Coal: Modeling a complex fuel source
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Summary for policymakers

Coal represented 30% of worldwide primary energy consumption in 2013 and would become the most consumed fuel through 2040, under the International Energy Agency (IEA) Current Policies Scenario. However, even in countries with policies designed to curb its supply and consumption, coal volumes have remained unexpectedly high. The key question for policymakers is: Why?

Quantitative models can help navigate the complex dynamics of coal markets and to understand the potential impacts of policy prescriptions. Therefore, understanding the drivers of change in the coal industry is crucial to more effective decision making about coal.

Within the last decade, coal has evolved into a truly global commodity. The consumption and production centers of North America, China, India, and Europe have coalesced into a complex system of integrated global coal flows. Domestic energy policies and domestic market conditions in one country can now influence coal production and demand around the globe. The key question is whether coal markets become even more integrated or, in the face of local policy drivers, revert to smaller regional markets?

Despite a widespread view that coal is not a sustainable fuel, new technologies still have potential to reduce carbon dioxide emissions and other pollutants significantly. Improvements in boiler technology, through the use of more advanced materials and manufacturing processes, can increase power plant efficiency by an additional 20-30%. Carbon capture and sequestration technology may help reduce carbon emissions from coal-fired generation; a key element of meeting stricter environmental standards.

Coal production costs may also fall significantly in coming years as prices deepen the economic imperative to remain competitive. Mining technologies such as self-driving trucks, remotely-operated drills, and automated longwalls are lowering costs and improving mine safety. But the question remains: Will all these advances be enough for the coal industry to remain competitive?

Quantitative models have become an increasingly important tool used by policymakers, coal producers, traders, and the environmental community to understand the complex interactions of energy systems. These models are used to estimate transitions in a country’s fuel mix or shifts in global trade flow, identify efficiency gains, or analyze infrastructure bottlenecks. Model results are most useful when tempered with other aspects of the market, including political, social, and security objectives that affect policymakers’ decisions. How can modelers incorporate these unconventional drivers to make models more robust and insightful?

Models of coal supply and consumption are easily quantifiable when predictable, liberalized markets are the norm. However, coal finds itself at the epicenter of a storm of externalities. Simple market competition models cannot properly predict future decisions that are based on more qualitative political judgments in which trade-offs between economic development, environmental sustainability and perceived energy security give no unique answer. Policy discontinuities challenge conventional models and demand a more flexible approach.
Background to the workshop

In October 2014, KAPSARC convened the third workshop in a series on energy systems modeling in Washington, D.C. Discussions addressed issues and techniques in understanding and modeling coal markets, framed by a comprehensive discussion about trends in the industry. Over two dozen international experts in coal production, sales, logistics, and modeling gathered to share their insights on issues spanning the trade and pricing of coal: technology trends in coal production and use, regional and environmental issues, and the outlook for coal. Three primary objectives of the workshop were to:

- Improve the understanding of the characteristics of global coal markets
- Discuss the state of research regarding the different modeling approaches for coal
- Identify insights and future research directions for modeling coal markets

Coal is likely to remain one of the main fuel sources in the years to come. This brief explores drivers of change in the coal industry, and how the lessons learned can be applied to quantitative models that incorporate more than just relative costs of supply, logistics and the value of consumption.

From fragmented markets to a truly global commodity

In China, coal is viewed as the chief culprit for high levels of air pollution in cities. Coal-intensive development cannot rely on the economic gains it supports without recognizing the environmental and health costs it imposes.

Shrinking public support, in turn, puts pressure on policymakers and most developed countries are now attempting to curb consumption through policy.

Despite these challenges, coal has been the fastest growing primary energy source of the last decade as shown in Figure 1. This growth was mainly due to the reliance of China and India on coal to power the development of their economies.

Demand growth in China and India has transformed coal markets and flows and has given coal the status of a true global energy commodity with a mature, liquid, and integrated market as shown in Figure 2. This is in contrast to the situation 20 years ago, when most coal trade was restricted to a few regional, fragmented markets: North America, China, India, and Europe.

A natural consequence of the integration of coal markets is that international coal flows have become sensitive to locational arbitrages, as well as to policy and regulatory changes in particular countries. One of the most visible market changes is the correlation that has developed between Chinese domestic FOB prices (Qinhuangdao Index) and Australian FOB coal prices (Newcastle Index) in the last three years. The physical link between the two markets was natural because China has used small seagoing vessels to supply coal-fired plants in coastal China for many years. This provided the ability to use existing infrastructure for either domestic or imported coal, enabling significant coal arbitrage opportunities as identified in Figure 3.

The development coal flows along China’s coast led forecasters to believe that import growth was almost certain. However, the scale of future imports is uncertain due to a new wave of regulations implemented by China in 2014. These regulations include new import taxes, increased controls in trace elements, and restrictions in the trade of low
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Figure 1: Growth in coal production has outpaced oil and natural gas since 1999.
Source: BP

Figure 2: Coal has evolved into a truly global commodity
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India’s coal market has also integrated with the international coal markets, but the drivers are different from those in China. Coal resources are geographically concentrated in eastern India while the demand centers are scattered throughout the country. Public railways are used as the main mode of transportation for domestic coal, which places significant strain on the country’s already tight infrastructure. The state-owned Coal India dominates supply but, due to regulatory, technical, and logistical challenges, it has had limited success in keeping up with the rate of demand growth. Even as the current government is taking measures to improve India’s ability to produce its own coal, imports are expected to remain strong.

The coal industry in the United States has had to adjust to rapid growth in supply of shale gas and new environmental regulations. Faced with declining domestic coal demand, the US has switched from being a net steam-coal importer in the mid-2000s to a net exporter in the early 2010s, as shown in Figure 4. However, in the export market, US coal producers have faced a lack of competitiveness with cheaper coal (including from Australia and Indonesia). These competitors benefit from more efficient logistics and lower geological complexity, as well as more supportive regulatory environments.

Figure 3: Chinese and international coal prices have become interconnected. Source: KAPSARC analysis, Global Coal, Platts

![Coal Price Trends](image)
The role of technology in the coal market of the future

The impact of new technologies can occur along the entire value chain, from the mining of coal to its ultimate consumption. At the mining stage, there are potential cost savings and process improvements from labor as processes become more automated (e.g. self-driving trucks, remotely-operated drills, automated longwalls), though there is a physical limit to how low costs can go as the geology of new coal-producing basins becomes increasingly complex.

At the power generation stage, progress has been made in combustion and boiler technologies. Available technology has gone from sub-critical power plants, with typical efficiencies of around 35%, to new ultra-supercritical units with efficiencies of 45% or more. Thermal efficiencies approaching more than 50% can be achieved by using advanced materials that are able to withstand higher operating temperatures and pressures.

However, despite the availability of better technologies, most of the globe’s coal-fired power plants are comprised of older subcritical units identified by the red bars in Figure 5. The replacement of inefficient units by newer ones will not happen unless two conditions are met:

- the market sends a clear signal to utilities and manufacturers
- government policies truncate the economic lives of these plants

So far, the environment has not been favorable for this transition given the lack of certainty on what role coal will play in the fuel mix of the future. In this sense, anti-coal policies such as EPA’s Clean Power Plan might prevent technological improvements that would benefit developing countries (and even the US).
Adoption of important new coal technologies is occurring in Southeast Asia where governments have started to build and use ultra-supercritical coal-fired power plants, faced with the high costs of other fuel alternatives. For example, in Indonesia and Vietnam, advanced power plants benefit from the availability of local coal resources and governments enjoying public support for issuance of licenses and underwriting finance for such high-efficiency coal-fired power plants.

As for carbon capture and storage technologies (CCS), the market is closely watching Boundary Dam, the first commercial-scale power plant fitted with CCS in Saskatchewan, Canada. Additionally, the commissioning of the Kemper County plant in Mississippi and the W.A. Parish plant in Texas will provide further ground for testing CCS at a commercial scale.

Review of coal market models

The type of modeling techniques used for coal depends upon the questions the model addresses. Short-run models consider a time-frame of weeks to months and are useful for making marketing and purchasing decisions. These short-run models balance the supply and demand of coal based on current market information and historical patterns. Longer-run models are used to measure the impacts of policies by finding an economic equilibrium given a set of policy, demand, and supply assumptions. Techniques such as mixed-complementarity modeling, game theory, and agent-based models can be used to explore market behaviors or identify inefficiencies and logistical bottlenecks.

Three models were presented at the workshop, each with a different geographical focus: The National...
Energy Modeling System (NEMS) of the US Energy Information Administration (EIA); COALMOD, an international coal trade model developed by DIW Berlin; and the KAPSARC Energy Model of China (KEM-China) that includes coal production and transportation networks.

The NEMS model covering the period 2014-40 is designed to provide a comprehensive understanding of the energy markets in the US. In the coal module, two of the main inputs are transport costs and coal-mine productivity across the different producing basins (i.e. production costs per basin). The demand for coal comes from the economics of coal demand in electricity generation, its own module in NEMS, and end-use demand by industries and other consumers. Another important input is overseas coal demand, which determines whether the model allocates tonnage to imports or exports. One of the many uses of this model is to improve the understanding of the impact of policies such as the sensitivity of the fuel mix to different prices for carbon dioxide allowances, and the implications of changes in natural gas prices for coal demand, illustrated in figure 6.

COALMOD is a mixed-complementarity model designed to study global trade flows by representing the market from production in coal basins to demand centers. It has been used to provide insight into the shifting patterns in coal demand and flows after Europe and the US implemented tighter environmental regulations (Figure 7). Another study examined the impact in China of locating generating units closer to coal mines and transmitting electricity to demand centers instead of transporting coal to generating units near demand centers (commonly referred to as “coal-by-wire”).

![Figure 6: The NEMS model illustrates the sensitivity of the U.S. fuel mix to different carbon dioxide allowance prices. Source: EIA, Annual Energy Outlook, 2014](image-url)
KEM-China is being developed as an equilibrium model that has so far been used to analyze the opportunity costs of the logistical bottlenecks in China’s coal transportation, identified in 2011. The model finds the competitive equilibrium that minimizes supply and transportation costs while meeting demand. It incorporates both domestic and international supply. The annual economic gain from debottlenecking, based on 2011 data, was RMB 130 billion. This more than justifies the investment on its own terms. However, the model shows that an annual economic gain of RMB 245 billion could have been achieved by allowing expansion of production from some key centers in combination with the logistical infrastructure investments. Figure 8 shows the marginal costs of delivered coal would have fallen in every province under an optimal expansion of rail and mine capacities based on 2011.
Challenges in coal modeling

Models can be made more comprehensive by adding complexity, but this comes at a cost in terms of simplicity. By contrast, using simple demand and supply curves may miss important texture. For example, freight prices play an important role in the delivered cost of coal, but the Chinese freight market is complex and carries multiple commodities (including iron ore and grains) on some rail lines, while other lines are dedicated entirely to coal. Expansion of coal-carrying capacity depends on the construction of both general freight and coal-dedicated lines. Furthermore, the inefficiency of using trucks to move coal long distances depends on whether they can be used for backhauls or not. Significant errors can be introduced by simplifying representation of the market and not optimizing for all commodity behaviors.

National security, social objectives, and geopolitics are major unconventional market drivers. They may be more important in some instances than the relative economics of different fuel sources. In China, for example, the government has emphasized strategic importance of the domestic coal industry and has sought to reduce dependence on coal imports. This initiative has resulted in significant investments in rail capacity and development of high-voltage lines to transfer coal-fired power from mining regions to industrial and urban centers. The government also intends to alleviate discontent within the general population about poor air quality in Beijing, Tianjin, and the Pearl and Yangtze River deltas by shifting coal-fired power stations west, where the population density is lower.

It is also important to look beyond coal to other (including non-energy) sectors of an economy. Decisions made for one sector might seem inefficient, but might make more sense when taken in the context of the wider economy. For example, operational inefficiencies identified in China’s coal transportation network might allow for higher returns in other sectors of the economy. Europe’s unexpected expansion of coal demand resulting from overlapping policies, each of which appeared sensible in isolation, provides another well-researched example of the need for systems-thinking.
Conclusion

Coal has evolved into a truly global commodity, with coal markets transitioning from a series of fragmented, local demand-and-production centers into a complex system of integrated global flows. Additionally, technological developments along the value chain could allow coal to remain a competitive fuel source for years to come.

Decisions about coal production, consumption, and investments are not made for purely economic reasons, but also are based on unconventional drivers such as social, security, or political priorities that can alter the structure of markets. Models of coal supply and consumption are easily quantifiable when predictable, liberalized markets are the norm. However, coal finds itself at the epicenter of a storm of externalities. Simple market competition models cannot properly predict future decisions that are based on more qualitative political judgments, in which trade-offs between economic development, environmental sustainability and perceived energy security give no unique answer.
About the workshop

KAPSARC convened the third workshop in a series on energy systems modeling in October 2014 with 34 international experts to facilitate a discussion to explore the challenges of modeling coal markets. The workshop was held under the Chatham House Rule of capturing the discussion on a non-attribution basis. Participants comprised:

Carlos Fernandez Alvarez – Senior Coal Analyst, International Energy Agency
Jeff Archibald – Project Manager, Coal Modeling, ICF International
Hayden Atkins – Bulk Analyst, Argus Media
Amy Bason – Energy Analyst, Aramco Services Company
Andy Blumenfeld – VP of Analysis and Strategy, Arch Coal
Rodrigo Echeverri – Research Fellow, KAPSARC
Brian Efird – Research Fellow, KAPSARC
Frank Felder – Director, Center for Energy, Economic & Environmental Policy
Fabio Gabrieli – Head of Bulk Research, Mercuria Energy Trading S.A.
Philipp Galkin – Research Associate, KAPSARC
Howard Gatiss – CEO, Coal Marketing Company
Clemens Haftendorn – Analyst, Wood Mackenzie
Gang He – Researcher at Energy Resources Group, UC Berkeley
David Hobbs – Head of Research, KAPSARC
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Amy Jaffe – Executive Director, UC Davis
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Dan Klein – Managing Director, International Coal, PIRA Energy Group
Ian Lange – Assistant Professor, Colorado School of Mines
David Livingston – Associate, Carnegie Endowment for International Peace
Gerard McCloskey – Chairman, Merlin Trade and Consultancy
Mike Mellish – US Department of Energy/Energy Information Administration
Jack Moore – Director, Aramco Services Company
Mark Morey – Director of Fuel Intelligence, Alstom Power
Richard O’Neill – Chief Economic Advisor, Federal Energy Regulatory Commission
Axel Pierru – Senior Research Fellow, KAPSARC
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David Wogan – Senior Research Analyst, KAPSARC
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About the team

Rodrigo Echeverri is a Research Fellow analyzing coal markets. He has worked at Adaro Energy in Indonesia and Cerrejon Coal in Colombia and Europe.

Frederick Murphy is a Senior Visiting Fellow collaborating with the energy systems modeling team at KAPSARC. He has worked at the Energy Information Administration (EIA).

Axel Pierru is a Program Director leading KAPSARC’s Energy Systems Modeling work. Axel holds a PhD in Economics from Pantheon-Sorbonne University in Paris.

Bertrand Williams-Rioux is a Research Associate developing energy systems models. He completed a Master’s thesis in Computational Fluid Dynamics at KAUST.

David Wogan is a Senior Research Analyst developing energy systems models. He holds Masters Degrees in Mechanical Engineering and Public Affairs from UT Austin.