northwest, we discover that no water will be left for coal, no matter how small the water requirement. Coal will probably have to displace other uses in those regions, such as crop irrigation and municipal water supply.

In the Soviet Union we should expect intense pressure for water in Ekibastuz, while less severe competition may be seen in Kansk-Achinsk, Tungusska, and Kuznetsk, in that order.

Overall, it appears that a four- or fivefold expansion of coal production in the Soviet Union and the US, as estimated in IIASA's High scenario of *Energy in a Finite World*, is likely to be constrained to some degree by the lack of readily available water. Both nations possess rich coal reserves, but both must confront the same problem of how to create fire with limited water.

ACKNOWLEDGMENTS

The author is indebted to his many colleagues at IIASA, particularly Eliodoro Runca, Arnulf Grübler, Kurt Fedra, Wolfgang Sassin, Leo Schrattenholzer, and Janusz Kindler for their helpful comments and support of this research. He also wishes to express his appreciation to Valerie Jones for editorial assistance, and to Anka James and Ewa Delpos for their graphics contributions to this publication.

APPENDIX A DEVELOPMENT OF REGIONAL COAL SCENARIOS

Details of the regional coal scenarios are described in this appendix. As noted in the text of this report, the scenarios consist of (1) total coal production for each region; (2) "type" of coal "products"; (3) technologies used to develop this coal; and (4) coal characteristics. This last item is discussed in Appendix C, together with other inputs to the water requirement model.

1 Regional Scenarios for the USSR

Tables A1 and A2 describe the regional scenarios that were disaggregated from the IIASA High and Low scenarios, respectively (Häfele 1981a). Since IIASA's region II combines Eastern Europe and the USSR, it was first necessary to subtract the coal production expected from Eastern Europe in the year 2030, most of which was assumed to come from Poland*. Figures from the 1977 World Energy Conference (Schilling 1979) suggest that by the year 2020 the coal production of Poland should be about 0.32 billion tce/yr, compared with 1.8 billion tce/yr from the USSR. If we apply this same ratio to the IIASA Low scenario, we obtain a production figure of 0.25 billion tce/yr for Poland, and 1.41 billion tce/yr for the USSR. The Soviet figure was then allocated to different coal "products" (coke, electricity, etc.), according to the proportions given in Häfele (1981a) (see Table A1).

For the IIASA High scenario, it was assumed that Poland's coal output would be limited to Schilling's (1979) estimate of 0.32 billion tce/yr since its production capacity is much lower than that of the USSR. This gives a coal production figure for the USSR of 3.5 billion tce/yr.

TABLE A1 USSR Low scenario, year 2030 (coal production in billion tce/yr).

Region	Total production	Coke	Electricity	Synfuel	Heat	Export
1. Ekibastuz	0.10[a]	0	0.05[a]	0	0.05[a]	0
2. Kuznetsk	0.50[e]	0.14[h]	0.10	0.04[j]	0.22[i]	0
3. Kansk-Achinsk	0.40[e]	0	0	0.40[j]	0	0
4. Donetsk	0.20[b]	0.03[h]	0.01[k]	0	0.16[k]	0
Other European-USSR	0.09[b]	0	0	0	0.09[k]	0
Karaganda	0.05[c]	0.02[f]	0.03[f]	0	0	0
Other Asian-USSR	0.06[d]	0.01[h]	0.01[l]	0	0.03[l]	0.01[l]
Total	1.4[a]	0.20[a]	0.20[a]	0.44[a]	0.55[a]	0.01[a]

[a] See text of Appendix A.
[b] Assuming 20% decline in 1975 European coal production.
[c] Assuming 1%/yr growth rate in 1974–2000; no growth in 2000–2030.
[d] 1975 production level.
[e] The remaining coal requirement was allocated to Kuznetsk and Kansk-Achinsk after all other regions had received their allocations. Kuznetsk production is greater because current output is higher.
[f] Assuming approximately the same use of coal as in the late 1970s (see Dienes and Shabad 1979).
[h] Most of the coke was allocated to Kuznetsk, which possesses 50% of the most economically recoverable reserves in the USSR. The remaining coke was assigned to Donetsk and Karaganda, which are current coke producers with reserves (see Lelyukhina 1973).
[i] Good-quality coal, suitable for heating purposes.
[j] Since Kansk-Achinsk has low-quality coal, it is assumed that this will be used for synfuels, and the remaining synfuel requirements will be met by Kuznetsk, the other future large coal-producing region.
[k] Assuming that most electricity will be provided by low-quality coal from Asian-USSR, and that European-USSR will provide high-quality heating coals.
[l] Assuming that all exports originate from these regions, since some coal is located in East Asia and is suitable for export to Japan. The remainder is allocated to electrical and heating needs in these regions.

*See, for example, WOCOL (1980a).

TABLE A2 USSR High scenario, year 2030 (coal production in billion tce/yr).

Region	Total production[a]	Coke	Electricity	Synfuel	Heat	Export
1. Ekibastuz[e]	0.10	0	0.05	0	0.05	0
2. Kuznetsk	1.00	0.14	0	0.34[b]	0.09	0.43[d]
3. Kansk-Achinsk	1.00	0	0.10	0.40[b]	0.34[a]	0.16[a,d]
4. Donetsk[e]	0.20	0.03	0.01	0	0.16	0
5. Tungusska	1.00	0.08[c]	0	0.30[b]	0.41	0.21[d]
Other USSR[e]	0.20	0.03	0.04	0	0.12	0.01
Total	3.5[a]	0.28[a]	0.20[a]	1.04[a]	1.17[a]	0.81[a]

[a] See text of Appendix A.
[b] Maintaining same synfuel output in Kansk-Achinsk as in Low scenario because production already very high (0.4 billion tce/yr). Remainder of synfuel requirement is allocated to Kuznetsk and Tungusska.
[c] Total coke production in High scenario exceeds coke production in Low scenario by 0.08 billion tce/yr; this is allocated to Tungusska, which has high-quality coal.
[d] Export allocated to large coal-producing areas: Kuznetsk, Kansk-Achinsk, and Tungusska, since it is assumed that other areas will satisfy domestic requirements of Soviet Union.
[e] Same as Low scenario.

The total Low scenario production figure for Ekibastuz given in Table A1 was determined by incorporating plans to construct four enormous mine-mouth power complexes, each containing eight 500 MW power stations. The total generating capacity of each complex will be 4000 MW, 40% of which will be transmitted over 2000 km to the European-USSR power system (Dienes and Shabad 1979). Assuming that each power complex will use about 16 million metric tons of coal per year (Dienes and Shabad 1979), this means that a total of 64 million te/yr will be needed from the Ekibastuz coalfields. The sum of this plus the present (1975) production of 46 million te/yr, means that 110 million te/yr will be required. Astakhov (1979), however, states that the production of Ekibastuz will probably not increase beyond the year 2000 because mining activity is already concentrated on the largest reserves. It was therefore assumed that a reasonable production limit for the year 2030 would be 50% greater than the computed 110 million te/yr, or 165 million te/yr. This is comparable with Shelest's (1979) estimate of 150 million te/yr as an upper limit to production in Ekibastuz. At a heat value of 4250 kcal/kg*, this is equivalent to roughly 100 million tce/yr.

Even though most of the coal in Ekibastuz is planned for power plant use, only half of the 100 million tce/yr for the year 2030 was allocated for electricity (Table A1). This is because the IIASA Low scenario calls for only 200 million tce/yr coal-electricity for the entire USSR in the year 2030, since the study assumes that nuclear power plants will replace coal-fired plants after the year 2000. Therefore, if the entire production of Ekibastuz (100 million tce/yr) was allocated to electricity, this would provide 50% of the coal-electricity of the country. Since this seemed to be an unreasonable assumption, only half of the output (50 million tce/yr) was assigned to electricity and the remainder to heating. This allocation resulted from: (1) assuming that synfuel use will be concentrated in Kansk-Achinsk, and (2) the shorter transportation distances to the main consumer centers justifies processing of heating coals.

*From Table C1.

TABLE A3 USSR regional coal technologies.

Technology	Efficiency (%)[a]	Regional use (%)[b]				
		1	2	3	4	5
Mining						
Surface	80	100[c]	75[f,g]	100		50
Underground						
Long wall[h]	85		25[g]		100	50
Room and pillar	57					
Local transport[d]						
Truck	100	50	50	50	50	50
Conveyor	100	50	50	50	50	50
Processing						
Enrichment	96.5	Depends on conversion and demand				
Cleaning and sizing	100.0					
Coke preparation	85.2					
Regional transport[e]						
Barge	100.0					
Slurry pipeline	98.0					
Mixed train	99.0	25	25	25	25	25
Unit train	100.0	75	75	75	75	75
Truck	100.0					
Conversion						
Power plant	38.0	Depends on allocation in Tables A1 and A2				
Liquefaction	60.0					

[a] Efficiency defined as:

$$\frac{\text{energy value of coal input}}{\text{energy value of output}} \times 100\% \quad .$$

Taken from Hittmann (1974) except liquefaction efficiency.

[b] Numbers refer to coal-producing regions:

1. Ekibastuz
2. Kuznetsk
3. Kansk-Achinsk
4. Donetsk
5. Tungusska

Percentages refer to the kind of technology used in each region. For example, in region 1 (Ekibastuz), 50% of all mining is surface-area and 50% surface-contour. Further down the column, in the "local transport" category, 50% is assumed to be by truck and 50% by conveyor.

[c] Surface mining is planned (see, for example, Krylov 1979).

[d] Assuming that 50% of local transport is mechanized.

[e] Coal currently transported by rail (Astakhov 1979, Shelest 1979). Assume no barge, slurry, or truck for regional transport.

[f] Relatively flat terrain, so ratio of area to contour mining is 2:1.

[g] Two-thirds of current mines are underground, but new production expected to be from surface mines (Shelest 1979).

[h] Almost all current underground mining is long-wall mining (Astakhov 1979, Krylov 1979), so hydraulic mining is assumed to be not significant.

The projected coal production from Ekibastuz, Donetsk, and miscellaneous other coal regions (denoted "other" in Tables A1 and A2), were the same in the High and the Low scenarios. Only the larger coal regions of Kuznetsk, Kansk-Achinsk, and Tungusska increased production. In other words, it was assumed that the reserves of these last three regions would provide the increased coal output required by the High scenario. Each region was assigned a production figure of 1 billion tce/yr, so that their scales of development would be similar.

The allocation of the 1 billion tce/yr output of Kansk-Achinsk proved difficult, since the coal from these fields is suitable for conversion to synfuels and electricity, but not for coking. However, as noted above for Ekibastuz, the coal-electricity requirement of the entire USSR in the year 2030 is estimated to be only 200 million tce/yr in the Low scenario, so that a large quantity of Kansk-Achinsk coal was allocated for export and heating purposes, assuming that lower-quality coal would be up-graded. Additional assumptions used in construction of these scenarios are presented in the footnotes of Tables A1 and A2.

Table A3 presents the assumed efficiencies of various technologies for the future Soviet coal industry, which are based primarily on efficiencies of existing processes (Hittman 1974). Also presented in Table A3 is the percentage use of each technology within each region. In USSR region 2, for example, it was assumed that 75% of mining would be surface and 25% underground; other assumptions are described in the footnotes to Table A3.

2 Regional Scenarios for the US

In the IIASA study, region I comprises the US and Canada. The expected coal production of the US for the year 2000 was disaggregated from the total region I figure using World Energy Conference estimates (Schilling 1977); i.e., 0.2 and 2.4 billion tce/yr for Canada and the US, respectively. Applying this ratio to the IIASA Low and High scenarios yields 1.45 billion tce/yr for the Low scenario and 2.6 billion tce/yr for the High scenario. The allocation of different coal categories (coke, electricity, etc.) were also proportionally based on IIASA's Low and High scenarios (Häfele 1981a). Other assumptions for the Low and High scenarios for the US are explained in the footnotes to Tables A4 and A5.

A breakdown of coal technologies is presented in Table A6 in the same format as that used for the USSR in Table A3. Footnotes to this table explain the derivation of the numbers.

TABLE A4 US Low scenario, year 2030 (coal production in billion tce/yr).

Region	Total production[b]	Coke[c]	Electricity[d]	Synfuel[e]	Export
1. Southwest	0.15	0.02	0.01	0.12	0
2. Northwest	0.41	0	0.02	0.39	0
3. Central	0.23	0	0.01	0.22	0
4. Northern Appalachia	0.26	0.11	0.01	0.14	0
5. Central Appalachia	0.32	0.11	0.02	0.19	0
Other	0.09	0	0	0.09	0
Total	1.46[a]	0.24[a]	0.07[a]	1.15[a]	0[a]

[a] See text of Appendix A.
[b] Proportionately based on High scenario case, year 2000 projections from OTA (1979). Production levels of different states are combined as follows:
Southwest: New Mexico, Arizona, Utah, Colorado.
Northwest: Wyoming, Dakotas, Montana.
Central: Illinois, Indiana, Missouri, Oklahoma, western Kentucky.
Northern Appalachia: Pennsylvania, Ohio, West Virginia (½).
Central Appalachia: West Virginia (½), Virginia, eastern Kentucky, Tennessee, Alabama.
Converted from t/yr to tce/yr using coal heating values given in Table C1.
[c] Production figures allocated according to existing US coking coal reserves. In round figures: 90% Appalachia, 10% Southwest (from Schmidt 1979).
[d] Assume electricity used locally since IIASA study assumes that nuclear plants will provide most of US electricity in 2030. Coal-electricity is allocated to each region in proportion to its fraction of total US coal production.
[e] Synfuel allocated after coke and electricity.

TABLE A5 US High scenario, year 2030 (coal production in billion tce/yr).

Region	Total production[b]	Coke[c]	Electricity[d]	Synfuel[e]	Export[f]
1. Southwest	0.27	0.02	0.01	0.24	0
2. Northwest	0.75	0	0.05	0.59	0.11
3. Central	0.43	0	0.03	0.29	0.11
4. Northern Appalachia	0.48	0.13	0.03	0.10	0.22
5. Central Appalachia	0.58	0.13	0.04	0.13	0.28
Other	0.16	0	0.01	0.12	0.03
Total	2.67[a]	0.28[a]	0.17[a]	1.47[a]	0.75[a]

[a] See text of Appendix A.
[b] Same proportional production as Low scenario (Table A4).
[c] Total coke production in High scenario is 0.04 billion tce/yr greater than Low scenario; this is allocated to Appalachia, which has 90% of US coking coal reserves (Schmidt 1979).
[d] Proportional to coal production level, as in Low scenario (see note in Low scenario, Table A4).
[e] Synfuel allocated after other coal categories are allocated. Synfuel and exports in Northern and Central Appalachia were balanced in rough proportion to their relative coal production.
[f] Exports based on "high coal case" of WOCOL (1980a): Appalachia, 66%; Central, 15%; Western, 15%; other US, 4%.

TABLE A6 US regional coal technologies.

Technology	Efficiency (%)[a]	Regional use (%)[b] 1	2	3	4	5
Mining[c]						
Surface	80.0	90[e]	90[e]	40[e]	25	25[e]
Underground						
Long wall	85.0	0	0	0	0	0
Room and pillar[d]	57.0	10	10	60	75	75
Local transport[f]						
Truck	100.0	50	50	50	50	50
Conveyor	100.0	50	50	50	50	50
Processing						
Enrichment	96.5	Depends on conversion and demand				
Cleaning and sizing	100.0					
Coke preparation	85.2					
Regional transport[g]						
Barge	100.0	0	0	20	20	20
Slurry pipeline	98.0	15	15	15	0	0
Mixed train	99.0	15	15	0	20	20
Unit train	100.0	70	70	65	40	40
Truck	100.0	0	0	0	20	20
Conversion						
Power plant	38.0	Depends on allocation in Tables A4 and A5				
Liquefaction	60.0					

[a] Efficiency is defined as

$$\frac{\text{energy value of coal input}}{\text{energy value of output}} \times 100\% \quad .$$

Taken from Hittman (1974), except liquefaction efficiency (from Probstein and Gold 1978).

[b] Numbers refer to coal-producing regions: 1. Southwest; 2. Northwest; 3. Central; 4. Northern Appalachia; 5. Central Appalachia. Percentages refer to the kind of "technology" used in each region. For example, region 1 (Southwest), 90% of all mining is surface mining, and 10% is underground, room and pillar mining.

[c] Surface and underground allocation based on OTA (1979); rounded figures, "High coal case" year 2000 projections:

	Surface (%)	Underground (%)
West	90	10
Central	40	60
Appalachia	25	75

[d] All underground mining is assumed to be room and pillar, as is current situation.

[e] Type of surface mining specified by Hittman (1974).

[f] Assuming 50% mechanization.

[g] Regional transport is allocated so that it roughly corresponds with year 2000 national projections (WOCOL 1980a, Table 16–16):

Mode	Fraction of mode
Conventional train	0.14
Unit train	0.50
Coal barge	0.17
Coal truck	0.09
Slurry pipeline	0.10

Barge transportation is assumed in Central and Appalachian regions only. Also, total slurry pipeline transport allocated to West and Central regions, but it is assumed that it does not carry more than 20% of total coal moved in any region.

APPENDIX B WATER REQUIREMENT MODEL

1 Surface Mining

For surface mining the only significant water loss was assumed to occur through evaporation during fugitive dust control of roads at the mining site. As in Probstein and Gold (1978), this loss was assumed to be significant only in regions where the potential evaporation rate clearly exceeded the precipitation rate. In rainy regions, fugitive dust was assumed to be controlled by the rain itself. The amount of evaporated water per year was found simply by multiplying the annual potential evaporation rate by the area that is wetted down (i.e., the road area). It was also assumed that the road area is equal to 12% of the total mine area; it follows that the amount of evaporated water at surface mines will be:

$$W_{11} = (b/e)(y_{11}\alpha_{11} + y_{12}\alpha_{12})\,12 \quad , \tag{B1}$$

where

W_{11} = water requirement of surface mining (m^3/yr)
b = annual potential evaporation rate (cm) (to prevent double counting of temporal units, b is input in units of cm in this equation)
e = coalfield yield (te/ha)
y_{11} = coal input, area mining (te/yr)
α_{11} = efficiency, area mining (fraction)
y_{12} = coal input, contour mining (te/yr)
α_{12} = efficiency, contour mining (fraction)

2 Underground Mining

As in surface mines, dust control was also assumed to be the principal water consumer in underground mining. Probstein and Gold (1978) give the quantity of water used in Appalachian underground mines as 100–300 gallons/min, or roughly 33–100 pounds (lb) water per 1000 lb of coal. This range reflects different levels of water availability and management in the mines. For the water requirement model, an intermediate value of 67 lb water/1000 lb coal was selected; since this is equivalent to 0.067 m^3 water/te coal, we obtain the simple expression

$$W_{13} = 0.067(y_{13}\alpha_{13} + y_{14}\alpha_{14}) \quad , \tag{B2}$$

where

W_2 = water requirement of underground mining (m^3/yr)
y_{13} = coal input, long-wall mining (te/yr)
α_{13} = efficiency, long-wall mining (fraction)
y_{14} = coal input, room and pillar mining (te/yr)
α_{14} = efficiency, room and pillar mining (fraction).

3 Coal Preparation

The various processes described in Figure 3 as "cleaning and sizing" include breaking, conveying, screening, crushing, and other standard procedures. Washing is not included. Probstein and Gold (1978) note that in coal preparation most water is used in dust control at transfer points such as surge bins, storage sites, etc. The amount of water used for this purpose in US mines is 10–15 lb/1000 lb of coal. Using an intermediate value of 12.5 lb water/1000 lb coal, we obtain

$$W_{32} = 0.0125 y_{32} \alpha_{32} \quad , \tag{B3}$$

where

W_{32} = water requirement of coal preparation (m^3/yr)
y_{32} = coal input, coal preparation (te/yr)
α_{32} = efficiency, coal preparation (fraction).

4 Slurry Pipelines

The water consumed in slurry pipelines was assumed to be simply the water used for slurry make-up:

$$W_{42} = f y_{42} \quad , \tag{B4}$$

where

W_{42} = water requirement of slurry pipelines (m^3/yr)
f = water:coal ratio (te water/te coal)
y_{42} = coal input, slurry pipeline (te/yr).

5 Flue Gas Desulfurization

The water requirement of only one pollution control device was included in the water requirement model. This was the flue gas desulfurization unit (FGD) that is used to control sulfur emissions. There are two principal ways in which water is lost in these devices: (1) with the scrubbed flue gas, and (2) in the water used to dispose of the spent scrubber sludge. For losses of the first type, Probstein and Gold (1978) present the following equations based on mass balance and stochiometric considerations*:

*See Probstein and Gold (1978) for a discussion of these equations and the operation of FGD units.

$$\frac{\text{moles flue gas}}{\text{lb coal}} = 4.76(1 + a')\left(\frac{c}{12} + \frac{s}{32}\right) + (3.76 + 4.76a)\left(\frac{h}{4} - \frac{x}{32}\right) \tag{B5}$$

and

$$\frac{\text{lb water}}{\text{lb coal}} = \left(\frac{\text{moles flue gas}}{\text{lb coal}}\right)\left(\frac{\text{moles water vapor}}{\text{moles dry flue gas}}\right) 18 - w - \frac{h}{4} \quad , \tag{B6}$$

where

a' = excess air fraction (wt. fraction)
c = carbon content of coal (wt. fraction)
s = sulfur content of coal (wt. fraction)
x = oxygen content of coal (wt. fraction)
h = hydrogen content of coal (wt. fraction)
w = moisture content of coal (wt. fraction).

If we assign

$$\frac{\text{moles water vapor}}{\text{moles dry flue gas}}$$

an average experimental value of 0.13, and a' a value of 0.15, as Probstein and Gold (1978) suggest, and combine eqns (B5) and (B6), we obtain

$$WF_1 = 1.07c + 0.4s + 2.51h - 0.33x - w \quad , \tag{B7}$$

where WF_1 = water lost in FGD unit with scrubbed flue gas (te water/te coal). Other variables are defined above.

The water required for ash disposal in the FGD unit is a function of the amount of sulfur removed from the flue gas, and can be expressed as

$$\frac{\text{lb make-up water}}{\text{lb sulfur}} = \frac{\text{lb ash solid}}{\text{lb sulfur}}\left(\frac{1 - m}{m}\right) \quad , \tag{B8}$$

where m = solid concentration in scrubber sludge. We can assign a value of 40% to the solid concentration in the scrubber sludge (m) and 5.9 to the ash solid:sulfur ratio (lb ash solid/lb sulfur). Using these values in eqn. (B8) yields

$$WF_2 = 8.85s \quad , \tag{B9}$$

where WF_2 = water lost in FGD scrubber sludge (te water/te coal), and s = sulfur content of coal (wt. fraction).

6 Power Plants

Water is consumed in coal-fired power plants in two major ways: (1) in cooling processes, and (2) in pollution control equipment. The computation of cooling water requirements is rather complicated, involving assumptions of the type of cooling process used, efficiency of the process selected, and many other variables. Since these computations are outside the scope of this water requirement model, a "black-box" approach was taken to compute the amount of water used. The water requirement is given simply by

$$W_{51a} = gX_{51} \quad , \tag{B10}$$

where

W_{51a} = water requirement for power plant cooling (m^3/yr)
g = cooling water required per energy input ($m^3/10^{15}$ J)
X_{51} = energy equivalent of coal input (10^{15} J/yr).

Assumptions of cooling mode, efficiency, etc., are built into the parameter g. The selection of values for g is discussed in Appendix C.

The amount of water consumed in the FGD unit of a power plant is computed using eqns (B7) and (B9), such that

$$W_{51b} = (WF_1 + WF_2)y_{51} \quad , \tag{B11}$$

where

W_{51b} = water requirement of power plant FGD unit (m^3/yr)
WF_1, WF_2 = FGD water losses, as computed in eqns (B7) and (B9) (te water/te coal)
y_{51} = coal input to power plant (te/yr).

7 Liquefaction

In addition to cooling process and FGD unit water requirements, liquefaction facilities also consume process water and water for dust control. As noted earlier, the model process used to compute these water requirements is the synthoil process. Make-up process water in a synthoil plant is needed for the major process streams, including coal preparation, slurry preparation, catalytic reactions, and oil and gas separation. These water requirements are aggregated into the parameter j of the following expression:

$$W_{52a'} = jX_{52} \quad , \tag{B12}$$

where

$W_{52a'}$ = process water requirement for liquefaction (m^3/yr)
j = process water required per energy input ($m^3/10^{15}$ J)
X_{52} = energy equivalent of coal input (10^{15} J/yr).

Estimates of j are presented in Table C1.

For dust control, Probstein and Gold (1978) report that about 8–12 lb water/1000 lb coal will be required in US synthoil plants currently being designed. Using an intermediate value of 10 lb water/1000 lb coal (equivalent to 1 m^3 water/100 te coal) we can estimate the water requirement to be:

$$W_{52a''} = 0.01 y_{52} \quad , \qquad \text{(B13)}$$

where

$W_{52a''}$ = dust control water requirement for liquefaction (m^3/yr)
y_{52} = coal input to liquefaction (te/yr).

Equations (B12) and (B13) are then combined in the water requirement model, yielding

$$W_{52a} = jX_{52} + 0.01 y_{52} \quad . \qquad \text{(B14)}$$

The same kind of approach used to compute power plant cooling water and FGD unit water requirements was also used to compute the water requirements in liquefaction facilities. The cooling water requirement is expressed as

$$W_{52b} = kX_{52} \quad , \qquad \text{(B15)}$$

where

W_{52b} = water requirement for liquefaction plant cooling (m^3/yr)
k = cooling water required per energy input ($m^3/10^{15}$ J)
X_{52} = energy equivalent of coal input (10^{15} J/yr).

The water requirement of the FGD unit in a liquefaction facility is given by

$$W_{52c} = (WF_1 + WF_2) y_{52} \quad , \qquad \text{(B16)}$$

where

W_{52c} = water requirement for liquefaction plant FGD unit (m^3/yr)
WF_1, WF_2 = FGD water losses (te water/te coal)
y_{52} = coal input to liquefaction (te/yr).

APPENDIX C MODEL INPUTS AND SENSITIVITY ANALYSIS

This Appendix describes inputs to the water requirement model, including climatic data, water content of pipeline slurries, certain water requirements of liquefaction and power plants, and the physical/chemical characteristics of coal for each region. The derivation of these numbers is described in the footnotes to Table C1. Also included are the results of an analysis to determine the sensitivity of the water requirement model to degrees of water conservation. Model inputs that reflect little concern with water conservation are used to compute water requirements, and these are then compared with inputs that assume a high degree of water-consciousness. This analysis is presented in Table C2.

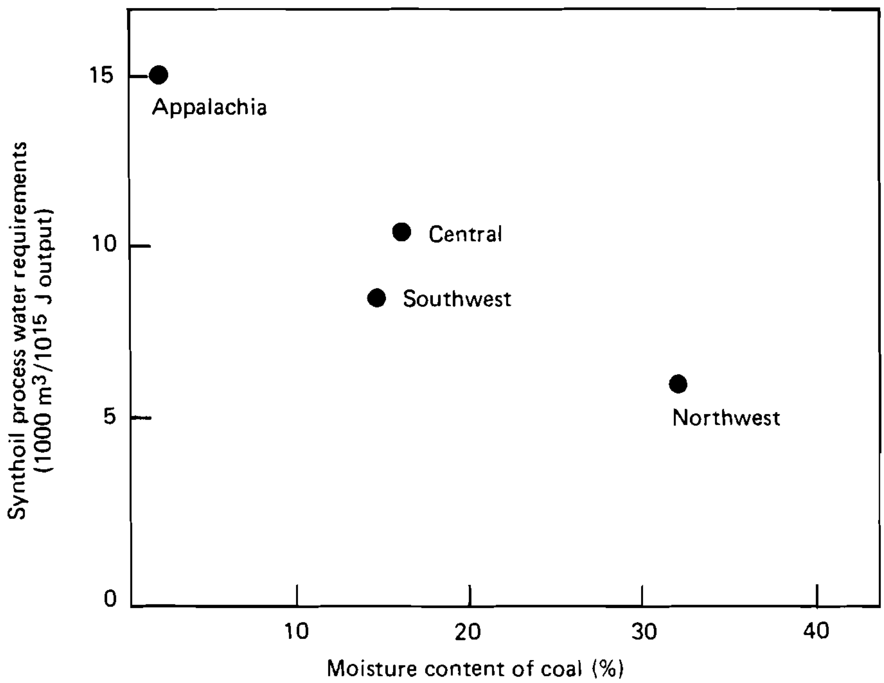

FIGURE C1 Water requirements of the synthoil liquefaction process as a function of the moisture content of US coal. Data from Probstein and Gold (1978).

TABLE C1 Constants in the water requirement model.

Parameter	Soviet Union[a] 1	2	3	4	5	United States[a] 1	2	3	4	5
Evaporation rate (cm/yr)[b]	70	55	55	80	NA	125	102	NA	NA	NA
Surface mining yield (te/ha)[c]	79 000	79 000	79 000	79 000	NA	67 000	116 000	NA	NA	NA
Water–coal slurry ratio (te water/te coal)[d]	NA	NA	NA	NA	NA	1	1	1	1	1
Power plant cooling water (m^3 water/10^{15} J input)[e]	152 000	152 000	152 000	152 000	152 000	152 000	152 000	152 000	190 000	190 000
Liquefaction process water (m^3 water/10^{15} J input)[f]	8000	8000	4000	9000	6000	5594	3996	6660	9590	9590
Liquefaction cooling water (m^3 water/10^{15} J input)[g]	19 000	19 000	19 000	19 000	19 000	18 648	18 648	42 624	41 292	41 292
Coal characteristics (wt. fraction)										
Ash	0.370[h]	0.109[h]	0.104[h]	0.225[h]	0.100[i]	0.157[k]	0.068[k]	0.089[k]	0.147[k]	0.112[k]
Carbon	0.450[j]	0.650[j]	0.450[j]	0.600[j]	0.600[i]	0.570[j]	0.458[l]	0.591[j]	0.693[j]	0.736[l]
Sulfur	0.007[h]	0.004[j]	0.005[h]	0.028[h]	0.030[i]	0.006[k]	0.009[k]	0.029[k]	0.031[k]	0.009[k]
Hydrogen	0.050[j]	0.040[j]	0.040[j]	0.040[j]	0.040[i]	0.036[l]	0.034[l]	0.041[l]	0.049[l]	0.049[l]
Oxygen	0.040[j]	0.100[j]	0.050[j]	0.060[j]	0.060[i]	0.093[l]	0.113[l]	0.083[l]	0.053[l]	0.053[l]
Moisture	0.080[h]	0.094[j]	0.348[h]	0.040[j]	0.160[i]	0.124[l]	0.304[l]	0.161[l]	0.023[l]	0.023[l]
Coal heating value (kcal/kg)	4250[m]	6150[m]	3560[m]	6000[m]	6000[i]	5457[k]	4878[k]	5890[k]	6557[k]	6723[k]

[a] Numbers refer to coal-producing regions:

USSR:		USA:	
1.	Ekibastuz	1.	Southwest
2.	Kuznetsk	2.	Northwest
3.	Kansk-Achinsk	3.	Central
4.	Donetsk	4.	Northern Appalachia
5.	Tungusska	5.	Central Appalachia

[b] Potential evaporation: data for USSR from UNESCO *World Water Atlas* (1978), interpolated from sheet 18. Data for US based on range of "open surface evaporation" presented in Probstein and Gold (1978). NA (not applicable) indicates that average annual potential evaporation does not exceed average annual precipitation. It is assumed in these cases that water is not consumed by dust control in surface mines.

[c] Estimate for the USSR represents an average national figure derived as follows (from Mel'nikov 1979). Overburden ratio, 1975 USSR average for surface mines: 3.8 m^3/te. Typical seam + overburden thickness ≈ 30 m. Therefore, "average" coalfield yield

$$\approx \frac{30 \text{ m}}{3.8 \text{ m}^3/\text{te}} \times 10\,000 \text{ m}^2/\text{ha}$$

$$\approx 79\,000 \text{ te/ha}.$$

US estimates from Probstein and Gold (1978).

[d] Assuming no slurry pipelines in the USSR. US data assume slurry mixture 50% coal, 50% water (after Probstein and Gold 1978).

[e] Gold *et al.* (1977) present economically optimal water requirements for six proposed Western US coal-fired power plants. From their calculations we derive 0.4 $km^3/10^{18}$ J output, which is also the lower range of wet-cooling tower water requirements presented by Harte and El-Gasseir (1978). It was therefore assumed that this represents a reasonable water requirement for water-scarce areas.

Since the water requirement model calls for "water required per energy input" to the plant, 0.4 $km^3/10^{18}$ J output was converted assuming 38% plant efficiency: 0.4 × 0.38 = 0.152 $km^3/10^{18}$ J input. For plants in water-plentiful areas, an intermediate value for wet-cooling tower water requirements was used (Harte and El-Gasseir 1978): 0.5 $km^3/10^{18}$ J output, which is equivalent (at 38% plant efficiency) to 0.19 $km^3/10^{18}$ J input. Power plants in the USSR were assigned "water-scarce" values.

[f] US data were derived from Probstein and Gold (1978, Figure 9-6), converted to input values assuming 80% process efficiency, as do Probstein and Gold (1978). Soviet water requirements for the synthoil process were based on the moisture content of Soviet coal (Table C1), and the trend of US data (Figure C1), converted to input values assuming 80% process efficiency.

[g] US estimates from Probstein and Gold (1978, Figure 9-6), converted to input values assuming 80% process efficiency. Numbers in Probstein and Gold for "maximum high wet cooling", but these authors note that in water-scarce areas these water requirements may be halved. For the Southwest and Northwest coal regions half of the water requirements specified in Probstein and Gold were assumed.

[h] From Astakhov (1977), mid-range values.

[i] Deduced from Astakhov (1977) and assigned typical characteristics of high sub-bituminous or low bituminous coals.

[j] Assigned based on typical values of coal rank.

[k] From Hittman (1974, 1975).

[l] "Representative" coals as given by Probstein and Gold (1978); their regions and those used in this report are matched as follows:

Probstein and Gold	This report
Four Corners	1. Southwest
Powder River	2. Northwest
Central Illinois	3. Central
Appalachia	4. Northern Appalachia
Appalachia	5. Central Appalachia

[m] From Astakhov (1979).

TABLE C2 Model sensitivity to assumed degree of water conservation.

Coal region	Type of water use	Water consumption (km^3/yr) "High" degree of water conservation[a]	"Lower" degree of water conservation
US: Northwest	1. Surface mine revegetation[b]	0	0.01
	2. Power plant cooling[c]	0.22	0.56
	3. Liquefaction cooling[d]	0.32	0.64
	Subtotal (1 + 2 + 3)	0.54	1.21
	Total – all uses	1.00	1.67
		(difference:	+67%)
US: Northern Appalachia	1. Surface mine revegetation[b]	0	0.001
	2. Power plant cooling[c]	0.17	0.33
	3. Liquefaction cooling[d]	0.12	0.12
	Subtotal (1 + 2 + 3)	0.29	0.45
	Total – all uses	0.51	0.67
		(difference:	+31%)
USSR: Kuznetsk	1. Surface mine revegetation[b]	0	0.03
	2. Power plant cooling[c]	0.22	0.49
	3. Liquefaction cooling[d]	0.25	0.49
	Subtotal (1 + 2 + 3)	0.47	1.08
	Total – all uses	0.84	1.45
		(difference:	+73%)

[a] Water uses calculated with the model described in Appendix B, and the model inputs presented in Table C1.

[b] No water use is assumed for mine revegetation in the "high" water conservation case. For the "lower" water conservation case, the water consumed by mine revegetation is calculated from:

$$W = y(1/e)\ 10\,000(\text{m}^2/\text{ha})\ n$$

where

W = water used for revegetation (m^3/yr)
y = coal input from surface mining (te/yr)
e = coalfield yield (te/ha)
n = water used for revegetation (m^3 water/m^2 land revegetated).

Values of e for the Northwest (US) and Kansk-Achinsk (USSR) are taken from Table C1. For Northern Appalachia e was assumed to be 80 000 te/ha. Appropriate values of y can be derived from Appendix A. Values of n were estimated from Harte and El-Gasseir (1978) as follows: for Northern Appalachia, $n = 0.05$ m^3/m^2; for Northwest and Kansk-Achinsk, $n = 0.1$ m^3/m^2.

[c] For the "high" water conservation case, it was assumed that a wet-cooling tower with storage was used for power plant cooling (0.4–0.5 $km^3/10^{18}$ J output). For the "lower" water conservation case, once-through cooling was assumed (1.0 $km^3/10^{18}$ J output). Water use data from Harte and El-Gasseir (1978).

[d] In the "high" water conservation case, it was assumed that the Western regions of US and all of the USSR would use half the values originally computed by Probstein and Gold (1978); see footnotes to Table C1. For the "lower" water conservation case, original figures from Probstein and Gold (1978) were used: for Northwest, 37 296 $m^3/10^{15}$ J input; for Kansk-Achinsk, 37 000 $m^3/10^{15}$ J input.

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