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The 1,000 GtC Coal Question: Are Cases of High Future Coal Combustion Plausible?

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RESOURCES
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Abstract

Twenty years ago, legacy reserve-to-production (R-P) ratios of 300 or more indicated a possibility of vastly expanding global coal consumption. Studies of energy futures commonly adopted similar R-P values as equilibrium conditions, establishing coal as a virtually unlimited backstop supply for long-term scenarios. Yearly consumption and market prices for hard coal have doubled since 1990, calibrating the next century's baseline. Over the same two decades, improving knowledge of global coal reduced estimates of total reserves by two-thirds, while costs increased much faster than anticipated by long-range coal resource models with long and flat supply curves. Consequently, the underlying assumptions for many future global energy projections no longer hold.

Past coal-dominant projections of future global energy supply now significantly exceed modern assessments of the reserves recoverable under baseline trends and need to be revised. The energy system reference cases used for future greenhouse gas (GHG) emission pathways in climate change research are a case in point: baseline emission scenarios commonly project levels of coal combustion many times higher than current reserve estimates by the year 2100. In this paper, we explain why baselines depicting vast expansion in twenty-first century coal consumption should not be used as a business-as-usual assumption.

Key Words: energy economics, climate change, coal resources, greenhouse gas scenarios, coal backstop

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1. The Conceptual Basis for a Coal Backstop in Long-Term Energy Scenarios

Studies of global energy futures commonly derive scenarios by assuming ongoing growth in primary energy demand. The resulting projections for corresponding energy supply greatly exceed plausible contributions from oil, gas, and other sources after midcentury. When demand for transportation and industrial fuels exceeds available output from oil and gas, baseline runs customarily illustrate vastly expanded coal production as the backstop (Energy Modeling Forum 1995; Grübler et al. 1998; Häfele 1981; IPCC 2000; World Energy Council 1993).

High reserve-to-production (R-P) values for coal through much of the 20th century provided a conceptual basis for the equilibrium coal supply conditions adopted by long-term energy scenarios: if existing coal resources were depleted, producers could, with sufficient incentive, readily explore for more coal reserves. Vintage reserve assessments indicated coal R-P ratios of well over 300 years. Global recoverable reserves of hard coal reported in the 1960s amounted to nearly 2,000 gigatons (Gt), or an R-P of more than 900 years (Flawn 1966). This contributed to a common perception that the total occurrences of coal in Earth's crust could compensate for either depletion of oil and gas or ambitious growth in energy demand.

Efforts to determine world coal reserves and resources have been fragmented, however, and inconsistent and poor coal data have compromised time-series analyses (Gordon 1987; Smil 2003). With unreliable information, determining the plausible extent of future coal use has amounted to a choice among Scylla, Charybdis, and Hades.

We characterize this choice as one of three modeling approaches: Method A, projecting a trend from a selected baseline window by assuming continued momentum in consumption growth, as common in medium-term outlooks[1]; Method B, adopting reserve figures known to be

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[1] Examples include the International Energy Agency's World Energy Outlooks and the Energy Information Administration's Annual Energy Outlooks.

inconsistent and incomplete; or Method C, expecting that coal follows the dynamics of oil and gas, and thus classifying marginal resources as reserves within a range of equilibrium R-P values to replace depletion (Adelman and Watkins 2008; Rogner 1997; Watkins 2006; Wellmer 2008; Wellmer and Berner 1997).

Demand-focused projections using Method A focus on likely growth rates for future consumption. Estimates that extrapolate consistent rates of demand can be abstracted from trends in coal technology, production, and economics. Studies that span longer timeframes have integrated Methods B and C to express the potential for realizable supply. Resulting future energy scenarios tend to treat global coal reserve estimates as a conservative lower bound, since the broader resource base is considered to replace depletion over time to maintain a constant range of R-P ratios. McCollum et al. (2014) illustrate how these methods are applied to evaluate energy supply scenarios in the Energy Modeling Forum 27 study: although the baseline runs of many models greatly exceed today's reserve estimates, these outlooks are characterized as plausible because they do not exceed the total geologic resource base.

When an equilibrium R-P value of several centuries is projected onto the total geologic occurrences of coal, production appears to have a vast potential for growth. Yet, over the past three decades, the global R-P ratio has not maintained an equilibrium and has continually declined. Recently, the world's coal R-P was measured at less than 100 years (BGR 2014). Growing production over this period has not resulted in additions to reserves but has instead produced the opposite outcome inferred by long-term energy scenarios, despite sustained all-time-high coal prices (measured in constant dollars).

Continued projections for vastly expanded coal production need to explain why coal use will continue to accelerate throughout the 21st century even though reserves have dwindled - despite theoretically favorable market conditions. Revisiting the heuristic of a vast coal backstop enabled by an equilibrium R-P and examining the implied market and technology trends can aid in this analysis.

Maintaining the argument that a high equilibrium R-P for coal will continue to inspire confidence in vastly expanded supply for the coming century assumes that a substantial fraction of the total resource base can readily be mined. This assertion must be supported by evidence on the direction and consequence of prices, technical change in the coal industry, and the process of determining recoverable coal.

Assessments of recoverable coal are a function of geologic, economic, and social factors that include the following (EIA 1996; Luppens et al. 2009):

- *total coal resource base:* the total measured, inferred, or hypothesized amount of coal occurrences in the Earth's crust;
- *coal-bed geology*: the coal-bed thickness, structure, depth, and geologic age;
- *coal quality*: the content of moisture, ash, sulfur, energy (heating value), and coal rank (anthracite, bituminous, sub-bituminous, lignite);
- *mining methods and technology factors*: for example, surface or underground;
- *recovery factors*: usually 50 percent for underground and 80 percent for surface mining to account for losses that occur during mining and washing;
- *restrictions on mining:* land-use constraints for lakes, streams, parks, cities, and highways;
- *economics*: costs of mining and transportation, which must be less than reasonable outlooks for market prices; and
- *compliance:* whether the coal quality, such as its sulfur content, meets regulations for air quality standards.

As information has improved, the economically recoverable portion of initially assessed coal deposits has been more accurately identified, and is always a much smaller quantity than the initial *in situ* amount recorded as reserves. Reserves are but a fraction of the total potential amount of geologic coal classified as resources. With appropriate caveats about possible changes in demand, technology, and economics, observation of the changes in global reserve assessments can indicate broader trends that will influence growth or decline in quantities of recoverable coal.

To inform the 21st-century coal baseline, we use primary sources on coal assessments to trace the history of falling reserves over the past three decades: the World Energy Council (WEC) and the German Federal Institute for Geosciences and Natural Resources (BGR).[2] The most prominent trends over this period are rising production (especially in China) and higher prices. Both have doubled between 1990 and 2016.

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[2] The International Energy Agency has used both WEC and BGR reports in its coal information studies. Rogner (1997) and Rogner et al. (2012) translate global coal assessment figures into energy units for use in long-term energy scenarios, such as the case study considered in this paper.

Since coal assessments tend to focus on mass-based measures, long-term scenarios have relied on secondary sources that convert these metrics to inform energy supply projections. Rogner (1997) and Rogner et al. (2012) report on the energy available in coal reserves and also indicate significant declines since 1990. For emissions from coal, assessments from the late 1980s indicated that unabated combustion of total coal reserves would release more than 1,200 gigatons of carbon (GtC). Modern assessments put this figure at less than 400 GtC (BGR 2015, 2014).

Technical progress along three frontiers explain the difference between modern and legacy assessments of coal reserves:

- Improved information management is leading to far greater global consistency in deposit characterization and subsequent classification of coal reserves by, for example, revisiting quantity-based reserve definitions used by the former Soviet Union and removing double-counting.
- Increased production has led to additional exploration and more information on the geology of coal deposits (e.g., depth of seam, angle of dip, degree of faulting, folding, washouts, denudation) and has determined the technological, social, and environmental constraints on their recovery.
- Advances in mining technology have brought larger machines that improve productivity but cannot be used for all deposits, constraining the characteristics of coal that can be mined.

Knowing the exact amount of coal recoverable during the 21st century requires perfect foresight of future resource discovery, production technology, energy economics, and regulation. Standard practice has been to use an equilibrium R-P heuristic to determine a range of plausible outcomes for future coal use. By applying past R-P ratios above 300, assessments developed during the latter half of the 20th century assumed the possibility of unlimited future growth. Will projections that rely on the modern R-P ratios, which are an order of magnitude smaller, eventually be perceived as overly conservative?

Confusion of “resources” with “reserves” has led to misguided interpretations of the meaning of *assessments* in many major producing regions (Grubert 2012; Wang et al. 2013). The standard definitions of reserves for oil, gas, and uranium do not directly map to coal resources. Interpreting the assessment process for each of these energy resources as equivalent results in a fundamentally flawed understanding of coal reserves.

For other energy and mineral resources, regulatory and market requirements establish a “reserve” base that indicates a dynamic working inventory. Reported reserves of coal have a different meaning: they specify a vaguely identified amount of mineral-in-place. Further recoverability studies and development expenditures determine the recoverable portion (Grubert 2012; Zimmerman 1975). Since each coal seam is relatively homogeneous and many seams are close to the surface, estimates for broad areas can be readily developed to determine the plausible amount in a region (Zimmerman 1983). Consequently, general information on the location of coal is very good.

Fully recovering the quantities of coal indicated as reserves by vintage assessments, however, requires deviating from baseline technology and market trends. For example, commercialization of underground coal gasification (UCG) which is unlikely. Defensible outlooks for greatly expanded future coal demand must also establish a case for new markets beyond steam and metallurgical coal, such as a wide adoption of synfuels, in which coal-to-liquids (CTL) technology replaces much of global oil production.

Expansion of UCG and CTL by several orders of magnitude would not occur in a vacuum: these technologies face not only a steep uphill battle to comply with environmental regulations far more stringent than when they were first demonstrated, but also competition from advances in renewables and unconventional oil and gas. Energy futures depicted by the case study in this paper implicitly or explicitly anticipate significant progress in these technologies.[3] Since our paper focuses on the recovery of energy from coal deposits, we concentrate on UCG, arguing that reference cases should not apply coal recovery rates that assume its widespread deployment.[4]

This paper examines the modern context for coal in future energy scenarios and is organized as follows. Section 2 addresses the baseline trends in coal supply since 1990 and explains why modern assessments indicate smaller reserves than vintage reports. Section 3 provides a case study to illustrate how legacy assessments have influenced widely used future

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[3] Though long-term energy scenarios may not specifically apply UCG technology, it is the only means possible of reaching the high recovery rates required to realize scenarios that use far more than today’s reserves. Common recovery factors are 80 percent for strip mining and 50 percent for underground reserves. However, Zimmerman (1983) studies the US coal industry and suggests that 50 percent is a reasonable estimate for the amount of reserves recoverable from any deposit.

[4] A full analysis of prospects for long-run CTL requires the exploration of many factors and technological potential for secondary energy conversion—factors that are beyond the scope of this paper.

energy scenarios. Section 4 analyzes the coal supply curves commonly used in the energy modelling literature to develop future scenarios. Section 5 concludes with a summary and recommendations for integrating future coal use in 21st-century energy scenario baselines.

2. Baseline Trends in Coal Reserves, Production, and Prices, 1990–2014

Trends in hard coal reserves, production, and markets over a period relevant to a coal baseline are depicted in Figure 1. Reserve and production data in this figure are from regular WEC and German Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe, BGR) reports (WEC 1989, 1992, 1995, 2001, 2004, 2007, 2013; BGR 2009, 2014, 2015). The International Energy Agency (IEA) annually relays select years of figures from both sources, along with regular updates on production (IEA 2001–2015).

Relevant coal supply trends for future energy scenarios must focus on hard coal reserves, which contain approximately 90 percent of the energy in the world's coal resource base (Rogner et al. 2012; Rogner 1997). A coal-dominant energy future would rely heavily on global trade in hard coal: the economics of lignite encourage consumption close to the site of extraction because of the fuel's low energy content, high water content, and primary use for electricity generation (BGR 2015).

Figure 1 plots the range of reported constant dollar prices from 1989 to 2014 across 10 major coal market indices (BP 2015; EIA 2012; World Bank 2016) shaded as a gray band.[5] The average of these benchmark coal prices (red) has more than doubled since 2000. The minimum price has increased by four times from the beginning of the time series. Rising prices have been concurrent with a doubling of global hard coal production (Figure 2).

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[5] Detail on included coal market indices: (a) BP—Northwest Europe Marker Price, US Central Appalachian Spot Price Index, Japan Coking Coal Import, Japan Steam Coal, Asian Market Price, EIA—Bituminous and Anthracite; World Bank– Coal (Australia), thermal GAR, f.o.b. piers, Newcastle/Port Kembla from 2002 onward , 6,300 kcal/kg (11,340 btu/lb), less than 0.8 percent, sulfur 13 percent ash; previously 6,667 kcal/kg (12,000 btu/lb), less than 1.0 percent sulfur, 14 percent ash, International Coal Report; Coal Week International; Coal Week; Bloomberg; IHS McCloskey Coal Report; World Bank), Coal (South Africa), thermal NAR, f.o.b. Richards Bay 6,000 kcal/kg from 2006 onward; during 2002–2005 6,200 kcal/kg (11,200 btu/lb), less than 1.0 percent, sulfur 16 percent ash; years 1990–2001 6390 kcal/kg (11,500 btu/lb) (International Coal Report; Coal Week International; Coal Week; World Bank), Coal (Colombia), thermal GAR, f.o.b. Bolivar, 6,450 kcal/kg, (11,200 btu/lb), less than 1.0 percent, sulfur 16 percent ash from August 2005 onward; during 2002–July 2005, 11,600 btu/lb, less than 0.8 percent sulfur, 9 percent ash, 180 days forward delivery (International Coal Report; Coal Week International; Coal Week; World Bank).

All else being equal, conventional resource economists theorize that higher resource prices lead to reclassifying hitherto uneconomical geological deposits as economically recoverable reserves. Yet since 2000, coal prices have doubled and production has doubled but reserves have declined by roughly 15 percent (Figure 3). Reported reserves do show an increase around 2000: as the decade-long expansion of coal production began, new mines were opened as new supply contracts were signed, temporarily increasing reported reserves. As the rate of mining continued to increase, however, total reported reserves declined despite rising market prices. Since global recoverable coal and price trends have not moved as expected, at least one of the simple assumptions applied to coal resource economics is not correct.

Rogner (1997) and Rogner et al. (2012) convert coal assessment figures to energy units and are important secondary references on coal supply for future energy projections. Rogner et al. (2012) report two-thirds less energy in the hard coal reserve base from the earlier assessment based on BGR (1989) and WEC (1992). This decline in available energy from coal led to a rapid decrease in the global coal R-P ratio from more than 300 years to less than 100 (Figure 4, right axis). Because of uncertainties in the energy content of recovered coal, we report normalized values to highlight this decline.[6] WEC reports that the large value for 1989 in Figure 4 results from a reclassification of China’s reserves as “proved recoverable” from a previous definition as “proved amount in-place.”

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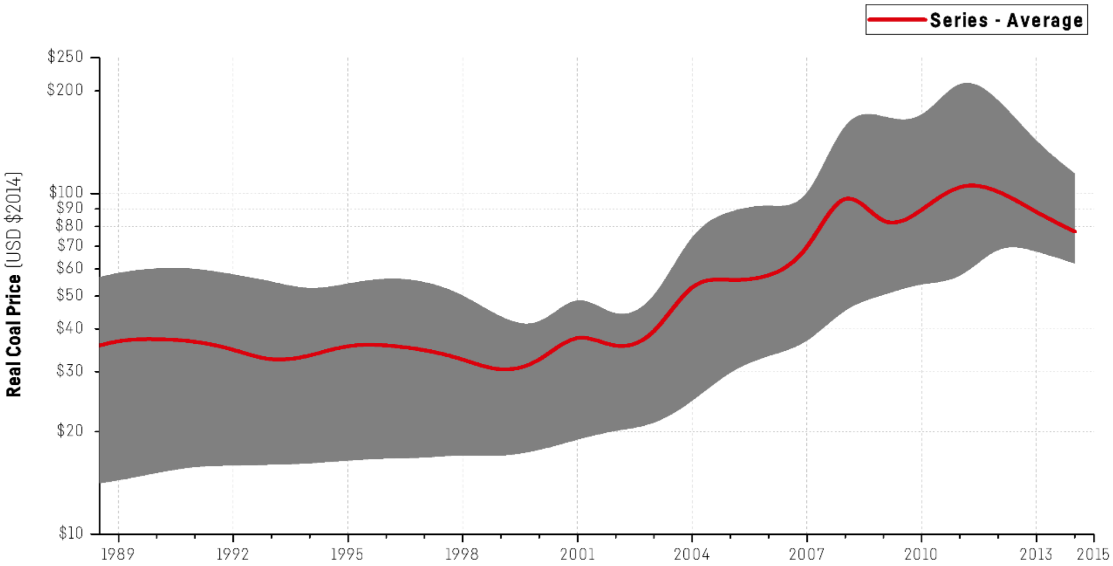
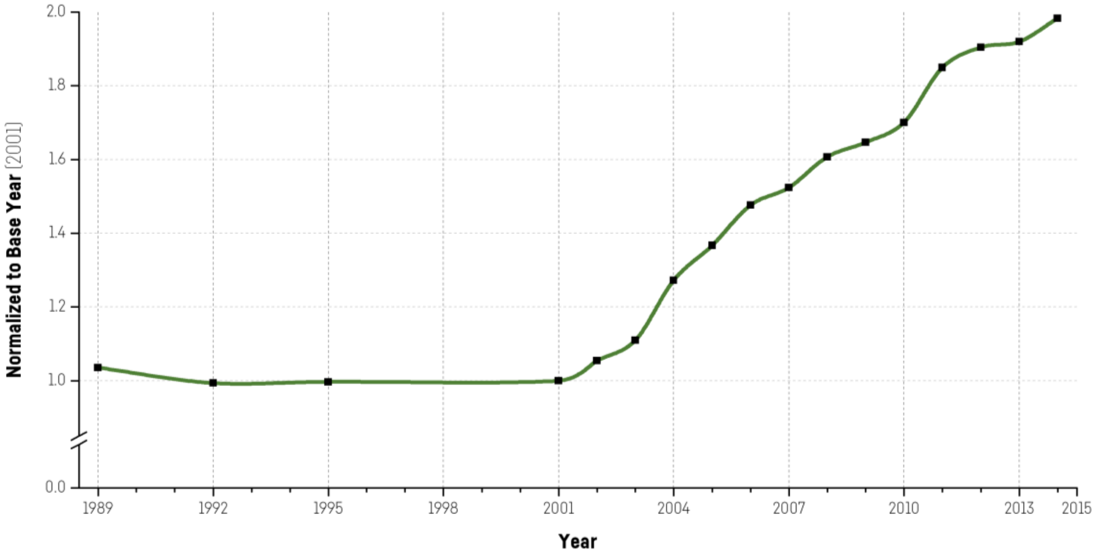
[6] Throughout this paper, where global coal reserve physical units are converted to energy units, we use the Rogner (1997) methodology of applying average energy content per region of reserves to calculate an internally consistent value for comparing assessment vintages.

Figure 1. Trends in Global Coal Market Benchmark Prices, 1989–2014



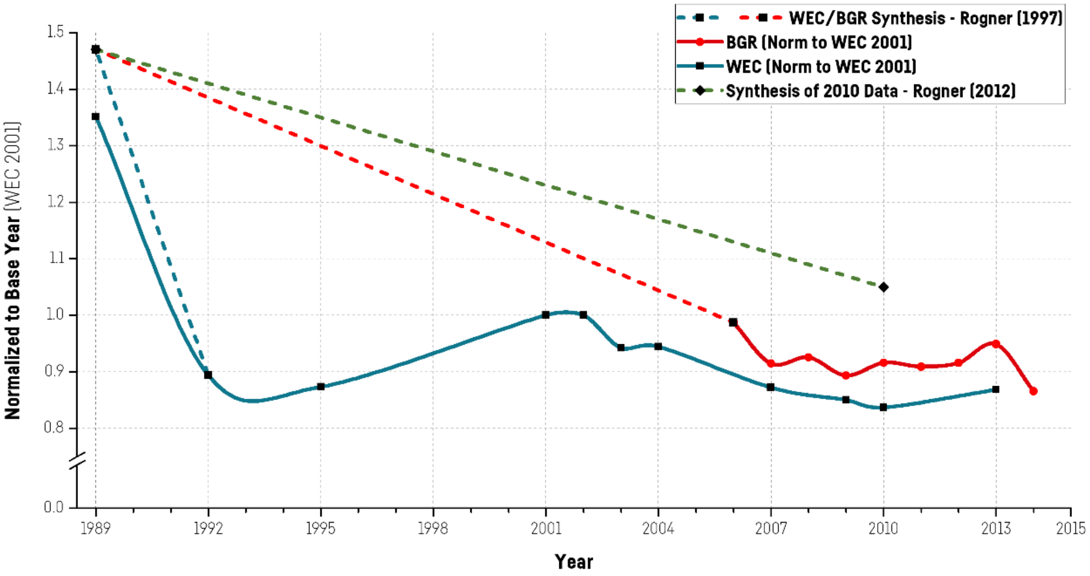
Note: Log-scale, constant USD (2014), average annual price per metric ton
Sources: BP (2015), EIA (2012), World Bank (2016)

Figure 2. Hard Coal Production, 1989–2014



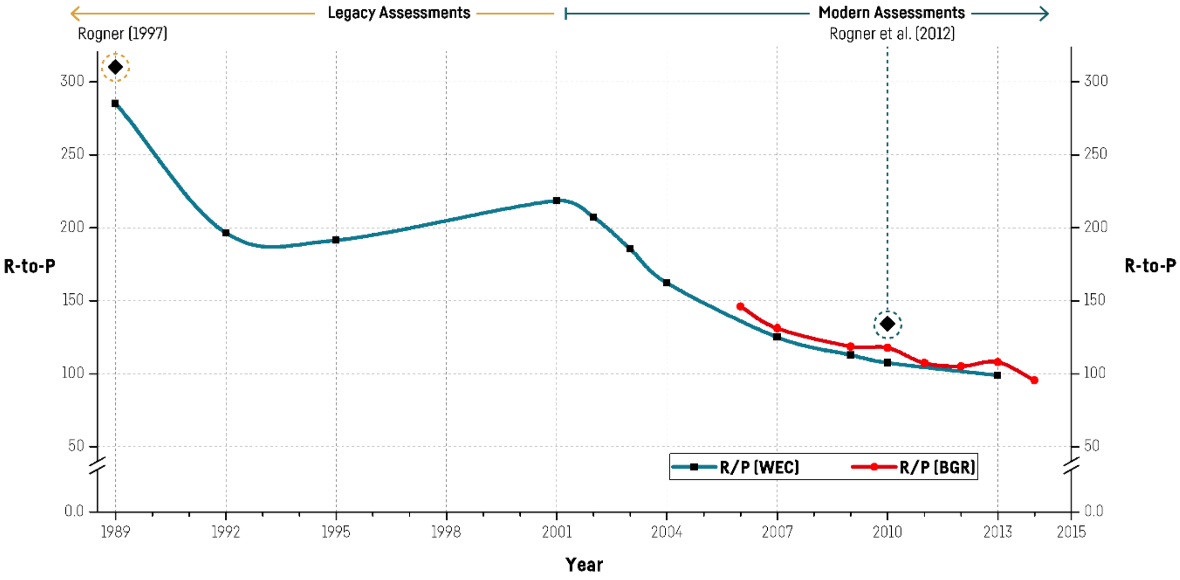
Note: Production is indexed to IEA values for 2001.
Sources: IEA Coal Information Reports, WEC, and BGR

Figure 3. Coal Reserves, 1989–2014



Note: Legacy assessments reflected by Rogner (1997) reported values from WEC, BGR, modern assessments follow Rogner et al. (2012)
Sources: Rogner (1997), Rogner et al. (2012), IEA Coal Information Reports, WEC, and BGR

Figure 4. Reserve-to-Production Ratio for Global Coal



Sources: Rogner (1997), Rogner et al. (2012)

2.1 The Decline in Coal Reserves with Increased Knowledge

Cumulative production reported by IEA since 2001 accounts for up to 80 percent of the *ceteris paribus* difference between hard coal figures at the start of the 21st century and recent BGR assessments. Thus, at least 20 percent of the net decline in reported global reserves has resulted from factors other than depletion, such as improved knowledge of the global reserve base, standardized definitions, and technical change.[7]

Doubling of hard coal production since 2000 (see Figure 2) has contributed to an improved understanding of the world's coal reserve base. Expanded mining in conventional and new areas provided more accurate information on previously assessed deposits. Updated reserve data are collected in active mining regions, and so knowledge improves as mining expands to new areas. Recoverability studies over this period have verified the geomining conditions of previously identified seams, and researchers have updated older coal availability studies by applying new technology, such as geographic information systems (GIS), and by factoring in modern societal constraints, such as environmental protection.

Grubert (2012) observes that recoverable coal from listed reserves is commonly overestimated because of the failure to distinguish between physically available coal and the coal that can be profitably and legally produced with social acceptance. For example, a coal deposit high in sulfur underneath a major city is unlikely to be exploited, but common assessment practices are likely to report it as "economically recoverable."

Grubert focuses on coal reporting standards, arguing they are less regulated than those for oil and natural gas, so assumptions of equivalence between reserve data for oil, gas, and coal resources lead to overconfidence on coal availability. Coal has lower global market exposure than oil and gas and is often supplied by infrequently negotiated contracts that depend on transportation from specific mines. Thus, she suggests, coal markets are more tolerant of inaccurate data on global supply because contracts secure supply from specific mines over many decades. Grubert also notes that coal owners obtain many benefits from overstating reserves to make a case for public investment in rail lines and infrastructure that make extraction profitable.

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[7] This *ceteris paribus* decline has occurred despite additions to the assessed reserve base in many regions. The detailed analysis of year-to-year source of declines or additions to the reserve base per region is beyond the scope of this study. However, since reserve additions have occurred in many regions, it is safe to assume that 20 percent is a lower-bound estimate of nondepletion related decline in coal reserves. The term "technical change" here captures shifts in the global macro-production function of labor and capital in the broadest sense, beyond technology.

Ruppert et al. (2002) discuss how US Geological Survey (USGS) coal assessments must now focus on quality issues such as sulfur content, whereas earlier availability studies did not (Averitt 1975). The USGS National Coal Resource Assessment (NCRA) beginning in 1995 found that updates of vintage assessments for present-day land-use, technology, and environmental regulations greatly reduce the mineable portion of known in-ground coal. The updated NCRA study indicated that in some regions, less than half of the original total reserve estimate could be mined, and only 10 percent would be economically recoverable.

The USGS study demonstrates how an initially high R-P ratio encourages less careful assessment of coal deposits: more accuracy is required as the ratio declines. Standard *in situ* reserve figures generally do not account for feasible recovery rates constrained by factors such as overburden, so the amount of total recoverable coal is often much smaller than initial assessments indicate. More than a century of experience in the United Kingdom’s mature coal industry parallels that of the USGS: both demonstrate how increasing knowledge leads to ongoing subtraction from an initially large assessment (Luppens et al. 2009; Rutledge 2011).

Coal reserve figures are not comparable with those for oil and gas for several further reasons: (1) rare cases of probabilistic assessment for potential coal recovery (e.g., no P1, P2, and P3 reserves, as in oil and gas)[8]; (2) unclear time horizons for access (sometimes recorded as “50 years” or “N/A”); and (3) limited clarity on extraction profitability, with coal reserves often calculated in a “breakeven” analysis, rather than under conditions for profitable extraction (Grubert 2012; Kavalov and Peteves 2007; Milici et al. 2013). Whereas oil and gas reserve figures indicate a dynamic working inventory that results from *development expenditures*, coal reserve figures indicate the maximum potential inventory assessed by *exploration expenditures (*Zimmerman 1983). Exploration expenditures are one step removed from development efforts that would confirm the viability of coal extraction from specific deposits.

Standardization of definitions in major coal-producing regions has also contributed to increasing information about global coal resources and reserves and their subsequent reclassification (CIM 2014; Hartnady 2010; JORC 2012; Wang et al. 2013). Assessments of coal

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[8] The Society for Petroleum Engineers notes that P1 “proven reserves” indicate at least a 90 percent probability that the quantities actually recovered will equal or exceed the low estimate. P2 reserves include proven + probable reserves, indicating a 50 percent probability that the quantities actually recovered will equal or exceed the best estimate. P3 reserves include proven, probable, and possible reserves, indicating a 10 percent probability that quantities recovered will equal or exceed the high estimate.

reserves in China, South Africa, and the former Soviet Union have been reexamined to determine whether any economic factors were considered beyond the basic geological presence of a deposit, and the reserve definitions applied by centrally planned economies in the Soviet Union and China with quantity-based production targets have been revisited. Because many older studies on coal relied on secondary sources, digital database technology has also created an opportunity to reduce the rate of double-counting (Noyes 1978).

Advances in modern mining technology have also improved knowledge of the economically recoverable portion of coal. Rogner et al. (2012) suggest that trends in mining have played a major role in reducing assessed reserves. Mechanization has considerably improved productivity and mine safety but only for the subset of mines with specific geological characteristics. Over recent decades, coal mining has depended on larger equipment and production units, channeling investment toward favorable seams in simpler geological environments (Wagner 2003). Therefore, many previously assessed coal seams requiring labor-intensive mining techniques no longer meet the criteria for reserves. Rogner et al. (2012) note that modern mining technology has contributed to a 90 percent reduction in Germany’s assessed reserves.

2.2 The Prospects for Underground Coal Gasification

Unforeseen and unanticipated developments in coal recovery technologies, such as in situ underground coal gasification, may lead to larger assessments of coal reserves in the future. Technological breakthroughs enabling wide-scale adoption of UCG for full recovery of deep deposits could expand reserves by up to 300 percent (Stephens et al. 1985). However, more than a hundred years of experience indicates significant barriers to adoption of UCG.

UCG, which promises to expand recoverable reserves by reaching deep deposits and simultaneously avoid mining accidents, was first proposed in 1868. Since then, test facilities and experiments in the Soviet Union (1934–1989), the United States (1973–1988), and elsewhere around the world have primarily evaluated the idea for seams at less than a few hundred meters’ depth (Bhutto et al. 2013; Grenon 1979; Perkins 2005). Other mining techniques are viable at these depths with lower environmental risks and higher energy recovery, leaving little justification for coal producers to pursue UCG further. Of the few dozen trials since the early 20th century, most tests have run for only a few days or weeks. Long-term demonstration of UCG in deep seams would justify its potential as an eventual commercial technology. However, this has never been accomplished.

Couch's (2009) assessment of UCG for IEA reference cases emphasizes that pilot projects over the past 50 years have proven one or two aspects of the technology while revealing many undesirable side effects. He argues the pathway to commercialization of UCG is unclear because (1) reactions take place underground where monitoring is difficult; (2) models of UCG productivity have been subject to little empirical verification; (3) broader criteria for site selection have yet to be well defined; (4) integrating the required interdisciplinary knowledge of geology, hydrogeology, and gasification faces acute talent shortages; and (5) environmental issues have plagued many test sites.

Experience with UCG from test projects have indicated significant constraints on site selection. For example, a 1997 pilot in Spain at a depth of 600 meters highlighted the importance of avoiding aquifer systems because of the potential for explosions. In this case, geological subsidence shifted the underground structure, leading to collapse and a subsequent explosion (Walker 2007). UCG pilots in many locations have caused severe groundwater contamination that persists for years after gasification ceased, with high concentrations of phenols and PAHs readily detected in aquifers extending dozens of kilometers from the gasification site (Campbell et al. 1979; Friedmann et al. 2009; Klimenko 2009; Liu et al. 2007). Given the public's response to hydraulic fracturing in many locations, it is likely that obtaining social licence to operate UCG facilities will face significant opposition, even if environmental challenges are successfully addressed.

UCG experiments in the Soviet Union reported recovery of less than 60 percent of the heating value of in situ coal. Net energy efficiencies from these experiments were less than 40 percent because of energy input to the gasification process. These older UCG sites had to be located near end uses, since the low-energy gas was less economical to transport than solid coal (Grenon 1979). It is likely that with the reduced cost of pipeline construction and further research, some of these limitations could be overcome, but siting would still remain an issue.

Estimating the possible economic and technical potential for UCG requires developing detailed criteria for site selection. However, even a single successful UCG project may not be a model for future sites, since coal seams are present in diverse geological and hydrological settings with many different rock formations and aquifers (Couch 2009).

Despite more than a century of experimentation, UCG still needs decades of foundational research to establish its commercial viability. Given recent advances in commercial-scale renewable energy technologies and unconventional oil and gas, it seems unlikely that new private funding can be attracted to development of UCG. Furthermore, given concerns about climate change and local environmental damage, designation of public funds to UCG is politically perilous. If it is appropriate to consider the implications and recovery rates of UCG in reference global energy scenarios, it would be equally appropriate to consider the role of experimental technologies such as nuclear fusion.

2.3 Implications of Modern Coal Reserve Assessments for Future Energy Scenarios

Since coal reserve figures do not accurately reflect the total stock of extractable geologic occurrences, the R-P ratio for coal should not be mistaken as a "lifetime index" indicating the terminal point for coal exhaustion (Zwartendyk 1974). Nevertheless, the economic factors contributing to higher R-P values from earlier eras (>150–1,200) were interpreted as framing an "equilibrium range" in long-term energy studies.

Around the R-P equilibrium that informs future scenarios, reserves are considered to be replenished from the broader resource base as they are used up (Rogner 1997; Thielemann 2012; Thielemann et al. 2007; Wellmer 2008; Wellmer and Berner 1997). Scenarios adopting this concept expect that coal follows the trend of oil and gas, where increasing production will classify more resources into reserves, growing the total size of the reserve bank (Adelman et al. 1983; Watkins 2006). Market and industry responses to low gas and oil R-P ratios have already been documented and analysed.

The R-P ratio for hard coal has fallen by an order of magnitude over the past quarter-century to unprecedented levels (see Figure 4).[9] The response of markets and industry to a low R-P ratio for coal is unknown. Furthermore, the process by which recoverable reserves are estimated for coal differs: oil and gas extraction involve lesser disturbance of the surface and its surroundings. Therefore, the heuristic of an equilibrium R-P for coal is not tested and provides untested support for projecting the future of coal. Zwartendyk (1974) observed, "If we do not know what the [reserve] figures really mean, they are not merely useless, they are worse than useless because they tend to mislead."

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[9] A recent decline in hard coal production has recently led to an R-P value of more than 100 (BGR 2015). It is very possible that the R-P ratio could increase in the near future if production growth maintains this trend. However, this possibility is not considered in the baseline energy scenarios of Section 3.

Maintaining a static equilibrium R-P range of values for an energy resource implies the following:

- Market conditions will always be sufficient to expand reserves.
- The total resource stock accurately reports quantities that will eventually become recoverable reserves—that is, resources will eventually be recoverable.
- Development expenditures will readily convert marginal coal to recoverable reserves.
- Supply is perfectly elastic—that is, quantity is infinitely responsive to price.
- The resource faces no substitutes that would significantly erode its market share across the horizon of indicated supply.
- The investment horizon for capital equipment necessary to access reserves anticipates sufficient demand, supply, social license, and amenable regulation.

Evidence presented in this section leads us to reject these assumptions as a basis to model future coal supply.

Today’s R-P values indicate a ceiling on growth rates in coal production. For example, Thielemann et al. (2007) consider that realizing 1 percent annual growth in global coal production is consistent over the long run with early-21st-century reserve figures. The relevant question for modeling coal use in the long term is whether throughout the time horizon of the study, reserve figures maintain a level that inspires confidence for *new investments* that rely on coal, and that economically recoverable supply is sufficient to substitute for a significant portion of oil and gas.

Gordon (1987) argues that comparisons of long-run economics for oil, gas, and coal based on reserve estimates fundamentally fail because detailed data are expensive to develop and therefore produced only when essential. As noted earlier, low R-P ratios have forced investment in better data for oil and gas. Coal R-P ratios are now approaching levels that prompt more careful (and expensive) analysis, and these have shown that reserves are lower than earlier estimates.

Further, Gordon (1987) suggests that the belief in an eventual return to coal arises from a misinterpretation of available data. Since more data are available on the location and total quantities of geological coal, it often appears a better bet than oil and gas in the long run. However, reported estimates of coal primarily indicate a geologic occurrence of coal deposits, which are not synonymous with "economically recoverable coal"—a term that creates the illusion of economic substitutability for oil with sufficient supply.

3. Case Study: Coal in Baseline Scenarios of Greenhouse Gas Emissions

In climate change studies, baseline scenarios of the global energy system intend to represent a range of possible futures absent specific actions to reduce GHG emissions (Clarke et al. 2014).[10] The scale and structure of these energy system baselines create reference points for estimating the scope and cost of mitigation efforts and determining climate impacts.

Baseline scenarios for GHG emissions generally make three assumptions: primary energy demand will grow, oil and gas supplies will wane, and coal supplies are the backstop. Under such assumptions and cost optimization, oil and gas will become more expensive and coal will provide ever-larger shares of total primary energy supply.

IPCC assessment reports and the broader climate change research community have developed four generations of GHG emission projections since 1990. Each of the IPCC's five assessment reports has presented a reference energy supply with the combustion of most or all coal reserves before the end of the 21st century as business-as-usual (BAU). Because they have all relied on the same information, described above, they have assumed a consistent and high baseline of emissions. Thus, for the past quarter-century, high emissions baselines have been the focus of research and either explicitly or implicitly shaped national policy benchmarks, such as estimates for the social cost of carbon (National Academies of Sciences, Engineering, and Medicine 2016).[11]

The four sets of scenarios have created a consistent foundation for model runs and communication of results throughout the climate change research community. Each generation of scenarios depicts one or more high-emissions cases exceeding 1,000 GtC from fossil fuels

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[10] Baselines are also commonly referred to as *reference cases* and are explicitly defined by the IPCC Data Distribution Centre: "The baseline (or reference) is any datum against which change is measured."

[11] Three integrated assessment models commonly calculate the social cost of carbon: DICE, FUND and PAGE. In DICE no marginal cost is assigned to fossil energy resources and 21st-century emissions from fossil fuels total more than 1,800 GtC (Nordhaus and Sztorc 2013). FUND uses an EMF14 standardized scenario (Energy Modeling Forum 1995) that assumes 300,000 EJ of available coal and results in a 21st-century run for GHGs around 1,500 GtC (Waldhoff et al. 2014). PAGE has commonly used a POLES-IMAGE (CPI) baseline scenario (Alberth and Hope 2007; Elzen et al. 2003; van Vuuren et al. 2003), which projects around 1,300 GtC from fossil fuels from 2000 to 2100.

through the 21st century, equivalent to an increase of 472 ppm in atmospheric CO_2. In the climate model runs of the IPCC First and Fifth assessment reports, these high-emission cases are the only illustrations of a BAU world without climate policy.

The next section briefly details the projections of future coal use in each generation of IPCC baseline emission scenarios. The First Assessment Report used the SA90 BAU scenario; the Second Assessment Report drew from the IS92 scenario family, the Third and Fourth Assessments built from the Special Report on Emission Scenarios, and the Fifth Assessment Report employed four representative concentration pathways and 1,184 Working Group III (WGIII) scenarios. [12]

3.1 Coal in GHG Scenario Baselines, 1990–2010

Reference cases in IPCC assessment reports have focused on pathways of high emissions from fossil fuels that exceed 1,000 GtC from 2000 to 2100. Figure 5 summarizes 21st-century coal use in these high-emissions cases for each scenario family, grouped by their use in the First (1990) and Second (1995) assessment reports (solid lines) and in the Third (2001) and Fourth (2007) assessment reports (dotted lines). The 32,000 EJ[13] difference between Rogner (1997) and BGR (2015) reserve assessments (horizontal lines) frame the total energy from coal in each high-emissions case.

In the First Assessment Report, a single BAU case projects a high-emissions pathway resulting in 10 W/m^2 of year 2100 radiative forcing (IPCC 1990a). In this scenario, coal accounts for more than two-thirds of the 1,700 EJ primary energy supply at the end of the century (as detailed by WGIII). With global annual coal use at around 160 EJ in 2014, this projection would constitute a further 600 percent expansion in annual coal use by 2100 (BP 2015). Coal-based synfuels—liquid and gaseous fuels produced through transformation of coal, assumed to begin after 2050—account for much of the increase.

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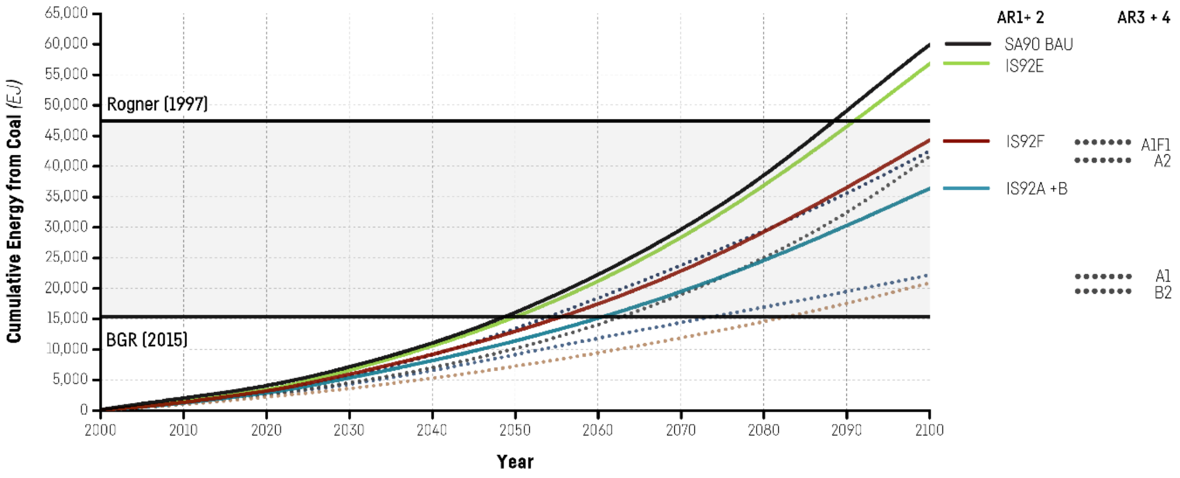
[12] This paper classifies the use of GHG scenarios by their use in assessments for policy and mitigation (IPCC WGIII). Generally, the use of scenarios in studies of climate impacts with general circulation models (GCMs) have lagged their application in IAMs. For GCMs of the physical climate, the IPCC First and Second assessment reports used equilibrium climate scenarios, the Third uses the IS92 scenarios, the Fourth uses SRES and IS92, and the Fifth uses the RCPs and a series of mitigation scenarios (Moss et al. 2010). For the First Assessment Report, IPCC WGIII uses a high and low emissions case, where the emissions, and consequently the energy supply from fossil fuel in the high emission case, correspond to the WGI BAU case.

[13] Exajoules (EJ) – for context, total global primary energy supply in 2015 used 550 EJ.

In the Second Assessment Report, four of the six IS92 scenarios resemble the original coal-focused future of the SA90 BAU case (Leggett et al. 1992). In the most commonly modeled pathways IS92a and IS92b (Strengers et al. 2004), total primary energy supply (TPES) reaches 4.8 times base-year levels (1,460 EJ) by 2100, with half supplied by coal. Coal-based synfuels supply nearly one-fifth of global primary energy in IS92a.

The Third and Fourth assessments applied 40 baseline scenarios from the IPCC Special Report on Emission Scenarios (IPCC 2000). Six marker scenarios depicted salient features of the core narratives for each set. Four of these marker scenarios are high-emissions futures: A1B (a balance among all energy sources), A1F1 (a fossil-intensive energy world), A2 (slow technological change), and B2 (more gradual changes in current trends). Coal consumption is most prolific in A2 futures, where annual coal use averages a multiple of 9.4 over base-year levels by 2100.

Figure 5. Cumulative Energy from Coal in IPCC Scenario Baselines for High Emissions, 2000–2100



Notes: First and Second assessment report baselines are represented by solid lines. Third and Fourth assessment report baselines are shown in dotted lines. The Rogner (1997) and BGR (2015) reported values for year-2015 available energy in hard coal reserves are indicated by the horizontal lines.
Sources: IPCC (1990b); IPCC WG3 (2000)

3.2 Coal in Recent IPCC Baselines: RCP and WGIII Mitigation Scenarios

Emissions scenarios in the Fifth Assessment Report draw from four representative concentration pathways (RCPs) and 1,184 WGIII mitigation scenarios. Each RCP summarizes the salient features for ranges of emissions scenarios in the broader literature. The RCPs are not explicit energy system scenarios but draw from marker scenarios, which employ projections of future energy systems (van Vuuren et al. 2011a).

The marker scenario for RCP 8.5 illustrates a BAU world that resembles the general features of coal-dominated energy futures from the previous sets of scenarios (Section 3.1) (IPCC 2014; Riahi et al. 2007, 2011). The other three RCPs (6.0, 4.5, and 2.6) represent mitigation steps to stabilize atmospheric GHG concentrations from baselines consistent with RCP 8.5.[14]

Four integrated assessment models (IAMs) develop the RCP marker scenarios: MESSAGE (RCP 8.5), AIM (RCP 6.0), GCAM (4.5), and IMAGE (RCP 2.6). The marker scenarios use coal-dominant reference energy supplies to inform RCP marker scenario baselines (Masui et al. 2011; Riahi et al. 2011; Thomson et al. 2011; van Vuuren et al. 2011c).

Figure 6 illustrates cumulative coal use in the baseline and mitigation scenarios of each RCP marker. The RCP marker scenario baselines project 28,900 to 39,500 EJ from coal over 2000–2100, while the three mitigation cases range from 14,400 to 20,200 EJ. In the mitigation cases, especially RCP 2.6, much of the coal use is coupled with carbon capture and sequestration (CCS).

RCP marker scenario baselines expect that global TPES more than triples year-2000 levels by the end of the century, with at least half of the resulting fossil fuel–based emissions from coal. Energy from fossil fuels from 1800 to 2000 totaled 13,340 EJ (BP 2015; Grübler 2008), with 43 percent from coal. Cumulative future fossil fuel use is projected to increase by 400 percent over the 1800–2000 values in these RCP marker baselines, reaching 70,000 to 89,000 EJ for the 21st century. In Figure 6 we compare total coal use, by RCP scenario, with total hard coal reserves as estimated by Rogner (1997) and BGR (2015).

The baseline scenarios for RCPs indicate a “back to the future outcome” for coal (Figure 7). When Marchetti (1977) developed a graphic approach to show the evolution of energy shares, where a “superior” energy form increasingly substitutes for “inferior” forms, he did not consider a market reversal. According to RCP marker scenario baselines, coal will once again dominate all energy forms by the end of the century.

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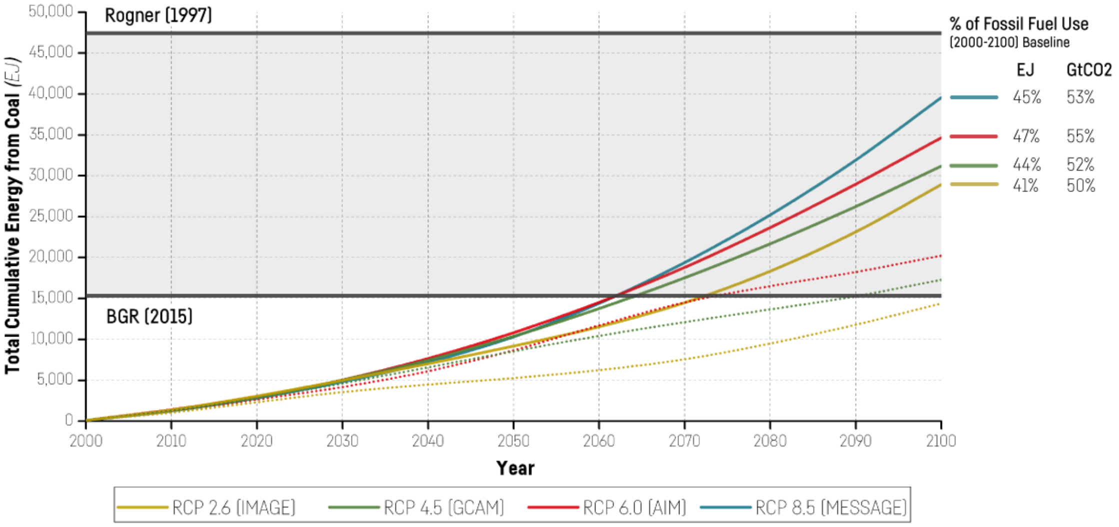
[14] Each RCP is labeled after a value for radiative forcing in 2100; for example, RCP 8.5 results in 8.5 W/m^2.

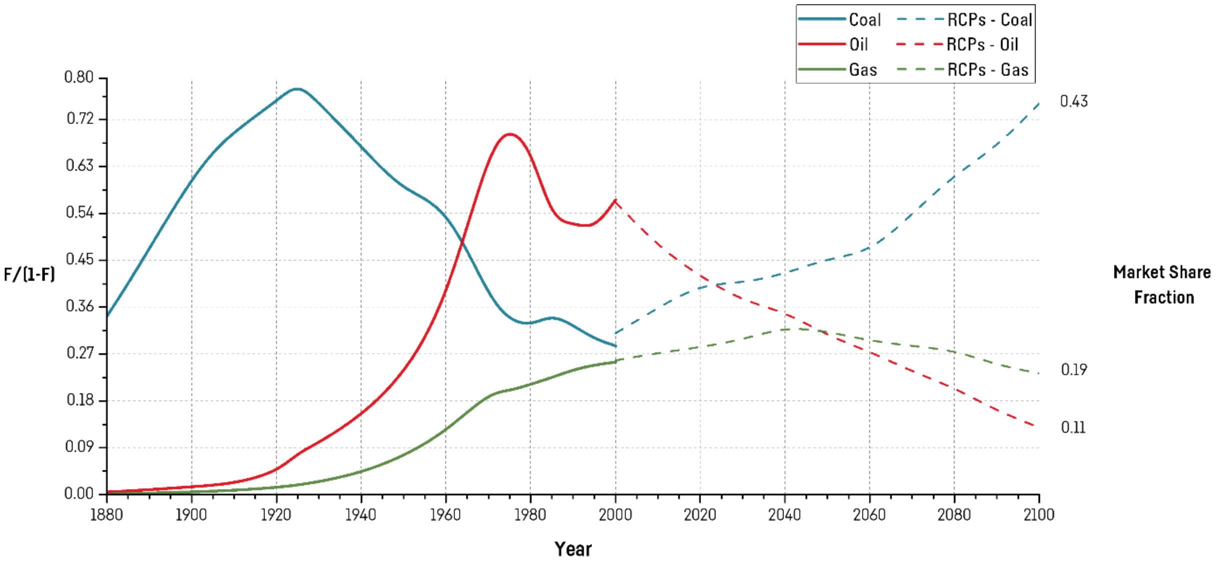
Figure 6. Representative Concentration Marker Pathway Baselines and Total Cumulative Energy from Coal, 2000–2100



Notes: Total cumulative energy from coal in RCP marker scenario baselines is represented by solid lines. Corresponding mitigation cases for final RCP 6.0, 4.5, and 2.6, 2000–2100, are shown by the dotted lines. The proportion of coal in RCP fossil energy baselines, by energy content (EJ) and $GtCO_2$, is indicated at the upper right.

Sources: Riahi et al. (2011), Masui et al. (2011), Thomson et al. (2011), van Vuuren et al. (2011c)

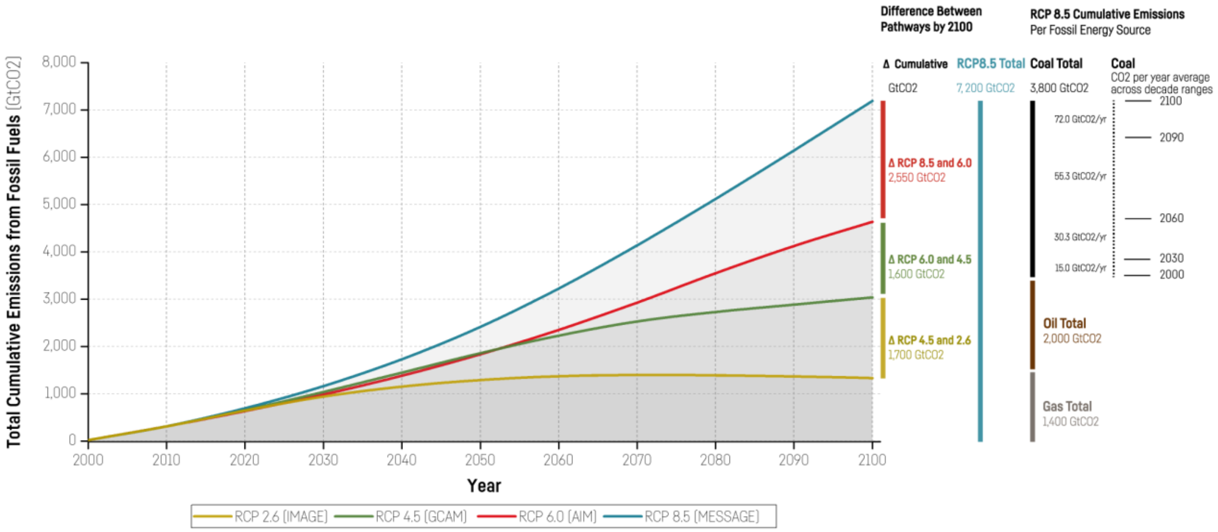
Figure 7. World Primary Energy Substitution, 1880–2000, and RCP Marker Scenario Baseline Averages, 2000–2100



Notes: Right axis indicates the market share fraction of total primary energy supply (TPES) in year 2100.

Sources: Marchetti (1977), Riahi et al. (2011), Masui et al. (2011), Thomson et al. (2011), van Vuuren et al. (2011c)

Figure 8. Total 21st-Century Cumulative CO_2 Emissions from Fossil Fuels in RCPs and RCP Baselines



Notes: The final RCP marker scenarios (2000–2100) are derived from baselines with separation between cumulative emissions between pathways (right). RCP 8.5 emissions from fossil fuels are indicated by the blue line, with energy system baseline of RCP 8.5 delineated by fossil fuel type indicated for coal (black), oil (brown), and gas (gray). Multidecadal averages of emissions from coal in RCP 8.5 baseline for coal are at far right.
Sources: Riahi et al. (2011), Masui et al. (2011), Thomson et al. (2011), van Vuuren et al. (2011c)

Cumulative 21st-century emissions from fossil fuels and industry (FF&I) for the RCP marker cases for are shown in Figure 8 (IIASA 2009). The RCP 8.5 scenario for a BAU world expects a cumulative 7,200 $GtCO_2$ from fossil fuels this century. The distribution of emissions from fossil fuel combustion in the RCP 8.5 marker scenario is illustrated on the right of the figure, where coal results in 3,800 $GtCO_2$. Use of oil and gas release 2,000 and 1,400 $GtCO_2$, respectively. The dotted lines on the right side depict the emissions attributable to coal over multidecade periods and the average annual rate of GHG emissions from coal across the time range. The growth in coal use in the RCP 8.5 marker leads to average coal emissions of 72 $GtCO_2$/year for 2090–2100, more than four times the level for 2015.

A total of 2,550 $GtCO_2$ separates the RCP 8.5 marker scenario from its nearest mitigation case (RCP 6.0), an amount equivalent to post-2050 coal combustion in the marker scenario. The varied assumptions on coal adoption after a maximum rate of oil production in 2060 entirely account for the separation between RCP 6.0 and RCP 8.5. Acceleration of coal use in earlier decades constitutes much of the difference in levels of GHG emissions between RCP 4.5 and RCP 6.0.

In the RCP 8.5 marker case, oil production declines from 160 million barrels per day (mbd) after midcentury, constituting a smaller portion of total cumulative emissions (2,000 $GtCO_2$). Gas combustion steadily grows, resulting in 1,350 $GtCO_2$. Total 21st-century coal use constitutes the full span of cumulative FF&I emissions that separate RCP 8.5 and RCP 4.5. These features of RCP baseline energy systems accurately represent the broader range of scenarios used in the Fifth Assessment Report.

WGIII for the Fifth Assessment Report draws from 1,184 scenarios of future GHG emissions (Blanford et al. 2014; IPCC WGIII 2014). These are mostly mitigation scenarios that model steps to reduce baseline emissions (Clarke et al. 2014). Eleven scenario baseline families project internally consistent sets of characteristics for future society through the year 2100.[15] Each baseline varies assumptions for the global energy system, such as constraining the deployment of nuclear power. Including the RCP baselines, these variations result in 223 runs of 42 baselines to the end of the century from 22 IAMs. This collection of WGIII baselines projects annual coal use in 2100 that averages a multiple of five times the base-year level.

We use Figure 9 to illustrate the decade when each of the 223 baselines exceeds current estimates of hard coal reserves (BGR 2015). The timeline spans the second half of this century (2050–2100). Each horizontal bar depicts one of the baselines projected within the groups of scenarios labeled on the left. A model’s cumulative coal use below 15,300 EJ is shown in green. Models’ projections that exceed the current estimates of reserves are colored yellow, red, and purple according to the level of exceedance: one to two times, two to three times, and more than three times, respectively. The top the heatmap shows percentage of all baseline projections and their probability of exceeding the reserves by decade. Note that 100 percent of runs exceed current reserves, 60 percent exceed twice that level, and 12 percent exceed three times the assessed coal reserves (in purple).

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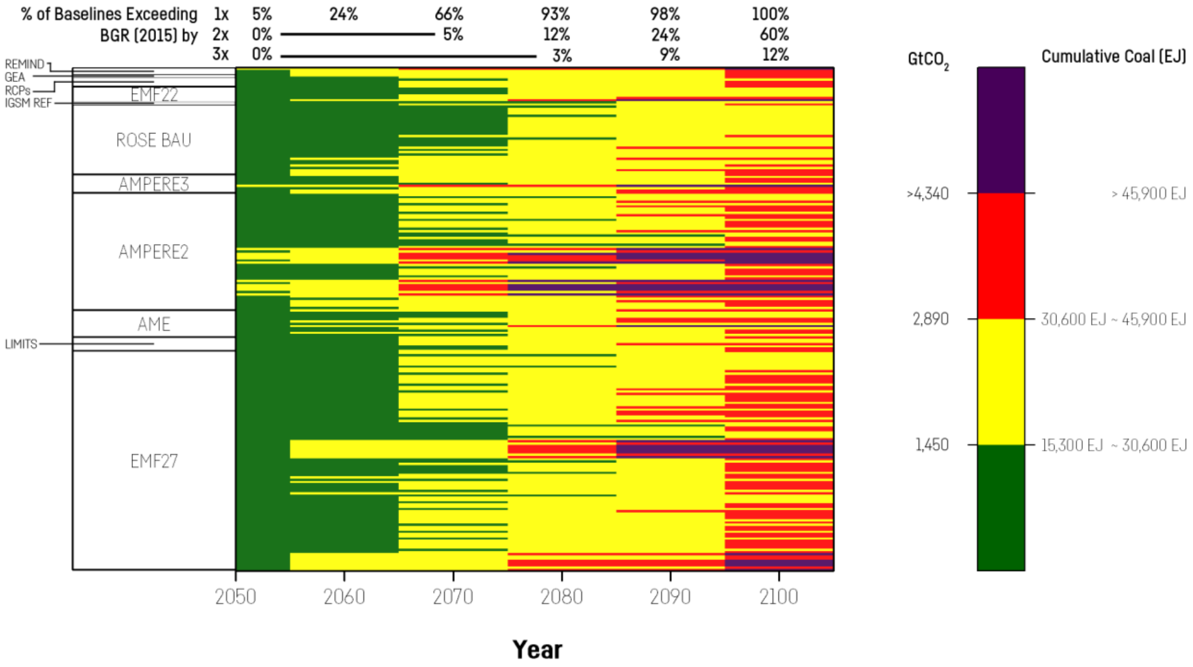
[15] The 11 baseline families are constituted by EMF27-Base (9 variants), LIMITS-Base, AME Reference, AMPERE2 (7 variants), AMPERE3, ROSE BAU (12 variants) , IGSM REF, EMF22 Reference (2 variants), RCP Baselines (4 variants) (MESSAGE, AIM, GCAM, IMAGE), GEA Counterfactual, REMIND baseline (3 variants) (Blanford et al. 2014; IPCC WGIII 2014; Masui et al. 2011; Riahi et al. 2011; Thomson et al. 2011; van Vuuren et al. 2011a).

Figure 9. Total Cumulative Primary Energy from Coal, 2050–2100, Compared with BGR (2015) Coal Reserves



Notes: The Fifth Assessment Report's 223 baseline runs are grouped by scenario family and compared with the amount of energy available in year-2015 coal reserves from BGR (2015). Levels in the heatmap are marked according to multiples of the 2015 coal reserve base at 1x (green), 2x (yellow), 3x (red), and greater than 3x (purple).

This section has demonstrated that GHG emissions scenarios over the past 25 years have considerably exceeded the use of coal reserves indicated by modern assessments. This characteristic follows from assuming coal supply curves that wholly adopt equilibrium R-P value approaches to inform their application of a coal backstop. We question the wisdom of such a modeling paradigm to address long-term uncertainty in recoverable coal reserves, and in the next section, we propose an alternative.

4. Finding a New Equilibrium for Coal Supply Curves and Long-Term Energy Scenarios

Applying an equilibrium R-P for coal in long-term energy system projections allows for the development of a vast coal supply curve, such that withdrawals inevitably lead to conversion of geological coal occurrences into a viable fuel source (Pacific Northwest National Laboratory 2012; Riahi et al. 2012; Rogner 1997). For example, the Energy Modeling Forum 14 baseline scenario informing the social cost of carbon in FUND reports 300,000 EJ of economically recoverable coal (Energy Modeling Forum 1995), suggesting a virtually unlimited supply, equivalent to an R-P of 1,875 at recent production levels. These coal supply curves are generally presented in the literature as generally long and flat, with a smooth, gradual continuous upward slope that levels off at one or more points to inform the eventual backstop price.

Legacy coal assessments have supported the construction of total carbon supply curves (Figure 10) to guide scenarios of possible future GHG emissions (Rogner 1997). Equilibrium R-P values applied to carbon supply curves introduce many low-grade coal resources (identified by Rogner as Grades D and E) and exceedingly high amounts of reserves (Grades A, B, and C).[16] Including the full extent of Earth's coal resource base as available for combustion leads to misunderstandings and inconsistencies for current studies, which interpret these geologic carbon deposits as viable climate model inputs (e.g., Tokarska et al. 2016). Accepting the implications of modern coal assessments removes approximately 4,000 GtC from the supply curve in Figure 10; an amended upper estimate for emissions from fossil fuels indicated by Rogner (1997) is then 1,000 GtC.

Figure 11 plots long-term coal supply curves reported for two leading IAMs: MESSAGE (green) and GCAM (purple) alongside the data widely used from Rogner (1997) (orange) (Pacific Northwest National Laboratory 2012; Riahi et al. 2012). These IAM supply curves inform GHG emissions scenarios by reaching values of 40,000, 90,000, and 140,000 EJ coal supply, anticipating that geologic deposits of coal classified as resources can become reserves in this century as the R-P maintains an equilibrium range.

Although extended flat supply curves are common in long-term studies of coal supply, Zimmerman (1977a, 1977b, 1975) suggests these indicate misinterpretations of coal data. In a detailed analysis of US coal supply economics, Zimmerman observes that high R-P ratios say nothing of the fuel quality, energy content, or cost of extraction and that the long-flat supply curves used in federal studies for a series of US mines miscalculated the cost of the marginal mine by a factor of several hundred percent.

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[16] Rogner (1997) defines Grade A reserves as "proved recoverable reserves," Grade B as "additional recoverable resources," Grade C as "additional identified reserves." and Grades D and E as "additional resources." These definitions assume that all assessed reserves are recoverable (i.e., no recovery factor is applied) and that identified reserves and recoverable resources will become recoverable in due time. Though Rogner (1997) is not clear on whether Grade B coal should initially count as reserves, the paper classifies them alongside Grade B oil and gas classified as reserves.

Zimmerman (1983) predicted the price and quantity trends that have been realized between 1990 and 2014 (see Figure 1). Using detailed mine-level US data, he calculated that doubling of coal production capacity would lead to price increases of 1.65 to 2.94-times the average cost of coal. Zimmerman’s detailed modeling work provides empirically observed evidence to refute the long-flat supply curves used to model global coal: he argues that coal supply cost estimation errors occur because of inaccurate extrapolations of seam geology, poor understandings of mining technique potentials, and the misinterpretations of the coal assessment process.

We suggest that long-term energy scenarios take these factors into account by reassessing their use of coal reserves. Researchers should not assume that coal resources will become reserves with sufficient technical change and market price increases, as with oil and gas resources. Rather, coal supply curves anticipating long-term developments should stop within a moving average range of modern reserve figures—the BGR (2015) line of Figure 11. Though future coal supply faces many uncertainties, the relevant uncertainty for long-term scenarios is *how many reserves will be recoverable* rather than *how many resources will become reserves*. This is a question answerable by analysis of reserve recovery rates per region, and it avoids the assumption that all reserves are recoverable. Further, the R-P ratio can actively inform projections, rather than providing a passive equilibrium that predisposes “vast” potential coal reserves and their eventual production from the outset.

Figure 12 provides a prototype scenario to illustrate these concepts. It adopts two features of the Section 3 projections: (1) coal production continues expanding in the medium run, and (2) coal reserves are discovered and assessed at a rate that maintains the current reserve level (BGR 2015). Subsequently, with ongoing expansion in production, the R-P ratio continues to fall. The R-P trend in coal supply provides confidence for multidecade investments in capital equipment for mining, transportation, and combustion. Thus, even as more reserves are added, it is reasonable to expect that investment in coal infrastructure would begin to decline once the R-P outlook signals uncertainty in lifetime utilization for new capital investments.

The stylized TPES of Figure 12 adapts the RCP 8.5 marker case of Riahi et al. (2011) to illustrate how modern coal assessments can inform projections of future energy supply. In this scenario, coal production expands in line with growth rates from the original RCP 8.5 marker. With accelerating coal production through 2040, eventually the coal R-P reaches 50. At this point, investment in future coal consumption becomes risky, leading demand to seek other sources of supply. This will lead to declining investment in coal discovery and production and a negative feedback system in coal demand and supply. All modern coal reserves are used by year 2100 to maintain consistency with the convention of GHG emissions scenario baselines.

Because the original RCP 8.5 marker anticipates around 40,000 EJ from coal, this modern coal baseline prototype scenario results in a residual demand for 27,000 EJ, depicted in Figure 12 in gray. Though a portfolio of energy supply strategies could substitute for coal, direct substitution of primary energy (EJ-for-EJ) with gas, renewables, and efficiency measures are considered on the right column of the figure.[17] If gas is substituted for the coal shortfall, the original RCP 8.5 total of cumulative emissions would decline 15 percent. In terms of final energy use, gas is far more efficient, so this value is a considerable overestimate of the GHG emissions that would result from substituting gas for coal. Substitution with renewables would lead to a 30 percent reduction. If energy efficiency measures are used to address the 27,000 EJ shortfall, total CO_2 emissions would mimic the RCP 6.0 pathway. Note that none of these alternatives are climate policies; rather, they are energy policies that posit a baseline where recoverable coal reserves are not unlimited. Note also that if we accept lower R-P values for coal, the overall price of energy rises and assumptions about TPES have to be revised downward in baseline scenarios. Integrated modeling should be used to fully explore the energy system implications of modern coal baselines.[18]

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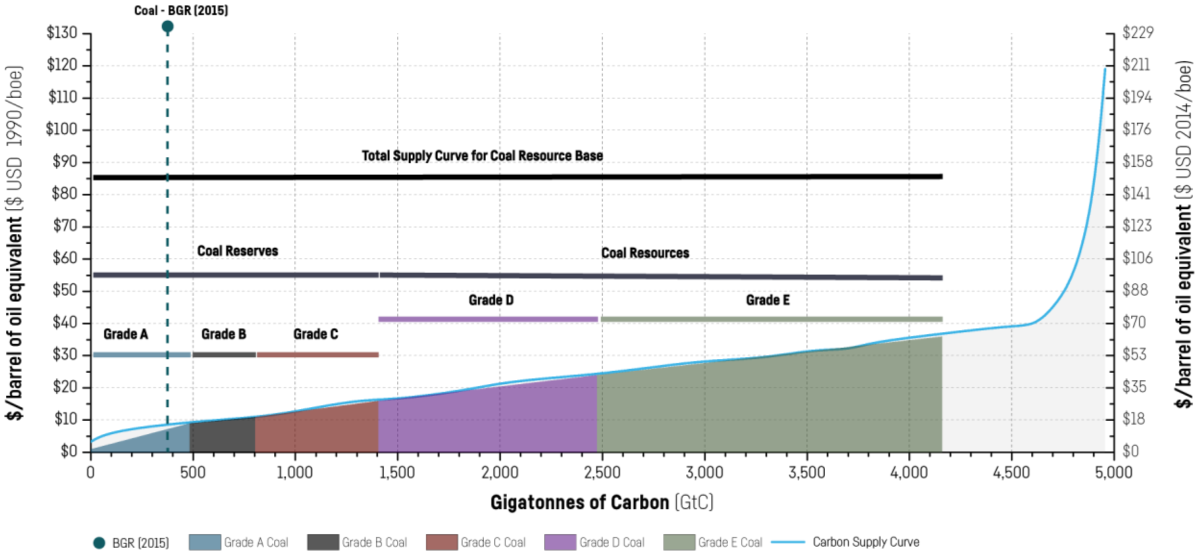
[17] The value for life-cycle emissions from renewables in this case draws from the median figure for utility-scale solar of 50g/kWh (Schlömer et al. 2014). This is also a high upper estimate for energy substitute because utility-scale solar is the most carbon-intensive value for renewables used in the IPCC’s Fifth Assessment Report.

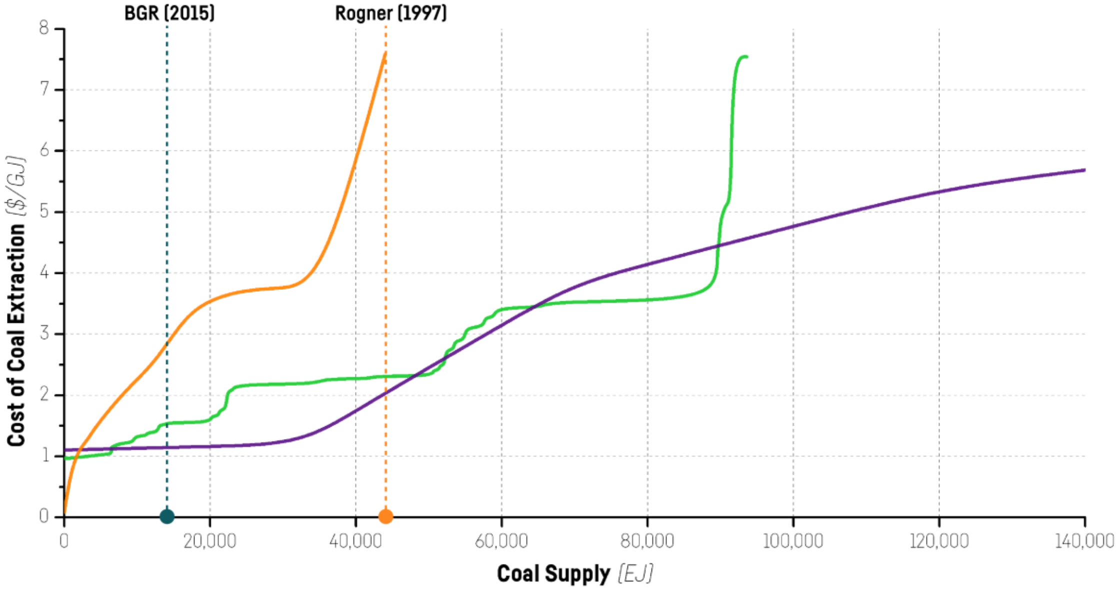
[18] This prototype scenario is a very static illustration of an amended coal baseline and is not intended to substitute for the results consistent with a full model scenario run.

Figure 10. Aggregate Carbon Supply Curve for Earth’s Fossil Occurrences Mapped to Coal



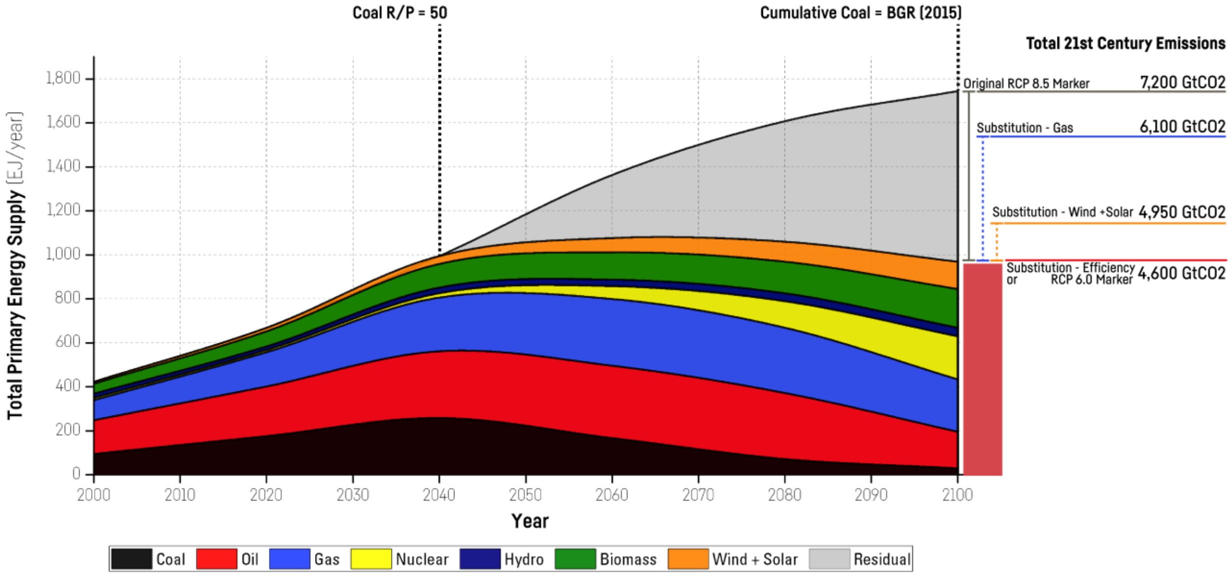
Notes: Reserves (Grades A, B, and C) are shown in blue, black, and red, respectively, and resources (Grades D and E) in purple and green. The assessment for BGR (2015) coal is the blue dotted line. Sources: Rogner (1997), BGR (2015)

Figure 11. Supply curves for coal adopted by IAMs to inform GHG emissions scenarios



Notes: The Rogner (1997) scenario is shown in orange, MESSAGE (RCP 8.5) in green, and Riahi et al. (2012) and GCAM (RCP 4.5) in purple (Pacific Northwest National Laboratory 2012). The modern assessment of coal reserves BGR (2015) (blue) is overlaid with the legacy assessment from Rogner (1997) (gold).

Figure 12. Prototype Long-Run Energy Supply Outlook based on Modern Coal Assessments



Notes: The RCP 8.5 marker scenario of Riahi et al. (2011) is amended to provide a stylized representation of an energy future with boundary conditions of BGR (2015). This case maintains the original RCP 8.5 marker TPES, but projections of coal production are adapted after 2040 to account for an R-P of 50, which erodes confidence in the viability of future capital investment for coal supply and demand. Coal production begins to decline after this point and cumulative supply illustrates combustion of all reserves to maintain consistency with other GHG emissions scenarios. A reduced contribution from coal leaves a 27,000 EJ residual in the RCP 8.5 TPES. On the right column, total 21st-century emissions from energy for various substitution cases for the residual are considered: the original RCP 8.5 marker projects 7,200 $GtCO_2$ (gray), direct substitution with gas leads to 6,100 $GtCO_2$ (blue), renewables to 4,950 $GtCO_2$ (orange), and efficiency to 4,600 $GtCO_2$ (red). The efficiency case is equivalent to the amount of 2000–2100 cumulative emissions illustrated by the RCP 6.0 mitigation case.

5. Summary and Recommendations for Future Energy Scenarios

All recoverable coal are reserves, but not all coal reserves and resources may be recoverable. Long-term energy studies face the challenge of determining how new resources may be discovered, what fraction are likely to become reserves, and the rate at which these are recoverable. The answers to these questions extend beyond geology to include economic factors determined by technology and demand. Though multidecadal patterns for coal do not wholly dictate the fuel source’s future, they provide a basis for distinguishing between plausible, possible, and doubtful future energy scenarios.

Assessing feasible rates of coal production over the long run must grapple with inadequate information on supply. To overcome this, scenarios of future energy supply have adopted the convention of projecting R-P equilibrium conditions to estimate the possibilities for expanded coal supply.

Modern trends in coal production, consumption, markets, and technology have pushed global coal R-P to ever-lower values, so the conditions predicted by the equilibrium framework have not been observed. Thus, future scenarios using legacy estimates of coal reserve potentials and conversion rates lack a conceptual basis. The baseline coal trends since 1990 (Section 2) suggest that the heuristic of an equilibrium R-P value for coal has no validity for modeling future supply over periods of vastly accelerating production—the context of all recent baselines (Section 3).

By relying on vintage assessments and assuming that marginal resources will readily become reserves with sufficient technical change and market price increases, these studies have considered total coal *resources* as a reasonable upper bound. Based on our analysis of historical reports and reserve definitions, we argue that only assessed coal *reserves* should be used in long-term energy studies. Application of per region recovery factors can further refine and provide confidence in this boundary. Geologic coal resources are vast, but they do not constitute a viable fuel source.

We suggest that considering all geologic coal resources as eventual reserves is equivalent to assuming that all oceans should be on a supply curve for drinkable water: the total quantity of ocean water is vast and existing technology could theoretically convert all saltwater to replace fresh water. However, rigorous analysis of desalination technology and resource potential is necessary to determine how much of the oceans could reasonably supply future global water demand. Simply placing all oceans on a water supply curve significantly reduces the resolution of data relevant to decisionmaking and distorts any subsequent analytical framing for studies on water.

Models of energy futures have considered that a falling R-P ratio for coal would eventually induce an incentive for significant discovery and improvements in technology. Given the capital lifetimes of coal production and consumption equipment, 50 to 60 years seems a possible equilibrium R-P inflection point, but ensuing developments in coal infrastructure at that juncture are purely theoretical. However, we emphasize that the R-P figures are indicative of many complex factors, including the coal assessment process, the technical aspects of production, and the end use for coal.

It is insufficient to use an R-P index passively to argue that coal is vast (or scarce). The conventional interpretation that a large R-P for coal indicates a virtually unlimited backstop supply has misinformed a generation of long-term energy scenarios. The greatest misconception is that reserves for coal are equivalent to reserves for oil and gas. Reserve and production trends of oil and gas are not an appropriate analogue for coal resources.

As demonstrated in Section 3, modelers of projected energy futures have applied pathways of vastly expanded coal production in long-run outlooks. The assumptions now significantly deviate from actual trends in coal prices (underprojected) and recoverable reserves (overestimated). Persisting with upwardly biased projected levels of coal combustion requires corroborative evidence for dramatic upward revisions in reserve estimates and recovery factors.

An order-of-magnitude increase in future recovery factors and production output requires technological breakthroughs in coal recovery that greatly outpace supply and demand technologies for other energy supply strategies. Underground coal gasification technology is the most likely technology capable of doing this. However, realizing such ambitious outlooks for UCG requires a reversal of more than a century of experience showing poor net calorific conversion of coal to gas, severe environmental harms, and curtailed production due to uncontrollable subsidence. Furthermore, UCG’s broad adoption will need to outpace improvements in the economics and availability of competing renewable, nuclear, and unconventional fossil sources.

Modern coal reserve assessments and feasible rates of coal production and consumption can recalibrate baseline scenarios of future global energy supply. Further research has the potential to update future baselines with integrated modeling efforts to determine whether coal can realistically compensate for oil and gas depletion while remaining less expensive than conservation and renewable energy options.

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