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The 1000 GtC coal question: Are cases of vastly expanded future coal combustion still plausible?

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A B S T R A C T

Decades ago, prospects seemed strong for significantly expanded global coal consumption. Studies of energy futures depicted the full geologic extent of coal as a virtually unlimited backstop energy supply, drawing justification from legacy ratios of reserves-to-production (R-P) on the order of several centuries. Annual consumption and market prices for hard coal have doubled since 1990, providing an opportunity to recalibrate the next century's reference case with an empirically constrained outlook for this important industrial fuel source.

Over the last two decades, improving knowledge of world coal deposits refined estimates of their recoverable portion, reducing assessed reserves by two-thirds. Coal supply costs during this period increased much faster than anticipated by models which mapped total geologic occurrences with long and flat supply curves. Consequently, underlying assumptions no longer hold for many multi-decade global energy reference cases depicting a rapid expansion of coal production – the conceptual framework for these scenarios needs revision. Energy system outlooks underlying pathways of future greenhouse gas (GHG) emissions provide a case study, since the climate change research community commonly uses business-as-usual scenarios with a strong carbon signal from coal combustion many times higher than current reserve estimates.

In this paper, we explain why vast expansion in 21st-century coal consumption should not be used to describe any plausible reference case of the global energy future. Illustrating coal as a practically unlimited backstop supply is inconsistent with the current state of coal markets, technology, and reserve estimates. Future coal production faces many uncertainties, but the key uncertainty for long-term scenarios is the recoverable portion of reserves, not how many total geologic resources will eventually become reserves.

1. Revisiting the conceptual basis for a coal backstop in long-term energy scenarios

Studies of global energy futures commonly derive scenarios by assuming continued growth in demand for primary energy. Long-run compounding in these projections leads to outlooks for a significant increase in fossil energy supply from today's levels. When demand for transportation and industrial fuels exceeds available output from oil and gas, reference cases 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; Clarke et al., 2014).

Through much of the 20th-century high ratios of reserves-to-production (R-P) for coal provided a conceptual basis for the theoretical conditions underlying such long-term energy scenarios: if existing coal reserves were depleted, producers could presumably have sufficient incentive to readily explore for more coal, reclassifying marginal geologic resources as recoverable 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 2000 gigatons (Gt) - an R-P of more than 900 years (Flawn, 1966). This contributed to a common perception that the total occurrences of coal in our planet's crust could provide the ultimate assurance of energy security, supporting ambitious growth in primary energy demand, or fully compensating for depletion of oil and gas.

However, efforts to determine the potentially recoverable portion of world coal resources have been fragmented, compromising time-series analyses with notoriously inconsistent and poor data (Gordon, 1987; Smil, 2003). Unreliable information has meant any determination of the plausible extent for future coal use amounted to a choice between Scylla, Charybdis, and the full scope of Hades.

We characterize these options as three distinct modeling approaches: Method A, projecting a trend from any selected baseline

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window by assuming continued momentum in consumption growth, as common in medium-term outlooks[1]; Method B, adopting reserve figures known to be inconsistent and incomplete; or Method C, expecting that coal follows the dynamics of oil and gas, and thus marginal geologic occurrences are reclassified as reserves, maintaining 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 attempt to infer likely growth rates for future consumption. However, estimates that extrapolate compounding demand can become abstracted from feasible trends in coal technology, production, and economics. Studies spanning longer timeframes tend to express the ultimate potential for realizable supply by integrating Methods B and C. Future energy scenarios derived from this approach interpret global coal reserve estimates as a conservative lower bound, since it is often considered that the vast resource base could be tapped into, replacing depletion over time while maintaining a constant range of R-P ratios.

Energy Modeling Forum (EMF) studies (Table 1) illustrate how this method is used to understand total geologic occurrences of coal in comparison to ultimately recoverable resource figures of oil and gas. While oil and gas resources are characterized by total resource-to-production ratios that describe centuries, coal is portrayed on the order of several millennia. McCollum et al. (2014) draw on these numbers to explain that although baseline runs of many 21st-century scenarios depict cumulative coal production which greatly exceeds today's reserve estimates, such outlooks should be considered plausible because they are well within use of the total geologic resource base.

The conceptual basis for this interpretation of total coal resource assessments applies an equilibrium R-P value of several centuries to the totality of geologic occurrences, depicting a vast potential for production growth. Yet, over the past three decades, the global R-P ratio did not maintain equilibrium and 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 instead produced the opposite outcome assumed by long-term energy scenarios, despite sustained all-time-high coal prices (measured in constant dollars).

This paper examines whether the use of total coal resource base figures have any analytical meaning for energy system reference cases, through seeking to understand the information conveyed by coal assessments, and the distinct context of terms such as ‘resources’, ‘reserves’ and ‘recoverable’ for descriptions of coal. In doing so, this process attempts to harmonize definitions suitable for recoverable coal with those of oil and gas for long-term studies of resource use which span the course of a century or more.

1.1. What factors determine the recoverable portion of coal resources?

Since assessed coal reserves have continued to dwindle despite theoretically favorable market conditions, continued projections for vastly expanded global coal production will need to revisit the heuristic of a vast coal backstop enabled by a dynamic R-P ratio maintained in equilibrium. Examining the relevance of implied market and technology trends can aid in this analysis.

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

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

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

- *the 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*: the portion of in-place coal extracted during mining, usually 50% for underground and 80% 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 on world coal has improved, the economically recoverable portion of initially assessed deposits has been more accurately identified - always a much smaller quantity than the initial in situ amount recorded as reserves. Reserves are only a fraction of the total potential amount of geologic coal occurrences classified as resources. Through this article, we distinguish *recoverable coal* from the broader terms of ‘reserves’ and ‘resources’ once a recovery and other economically and socially relevant factors are applied. This definition allows for a contrast between coal in-place and the coal available as a potential source of fuel for economic use.

With appropriate caveats about possible changes in demand, technology, economics, and uncertainties due to information quality, observation of the changes in global reserve assessments can indicate the broader dynamics that empirically constrain the plausible quantities of recoverable coal in multi-decade scenarios.

To inform 21st-century coal reference cases, we use the main sources compiling global coal assessments to trace and understand the history of a dynamic reserve base over the past three decades: the World Energy Council (WEC) and the German Federal Institute for Geosciences and Natural Resources (BGR). The most prominent trends over this period are rising production (especially in China) and higher prices. Both have doubled between 1990 and the early 21st-century. Despite these conditions, reported global coal reserves have continued to decline.

Since coal assessments tend to report physical quantities in mass-based measures, long-term scenarios of primary energy use have relied on secondary sources that convert these metrics to inform projections. Rogner (1997) and Rogner et al. (2012) provide estimates of the primary energy available in hard coal reserves. These studies also indicate significant declines since 1990 – from as much as 47,000 EJ to around 18,000 EJ.

Using the methodology of these studies to harmonize their estimates of primary energy content with the mass-based units from more recent reports indicates a value on the order of 15,000 to 17,000 EJ is a reasonable upper bound for ultimately recoverable coal in today's long-run scenarios. The figure we obtain of 15,300 EJ is consistent with the range provided by recent studies (e.g. Mohr et al., 2015). This smaller value stands in contrast to the 440,000 EJ of primary energy theoretically available in the total geologic coal resources distributed throughout the Earth's crust (BGR, 2014, 2015).

However, pinpointing the precise quantity of primary energy reflected by hard coal reserve assessments is of subsidiary importance to understanding why these estimates have continued to decline. Long-run studies must capture the limitations of today's knowledge

Table 1
Global fossil energy resource base for two EMF studies (EMF, 1995; McCollum et al., 2014).

Total resource[b]	EMF 14 (1995)[a]		EMF 27 (2014)[b]	
	Quantity *Exajoules (EJ)*	Resource-to-production *1995 production rate*	Quantity *Exajoules (EJ)*	Resource-to-production *2014 production rate*
Oil (conventional)	14,200	100	13,800	80
Gas (conventional)	16,340	200	16,000	120
Coal	300,000	3190	456,100	2840

[a] EMF 14 (1995) figures for crude oil and natural gas include reserves alongside undiscovered resources, while the quantity reported for coal is listed as "ultimately recoverable resources"; the EMF 27 study provides clearer distinction between the conventional and unconventional quantities of oil and gas.
[b] Includes reserves and resources.

by considering the potential for dynamic boundaries in definitions of reserves and resources. This requires identifying the general influence of aggregate technological progress and increasing information on our collective understanding of hydrocarbon energy deposits.

1.2. Why are modern assessments of coal reserves much smaller than vintage reports?

This paper (Section 2.1) provides evidence that technical progress along three frontiers explain the difference between smaller modern and larger legacy assessments, and the direction of the dynamic boundary that separates assessed coal reserves and total resources:

- 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 developed larger machines that improve productivity but cannot be used for all deposits, constraining the characteristics of coal that can be economically mined.

Knowing the exact amount of coal recoverable during the 21st-century requires perfect foresight of future resource discovery, production technology, socioeconomics, and regulation. Standard practice has been to use the equilibrium R-P heuristic to determine a range of plausible outcomes for technological change in future coal supply. Application of vintage R-P ratios above 300 led to projections that assumed the possibility of unlimited future production growth. Will projections that rely on the modern R-P ratios, which are as much as an order of magnitude smaller, eventually be perceived as overly conservative?

Section 2.1 argues that the ongoing accumulation of knowledge about the Earth's geology, and the coal within it, has continually highlighted how the confusion of "resources" with "reserves" has led to misguided interpretations of assessments in many major producing regions such as the United States and China (Grubert, 2012; Wang et al., 2013). Thus, standard definitions of reserves for oil, gas, and uranium do not directly map to coal. Interpreting the assessment process for each of these energy resources as equivalent results in a fundamentally flawed understanding of the future potential energy ultimately realizable from geologic coal occurrences.

For other energy and mineral resources, regulatory and market requirements establish an assessed reserve base that indicates a dynamic working inventory of economically and technically accessible commodities. Reported reserves of coal have a different meaning: they specify a vaguely identified amount of mineral-in-place, and thus all coal reserves are not recoverable.

Since each coal seam is relatively homogeneous and many are close to the surface, estimates for broad areas can be readily developed to determine the upper boundary for a physically present amount in any region (Zimmerman, 1983). Consequently, information on the general location of coal is very good (Gordon, 1987). Further recoverability studies and development expenditures determine the recoverable portion of coal reserves, creating a critical discontinuity between reserve definitions for coal and other hydrocarbon energy resources (Grubert, 2012; Zimmerman, 1975).

Today, coal is the fuel used for more than 40% of the world's electricity generation, and stands at a 29% share of global primary energy supply (IEA, 2016). Coal is also a critical input to steelmaking and industrial processes. The coal that generates electric power is steam or thermal coal, while metallurgical or coking coal is used by industrial operations, and typically of higher quality. Coal is classified by a rank that measures its stage of geologic progression from lignite to anthracite. High ranked coals of anthracite and bituminous have a higher energy density and greater carbon content than lower ranks of sub-bituminous and lignite. This paper applies the BGR (2015) definition of hard coal: sub-bituminous, bituminous and anthracite with energy content greater than or equal 16,500 kJ/kg.

To understand how the full extent of geologic coal resources could be recovered to a high degree, as in the many modern energy system reference cases depicting combustion of far more than today's reserves, this work argues such scenarios will require significant deviation from baseline technology and market trends. For example, the primary technology needed for a return to pre-1990 reserve levels is commercialization of underground coal gasification (UCG) that would extract gasified coal from in-situ deposits (Section 2.2). Gasified coal, if available, is particularly suitable for meeting demand beyond steam and metallurgical applications, and in end-uses such as liquid transportation fuels. Corresponding outlooks for greatly expanded future coal production must also establish a case for new market segments to justify such high levels of demand.

Expansion of UCG and coal-to-liquids (CTL) by several orders of magnitude would not occur in a vacuum: these technologies face a steep uphill battle to comply with environmental regulations far more stringent than when they were first demonstrated, and competition from advances in renewables, unconventional oil and gas and more efficient end-use technologies. Energy futures depicted by the case study in this paper (Section 3) implicitly or explicitly anticipate significant progress in UCG and CTL because of their high coal production, demand and recovery rates.[2] Since our paper focuses on the recovery of energy from coal deposits, we concentrate on UCG, arguing that reference cases should not apply high rates of geologic coal recovery that imply its widespread deployment.[3]

[2] Though long-term energy scenarios may not explicitly apply UCG technology, it is the only plausible means to achieve the high recovery rates required to realize scenarios which tap into the vast coal resources base by using far more than today's reserves. Common recovery factors are 80% for strip mining and 50% for underground reserves. However, Zimmerman (1983) studies the US coal industry and suggests that 50% is a reasonable estimate for reserves recoverable from any deposit. Reserve recovery in some regions such as India can be as low as 20% (Bauer et al., 2016).

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

To examine the modern context for coal in scenarios of the global energy future, this paper is organized as follows: Section 2 addresses the trends in coal supply since 1990 suitable for inclusion in 21st-century reference cases, explaining why modern assessments indicate fewer reserves than vintage reports. Section 3 provides a case study to illustrate how legacy assessments have influenced widely used future energy scenarios in the climate change research community. Section 4 analyzes the coal supply curves commonly applied in the energy modeling literature and proposes an empirically constrained concept of dynamic coal reserves. Section 5 concludes with a summary and recommendations for integrating future coal use in multi-decade energy system reference cases.

2. Reference case trends in coal reserves, production, and prices, 1990–2016

Calibration of a relevant 21st-century coal reference case must focus on *hard coal* reserves, which contain approximately 90% of the energy in the world's coal resource base (Rogner et al., 2012; Rogner, 1997). A future coal backstop would rely heavily on global trade in hard coal, or its transformed products, since the economics of lignite encourage consumption close to the site of extraction in regional electricity generation because of the fuel's low energy density and high water content (BGR, 2015).

Trends in hard coal reserves, production, and markets since the late 1980s are depicted in Figs. 1a, 1b, 1c, 1d. Reserve and production data in this figure draw from regular reports by the WEC and German Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe, BGR) (WEC 1989, 1992, 1995, 2001, 2004, 2007, 2013, 2016; BGR 2009; BGR, 2014, 2015). The International Energy Agency (IEA) annually relays select years of figures from both sources, along with regular updates on production (IEA 2001-2016).

Fig. 1a plots the range of reported constant US dollar (USD) prices from 1989 to 2016 across 10 major coal market indices (BP, 2016; EIA, 2012, 2017; World Bank, 2017) shaded as a gray band.[4] Average benchmark coal prices (red) more than doubled between the early 1990s and the first decade of the 21st-century. These rising average prices were concurrent with a doubling of global hard coal production through 2014 (Fig. 1b).

Given the heterogeneous domestic conditions for coal markets among regions, the impact of exchange rates is important to note, otherwise interpretations of price are overly conditioned by the United States perspective. Though USD denominated coal markets have declined from 2012 to 2016, local exchange rates in major exporting nations such as Russia, Colombia, South Africa and Australia held domestic prices steady over this four-year period (IEA, 2016). Since many of the production costs in these countries are paid in rubles, pesos, rand and Australian dollars, average national coal market prices through 2016 remained flat or higher than 2012. This context of devaluation allows domestic producers to cover costs, holding their output steady, creating uncompetitive bear market conditions for the relatively expensive US coal industry.

All else equal, conventional resource economists theorize that higher sustained commodity prices lead to a reclassification of marginal geologic deposits as economically recoverable reserves. Yet, since the doubling of coal prices and production in 2000, reserves declined by roughly 15% (Fig. 1c). Reported reserves show a modest increase around 2000: as a decade-long expansion of coal production began, new mines were opened and initial supply contracts were signed, temporarily increasing reported reserves. Once the rate of mining continued to increase, however, total reported reserves declined despite rising market prices.

Because long-run global coal reserve and price trends have not moved as expected from simple equilibrium supply–demand assumptions, the conceptual foundation of multi-decade coal resource economics are ripe for revision.

Rogner (1997) and Rogner et al. (2012) convert mass-based assessments to energy units and provide 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 marks a rapid decrease in the global coal R-P ratio from more than 300 to 100 years (Fig. 1d).

Because of uncertainties in the energy content of recoverable coal, we provide normalized values to understand this decline.[5] WEC reports that the large number of assessed reserves from the late 1980s in Fig. 1d results from an accidental reclassification of China's reserves as “proved recoverable” from a previous definition as “proved amount in-place.”

Declining reserves over time indicate that a stable R-P ratio for coal is unobserved, and does not provide a workable assumption to support long-run energy scenarios which tap into the larger assessed coal resource base. In the following section, we review key literature to understand the factors underlying this ongoing decline in assessed hard coal reserves, and why they indicate the larger vintage figures will not be readopted without significant deviation from reference case trends of technological change.

2.1. Interpreting the information dynamics of global coal reserves: accumulating knowledge revises boundary conditions

Cumulative production reported by IEA since 2001 accounts for up to 80% of the ceteris paribus difference between hard coal reserve estimates at the start of the 21st century and recent BGR assessments. Thus, at least 20% of the net decline in reported global reserves over this period has resulted from factors other than depletion, such as improved knowledge of the global reserve base, standardized definitions, and technical change.[6]

Doubling of annual hard coal production since 2000 (see Fig. 1b in mass-based units) has provided an incentive for 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 it is reasonable to expect that knowledge improves as mining expands to new areas. Recoverability studies during this period

[4] 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; (b) EIA: Bituminous and Anthracite; (c) World Bank: Coal (Australia), thermal GAR, f.o.b. piers, Newcastle/Port Kembla from 2002 onward, 6300 kcal/kg (11,340 btu/lb), less than 0.8%, sulfur 13% ash; previously 6667 kcal/kg (12,000 btu/lb), less than 1.0% sulfur, 14% 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 6000 kcal/kg from 2006 onward; during 2002–2005 6200 kcal/kg (11,200 btu/lb), less than 1.0%, sulfur 16% 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, 6450 kcal/kg, (11,200 btu/lb), less than 1.0%, sulfur 16% ash from August 2005 onward; during 2002–July 2005, 11,600 btu/lb, less than 0.8% sulfur, 9% ash, 180 days forward delivery (International Coal Report; Coal Week International; Coal Week; World Bank).

[5] Throughout this paper, where physical units of global coal are converted to energy units, we use the Rogner (1997) methodology of applying average energy content per regional reserves to calculate an internally consistent value for harmonized comparison of assessment vintages. This method results in an estimate of 15,300 EJ of primary energy in BGR (2015) reported hard coal reserves. This is slightly lower than the value reported for hard coal reserves by BGR (2015) of 17,390 EJ. Note: The Rogner (1997) and Rogner et al. (2012) values in Fig. 1c and d are converted to a mass-basis for comparison with IEA, WEC and BGR.

[6] This ceteris paribus decline has occurred despite additions to the assessed reserve base in many regions. The detailed analysis of regional year-to-year reserve base declines or additions is beyond the scope of this study. However, since reserve additions have occurred in many nations, it is safe to assume that 20% is a lower-bound estimate of non-depletion related decline in 21st-century coal reserves. The term “technical change” applied here intends to capture shifts in the global macro-production function of labor and capital in the broadest sense, beyond specific mining technology.

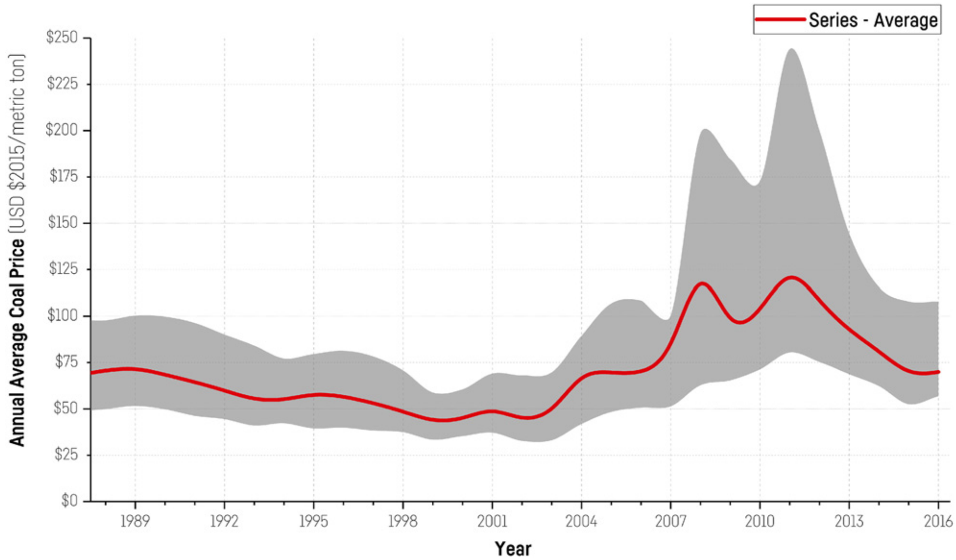

Fig. 1a. Trends in global coal market benchmark prices (BP, 2016; EIA, 2012, 2017; World Bank, 2017), minimum and maximum values indicated by gray range, while red line follows the average of benchmark prices.

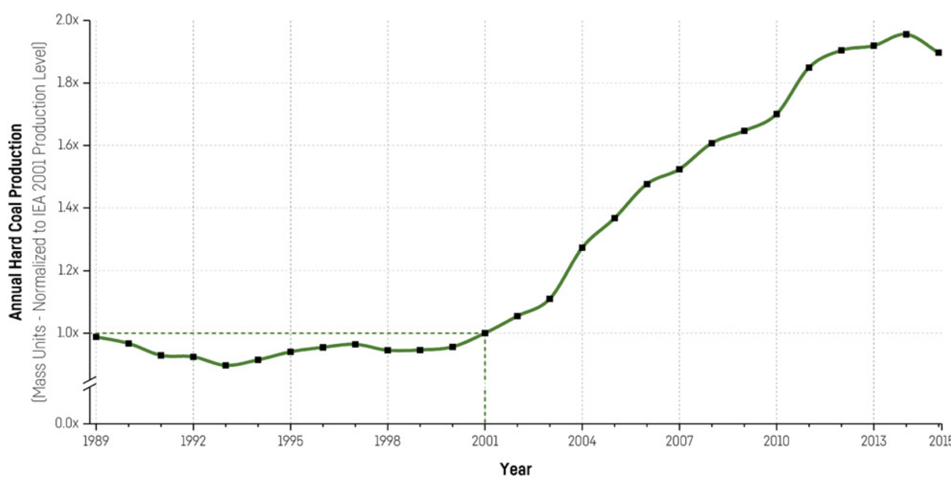

Fig. 1b. Annual hard coal production as reported by IEA Coal Information Reports, WEC and BGR (indexed to IEA reported values for 2001 in mass units); note y-axis break.

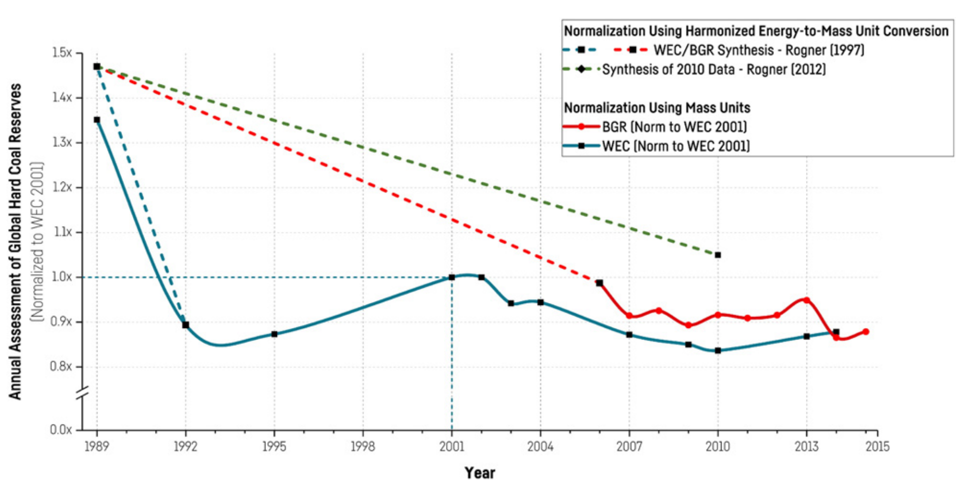

Fig. 1c. Coal reserves in mass units from successive WEC and BGR reports indexed to WEC (2001). The WEC-BGR synthesis reported by Rogner (1997), and the updated Rogner et al. (2012) normalized to WEC (2001) using harmonized energy-to-mass units; note y-axis break.

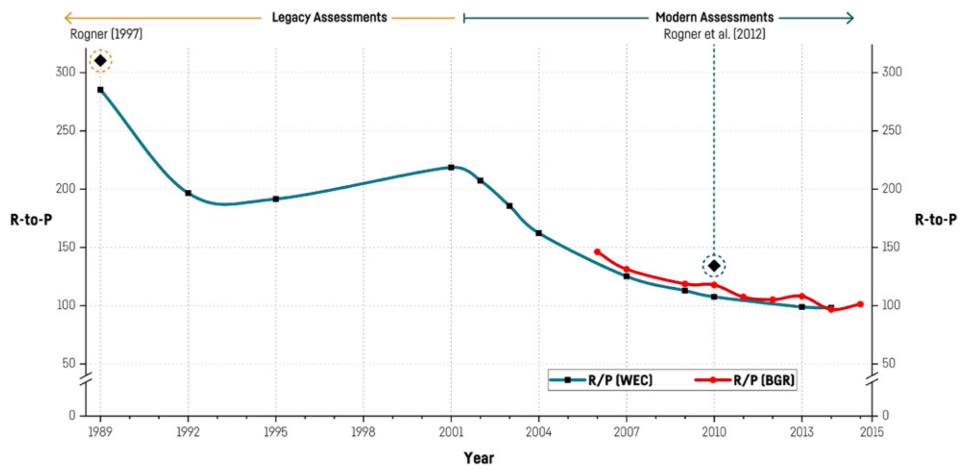

Fig. 1d. Reserve-to-production ratio for global coal [mass-basis] – Rogner (1997) and Rogner et al. (2012) illustrate the distinction between legacy and modern assessments; note y-axis break.

have verified the geologic conditions needed to mine 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 that include environmental protection. In general, knowledge of energy resource potentials is not scale invariant, because increased production provides an incentive to improve information quality.

Grubert (2012) observes that the recoverable portion of listed reserves is commonly overestimated because of the failure to distinguish between physically available coal and the amount profitably and legally producible 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's study of reserve definitions 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 all hydrocarbon 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 which depend on transportation from specific mines. Thus, she suggests coal markets are more tolerant of inaccurate data because contracts secure supply from specific mines over many decades. This dynamic would lead to more accurate reserve estimates as production increases, and more contracts are signed. 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.

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 identified 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% would be economically recoverable.

The USGS study demonstrates how an initially high R-P ratio reflects 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 reported oil and gas reserves 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)[7]; (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).

Where 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). These exploration expenditures are one step removed from development efforts that would confirm the viability of coal extraction from specific deposits. Thus, recoverable coal is always less than the total indicated by reserves.

Standardization of definitions in major coal-producing regions has also contributed to improved information about global coal reserves and their subsequent reclassification. Recently, assessments of coal reserves in China, South Africa, and the former Soviet Union have been re-examined to determine whether any economic factors were considered beyond the basic geological presence of a deposit (CIM, 2014; Hartnady, 2010; JORC, 2012; Wang et al., 2013). This process has revisited reserve definitions applied by centrally planned economies in the Soviet Union and China under quantity-based production targets (Wang et al., 2013). As the USGS NCRA explains, digital database technology has also created an opportunity to reduce the rate of double-counting identified by older-studies (Noyes, 1978).

Advances in modern mining technology have also refined knowledge of the economically recoverable portion of global coal occurrences. 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 mineable geological characteristics.

Over recent decades, coal mining has depended on ever larger equipment and production units, channeling investment toward favorable seams in simpler geologic environments (Wagner, 2003). Therefore, many previously assessed coal seams which require labor-intensive mining techniques no longer meet the criteria for reserves. Rogner et al. (2012) note that modern mining technology has

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

contributed to a 90% reduction in Germany's assessed reserves, alongside modified subsidy regimes.

2.2. Underground coal gasification: the key technology for tapping into the total coal resource base

Unanticipated developments in experimental and hypothetical coal recovery technologies may enable access to the total quantity of identified geologic occurrences. In-situ underground coal gasification (UCG) is the prime technology capable of recovering these resources. Successful development and implementation of UCG would lead to larger future assessments of coal reserves, that re-adopt the larger vintage figures.

UCG technology involves drilling injection wells into a coal seam, allowing the introduction of pressurized air/oxygen and steam. In-situ coal is then ignited as seam temperatures reach between 500 and 900 °C. These conditions convert the in-ground coal to producer gas (a mixture of CO_2, CO, CH_4 and H_2), which is removed using extraction wells drilled into the seam.

If commercialized UCG were to achieve its full theoretical potential, it would enable access to a significant number of otherwise unreachable coal deposits. It has been argued that technological breakthroughs enabling wide-scale adoption of UCG for full recovery of deep deposits could expand reserves by up to 300% by tapping into the broader geologic resource base (Stephens et al., 1985). However, more than a hundred years of experience indicates significant barriers to UCG experiments, adoption and deployment.

The promise of using UCG 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 at depths less than a few hundred meters (Bhutto et al., 2013; Grenon, 1979; Perkins, 2005). Other mining techniques are viable for seams 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 limited 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) severe environmental issues have plagued many test sites.

Experience from UCG test projects have indicated significant constraints on site selection. For example, a 1997 pilot in Spain at a depth of 600 m 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 documented public response to large-scale coal synfuel and syngas projects (Yanarella and Green, 1987), it is reasonable to expect that any social license for operation of UCG facilities will face significant opposition, even if many of its environmental challenges are successfully addressed.

UCG experiments in the Soviet Union reported less than 60% recovery of the primary energy content of in situ coal. Net energy efficiencies from these experiments were less than 40% 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).

Estimating the possible economic and technical potential for UCG requires developing detailed and robust 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, recent meta-assessments conclude that UCG still needs decades of foundational research to establish any reasonable estimate of its commercial potential (Couch, 2009). In this context UCG would need to contend with rapid progress in commercial-scale renewable energy, unconventional oil and gas and more energy efficient technologies (IEA, 2016). This is a challenging environment to justify a new wave of sustained public or private funding for research and development of UCG. Thus, any plausible future reference case for global coal recovery should not include estimates of total resources which are implicitly or explicitly consistent with theoretical potentials of UCG or other similar hypothetical technologies.

In this vein, if it is appropriate to consider the implications and recovery rates of coal consistent with UCG deployment 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 the conceptual basis of 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 (>150–1200) were interpreted as framing an “equilibrium range” in long-term energy studies.

Around the coal 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). In this sense, the moving R-P boundary between reserves and resources intends to capture the dynamic influence of technology and information over the long-run. 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 analyzed.

Although the R-P ratio for hard coal has fallen by an order of magnitude over the past quarter-century to unprecedented levels (see Fig. 1d), the response of markets and industry to a low R-P ratio for coal is unknown.[8] Therefore, the heuristic of an equilibrium R-P for coal is not verified and provides untested support for conceptualizing coal reserves as a continual flow that endlessly draws from the total stock of geologic occurrences.

Maintaining an 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

[8] A recent decline in hard coal production has recently led the global coal R-P value to increase above 100 (BGR, 2015). If production declines maintain this trend for several decades, it is very possible that the global coal R-P ratio could re-adopt older larger figures of several centuries. However, this possibility is not considered in the reference case energy scenarios of Section 3.

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 about the meaning of reserve assessments and the prospects of technology needed to access total resources leads us to reject these assumptions as a basis to model future coal supply. The reserve-to-resource boundary for coal is certainly dynamic, and it has reflected technological progress that has more clearly identified *the smaller recoverable portion of coal deposits formerly classified as reserves*.

The relevant question for modeling long-term coal use is whether reserve figures maintain a level that inspires confidence for *new investments* throughout the time horizon of the study, and whether this empirically constrained supply of economically recoverable coal is sufficient to substitute for a significant portion of oil and gas demand as a backstop. We suggest this is a plausible R-P value consistent with the lifetimes of several vintages of capital equipment for coal mining and combustion: a horizon around 50 years - more in-line with R-P values from oil and gas of 30–50 years.

Today's lower R-P values indicate a ceiling on plausible growth rates in coal production. For example, Thielemann et al. (2007) consider that realizing 1% annual growth in global coal production is consistent over the long run with reserves reported in the early 21st-century.

Gordon (1987) argues that long-run economic comparisons of 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 investment in more careful analysis, and these have shown that hard coal reserves are lower than earlier estimates.

Further, Gordon (1987) suggests that any 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 appears a better bet than oil and gas in the long run. However, he argues this is a mirage because reported estimates of coal primarily indicate a geologic occurrence of coal deposits, which are not synonymous with “economically recoverable coal”.

Misinterpretations of the information provided by the coal assessment process have created the illusion of a vast backstop supply which is economically substitutable for other hydrocarbon energy resources, and capable of meeting virtually any level of expanded demand. This faulty conceptualization of a dynamic coal reserve boundary that endlessly draws from the total resource base has misguided generations of widely used energy system reference cases.

3. Case study: coal resources in climate change scenarios

In climate change studies, reference case scenarios of the global energy system intend to represent a range of plausible futures absent specific actions to reduce GHG emissions (Clarke et al., 2014). 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.[9] These scenarios have applied the dynamic reserve concept for coal, so that combustion of all reserves are considered a reasonable lower boundary on future coal use.

Scenarios of future GHG emissions are generally constructed with energy system reference cases of compounding growth in demand for primary energy resources, more limited oil and gas, and a coal backstop supply. Under such assumptions, production of oil and gas will not be high enough to meet future demand, leading coal to provide ever-larger shares of total primary energy supply. Accordingly, as illustrated in this section, reference scenarios for GHG emissions have depicted high levels of future coal use. The concepts addressed in Section 2 provided justification for early unrefined climate models to use a strong carbon signal which could only result from combusting a significant portion of total geologic coal occurrences during the 21st-century.

Intergovernmental Panel on Climate Change (IPCC) assessment reports and the broader climate change research community have developed four generations of future climate change scenarios since 1990. These four sets of scenarios created a consistent foundation for model runs and communication of results throughout the climate change research community. Each of the IPCC's five assessment reports use business-as-usual (BAU) scenarios that combust most or all coal reserves before the year 2100. In the climate model runs of the IPCC First and Fifth assessment reports, these high-coal emission cases are the only explicit illustrations of a BAU world without climate policy.

Because these reference case scenarios draw from a literal interpretation of vintage coal assessments, they have depicted combustion of all legacy reserves, leading to a consistently high GHG emission baseline. Thus, for the past quarter-century, high emission baselines have been the focus of research, explicitly or implicitly shaping national policy benchmarks, such as estimates for the social cost of carbon (National Academies of Sciences, Engineering, and Medicine, 2016).[10]

This section briefly details projections of future coal use in each generation of IPCC baseline emission scenarios. The First Assessment Report (FAR) used the SA90 BAU scenario; the Second Assessment Report (SAR) drew from the IS92 scenario family, the Third (TAR) and Fourth Assessments (AR4) built from the Special Report on Emission Scenarios (SRES), and the Fifth Assessment Report (AR5) employed four benchmark representative concentration pathways (RCPs) and 1184 Working Group III (WGIII) scenarios.[11]

3.1. Coal in GHG scenario baselines, 1990–2011

Global energy system reference cases in IPCC assessment reports have focused on pathways of fossil fuel use that lead to cumulative carbon emissions exceeding 1000 gigatons carbon (GtC) from 2000 to 2100. Fig. 2 summarizes 21st-century coal combustion in these cases from 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

[9] In IPCC assessments, the term *reference case* is often used interchangeably with *baseline* which is explicitly defined by the IPCC Data Distribution Centre as “The baseline (or reference) is any datum against which change is measured.”

[10] DICE, FUND and PAGE inform social cost of carbon estimates in the 2016 National Academies study cited. These IAMs adopt similar reference case assumptions for coal in relation to total hydrocarbon resources. In DICE no marginal cost is assigned to fossil energy resources and 21st-century cumulative emissions from fossil fuels are more than 1800 GtC with total carbon supply of 6000 GtC (Nordhaus and Sztorc, 2013). FUND uses the EMF14 standardized scenario (Energy Modeling Forum, 1995) detailed in Table 1 which assumes 300,000 EJ of available coal (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 1300 GtC from fossil fuels from 2000 to 2100.

[11] This paper classifies the use of GHG scenarios by their use in assessments for policy and mitigation (IPCC WGIII). Generally, use of scenarios in studies of climate impacts with general circulation models (GCMs) has 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). In 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.

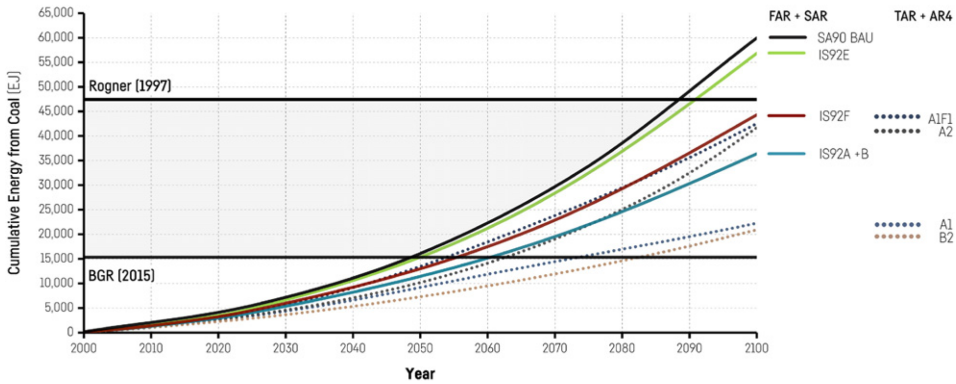

Fig. 2. Cumulative 21st-century primary energy from coal in IPCC AR high-emission scenario baseline cases (2000–2100); First (FAR) and Second AR (SAR) baselines illustrated in solid lines; Third Assessment (TAR) and Fourth Assessment (AR4) baselines depicted with dotted lines. The Rogner (1997) and BGR (2015) values for available energy in hard coal reserves frame each baseline [horizontal lines] (IPCC, 1990b, 1992; IPCC WGIII, 2000).

32,000 EJ[12] difference between reserves reported in Rogner (1997) and the value of 15,300 EJ we calculate from the energy-mass unit conversion of the BGR (2015) reserve assessment (horizontal lines) frame the total energy projected from coal in each of these high-emission case.

In the FAR, a single BAU case projects a high-emission 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 1700 EJ primary energy supply at the end of the century, as detailed by WGIII. With global annual coal use at 160 EJ in 2015, this projection would constitute a further 600% expansion over the next eight decades (BP, 2016). Coal-based synfuels—liquid and gaseous fuels produced through transformation of coal, assumed to begin after 2050—account for much of this increase.

In the SAR, four of the six IS92 scenarios resemble the original coal-focused future of the SA90 BAU case (IPCC, 1995; 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 (1460 EJ) by 2100, with half supplied by coal. Coal-based synfuels provide nearly one-fifth of global primary energy in the IS92a scenario.

TAR and AR4 applied 40 baseline scenarios from the IPCC SRES (IPCC, 2000, 2001, 2008). Six marker scenarios depicted salient features of several core narratives for possible developments in future society. 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.

3.2. Coal in recent IPCC baselines: RCP reference cases and WGIII mitigation scenarios

The IPCC Fifth Assessment Report depicts future trajectories of GHG emissions with four RCPs and 1184 detailed WGIII scenarios. Each RCP summarizes the salient features of emission scenario ranges in the broader literature and does not intend to illustrate explicit energy system projections. However underlying reference case scenarios of RCPs provide detail on fossil fuel use consistent with pathways that lead to each level of year-2100 radiative forcing (van Vuuren et al., 2011a).

Four integrated assessment models (IAMs) provide the underlying RCP reference cases: MESSAGE (RCP8.5), AIM (RCP6.0), GCAM (RCP4.5), and IMAGE (RCP2.6). The scenario provided for RCP8.5 illustrates a BAU world which resembles the general features of coal-dominated energy futures from the previous sets of scenarios in Section 3.1 (IPCC, 2014; Riahi et al., 2007, 2011). The other three RCPs (6.0, 4.5, and 2.6) were designed to represent mitigation steps that stabilize atmospheric GHG concentrations from baselines resembling RCP8.5 (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011b).[13]

Fig. 3a illustrates cumulative coal use in the baseline and mitigation scenarios of each published RCP reference case compared with total hard coal reserves as estimated by Rogner (1997) and BGR (2015). The RCP reference case 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 RCP2.6, much of the coal use is coupled with carbon capture and sequestration (CCS).

The original RCP reference cases provide an end-of-century outlook for global primary energy that more than triples the annual year-2000 level, with at least half of the resulting fossil fuel–based emissions from coal. Energy from fossil fuels over 1800 to 2000 totaled 13,340 EJ (BP 2015; Grübler, 2008), with 43% from coal.

These marker scenarios for each RCP indicate a "return to coal" (Fig. 3b) best illustrated by the graphic approach developed by Marchetti (1977) to show the evolution of primary energy shares over time. Though this graphic technique was intended to depict how a "superior" energy form increasingly substitutes for "inferior" forms, he did not originally show a market reversal for a solid fuel source like coal. According to the original RCP reference cases, coal is poised to once again dominate all energy forms by the end of the century.

Cumulative 21st-century emissions from fossil fuels and industry (FF&I) for the RCP marker cases are shown in Fig. 3c (IIASA, 2009). The RCP8.5 scenario for a BAU world expects a total of 7200 $GtCO_2$ from fossil fuels this century. The distribution of emissions from fossil fuel combustion in the RCP8.5 marker scenario is illustrated on the right of the figure, where coal results in 3800 $GtCO_2$. Use of oil and gas release 2000 and 1400 $GtCO_2$ 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. Growth in RCP8.5 marker scenario coal use leads to average coal emissions of 72 $GtCO_2$/year for 2090–2100, more than four times the level in 2015.

A total of 2550 $GtCO_2$ separates the RCP8.5 marker scenario from its nearest mitigation case (RCP6.0), an amount equivalent to projected post-2050 coal combustion. The varied assumptions on coal adoption after a maximum rate of oil production in 2060 entirely account for

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

[13] Each RCP is labeled after a value for future radiative forcing; for example, RCP8.5 leads to 8.5 W/m^2. It is important to note that each IAM scenario analyzed here from the initial RCP publications is not intended to provide an exclusive description of each future radiative forcing trajectory. Though the research community selected these specific scenarios and their corresponding baselines to illustrate the four RCPs, the full set of IPCC AR5 WGIII scenarios explored in this section provide a more comprehensive description of coal reference cases used to describe 21st-century climate change.

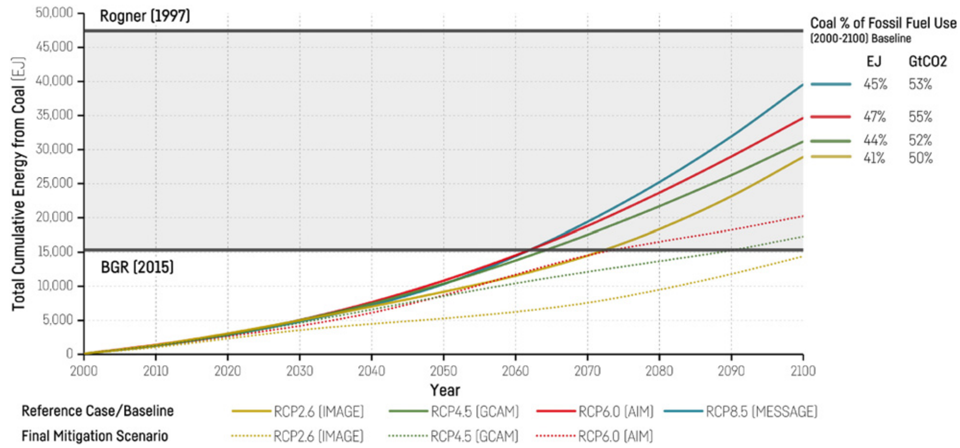

Fig. 3a. Cumulative 21st-century primary energy from coal in original RCP baselines [solid lines] and corresponding mitigation cases for final RCP6.0, 4.5 and 2.6 [dotted lines] scenarios; [upper right] proportion of coal in RCP fossil energy baselines by energy content (EJ) and gigatons carbon dioxide emissions ($GtCO_2$).

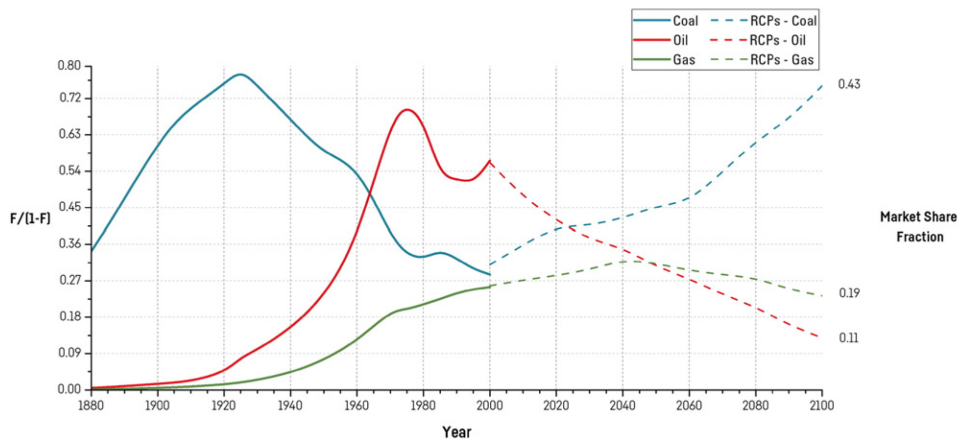

Fig. 3b. Marchetti (1977) curves of world primary energy substitution for coal, oil and gas (Historical – 1880 to 2000) [solid lines] and RCP reference case scenario baseline averages (2000–2100) [dotted lines]; [right] market share fraction of total primary energy supply (TPES) in year 2100.

the separation between RCP6.0 and RCP8.5. Acceleration of coal use in earlier decades constitutes much of the difference in levels of GHG emissions between RCP4.5 and RCP6.0.

In the RCP8.5 marker scenario, oil production declines from 160 million barrels per day (mbd) after midcentury, constituting a smaller portion of total cumulative emissions (2000 $GtCO_2$) while gas combustion steadily grows, resulting in 1350 $GtCO_2$. Total 21st-century coal use accounts for the full span of cumulative FF&I emissions that separate RCP8.5 and RCP4.5. These features of RCP marker scenario baseline energy systems accurately represent the broader range of scenarios used in the Fifth Assessment Report.

The 1184 scenarios of future GHG emissions developed by Working Group III (WGIII) for AR5 are mostly mitigation scenarios that model steps to reduce baseline emissions (Blanford et al., 2014; IPCC WGIII,

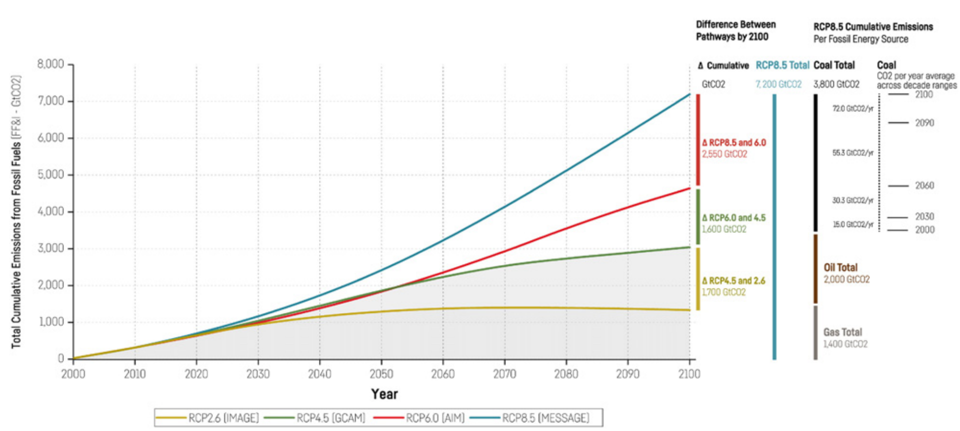

Fig. 3c. 21st-century (2000–2100) cumulative CO2 emissions from fossil fuels [FF&I] in final RCP scenarios with separation between cumulative emissions between pathways [*right*], RCP8.5 emissions from fossil fuels indicated by blue line with energy system baseline of RCP8.5 delineated by fossil fuel type indicated for coal [black], oil [brown] and gas [gray]. Multi-decadal averages of emissions from coal in RCP8.5 baseline for coal [*far right*].

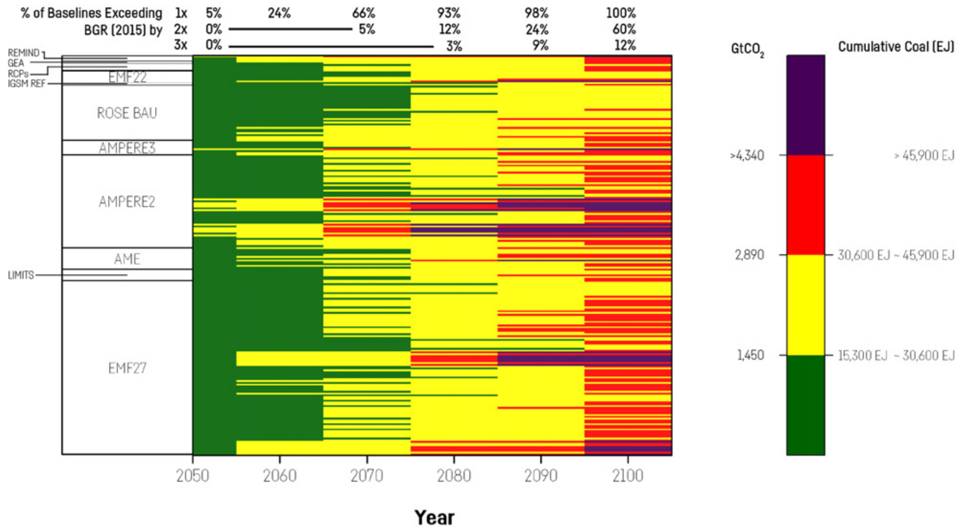

Fig. 4. Cumulative primary energy from coal in the 223 AR5 WGIII baseline runs (2050–2100) grouped by scenario family (left) and compared to the amount of energy available in year-2015 hard coal reserves from BGR (2015) - levels in the heatmap are marked according to multiples of the BGR (2015) coal reserve base at 1× [green], 2× [yellow], 3× [red] and greater than 3× [purple].

2014; Clarke et al., 2014). Eleven scenario baseline families project internally consistent sets of characteristics for future society through the year 2100.[14] 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 Fig. 4 to illustrate the decade when each of the 223 reference cases exceeds BGR (2015) coal reserves with a timeline spanning the second half of this century (2050–2100). Each horizontal bar depicts a single baseline, collected by scenario group (labeled on the left). A model's cumulative coal use below 15,300 EJ is shown in green, while 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 of the heatmap shows the proportion of baseline projections exceeding the reserves by decade. Note that 100% of runs exceed current reserves, 60% exceed twice that level, and 12% exceed three times the assessed coal reserves (in purple).

This section has reviewed how the scenarios of future climate change used over the past 25 years have drawn from global energy system reference cases which depict high levels of future coal combustion, justified by the vintage assessments which have since been invalidated.

The IAMs referenced in this section illustrate each pathway of future GHG emissions with scenarios which draw from energy resource supply curves structured by the total geologic occurrences of coal. These cumulative assessments of coal availability make no meaningful distinction between coal reserves and resources because they expect coal combustion to exceed the total reserve estimates by default, through interpreting information from legacy coal assessments within the theoretical framework of an equilibrium R-P (Section 2). 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 that can inform revised 21st-century reference case scenarios of coal use.

4. Finding a new reserve-to-production equilibrium: empirically constrained coal supply curves for long-term energy scenarios

Applying an equilibrium R-P to the total geologic occurrences of coal allows for the development of a vast coal supply curve, such that withdrawals inevitably anticipate conversion of resources 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 in Table 1 reports 300,000 EJ of economically recoverable coal (Energy Modeling Forum 1995). This suggests a virtually unlimited supply, equivalent to a *resource*-to-production ratio of more than 3000 years when it was published – an order of magnitude above the *reserve*-to-production values we review earlier in this work, and nearly 40-times a reasonable investment horizon of other energy resources. Coal supply curves in IAMs draw from this total geologic resource base, presented in the literature with long and flat portions, where a gradual upward slope that levels off at one or more points informs the eventual backstop price.

Legacy coal assessments have supported the construction of these total geologic carbon supply curves (Fig. 5a) as a guide for scenarios of future GHG emissions (Rogner, 1997). Expectations of an equilibrium coal R-P in such carbon supply curves introduce many low-grade coal resources (originally identified by Rogner as Grades D and E) and exceedingly high amounts of reserves (Grades A, B, and C).[15] Presenting the full extent of Earth's coal resource base as ready 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). Approximately 4000 GtC is removed from the supply curve in Fig. 5a by accepting the implication of modern coal assessments, namely that improving information on

[14] 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).

[15] 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.

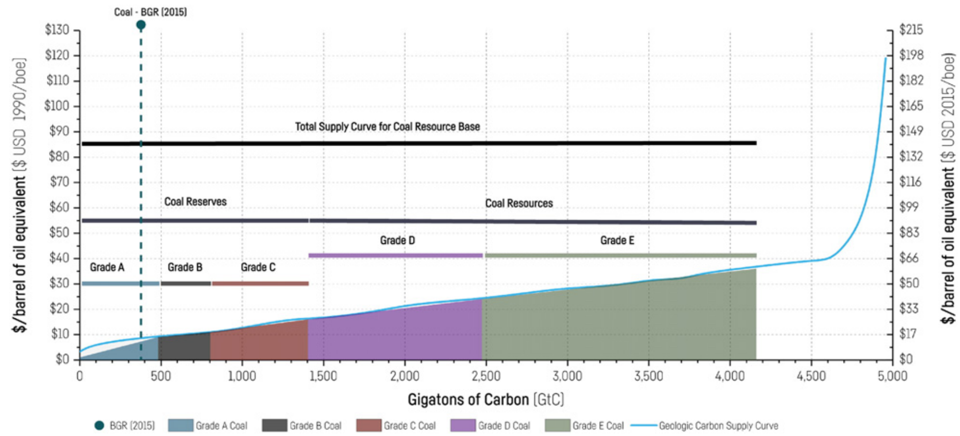

Fig. 5a. Geologic carbon supply curve for Earth's fossil occurrences (Rogner, 1997) mapped to coal reported at that time; with reserves (Grades A, B, C) in blue, black and red respectively and resources (Grades D, E) in purple and green; assessment for BGR (2015) coal marked in blue dotted line.

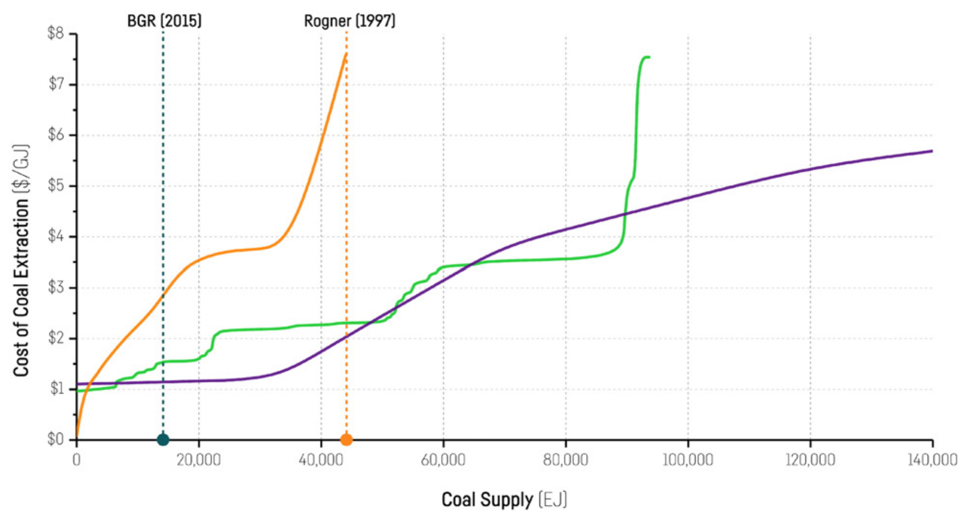

Fig. 5b. Supply curves for coal adopted by IAMs with Rogner (1997) [*orange*], MESSAGE (RCP8.5) [*green*] Riahi et al. (2012) and GCAM (RCP4.5) [*purple*] (Pacific Northwest National Laboratory, 2012). Modern assessment of hard coal reserves BGR (2015) is overlaid [*blue*] with the legacy assessment from Rogner (1997) [*gold*].

reserves has more clearly defined the plausible recoverable portion of the Earth's geologic coal occurrences.[16]

Fig. 5b plots the long-term coal supply curves reported for two leading IAMs: MESSAGE (green) and GCAM (purple) alongside the widely used data from Rogner (1997) (orange) (Pacific Northwest National Laboratory, 2012; Riahi et al., 2012). These IAM supply curves reach values of 40,000, 90,000, and 140,000 EJ for total coal supply, anticipating that the geologic deposits of coal classified as resources will readily become recoverable reserves this century, maintaining vintage R-P values in equilibrium.

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 - similar long-flat supply curves used in US federal studies at that time miscalculated the cost of the marginal mine by a factor of several hundred percent.

Zimmerman (1983) predicted the price and quantity trends that have been realized since 1990 (see Figs. 1a, 1b, 1c, 1d). 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 complements empirically observed evidence to refute the long-flat supply curves used to model total global coal resources. He argues that coal supply cost estimation errors occur because seam geology is inaccurately extrapolated, mining technique potentials are poorly understood, and the unique context of the coal assessment process is misinterpreted.

We suggest that 21st-century energy scenarios take these factors into account by reassessing their use of coal resource data. As covered in the previous sections, not enough evidence remains to support a case that significant amounts of the identified geologic coal occurrences will become reserves with sufficient technical change and market prices. Therefore, a revised definition of ultimately recoverable coal should draw from the reserves indicated by modern assessments. This treatment achieves consistency with terms used to understand ultimate resource potentials for oil and gas.

[16] This calculation applies IPCC (2006) values to estimate the carbon released from unabated combustion of the BGR (2015) reported 699 Gt coal reserves [mass-unit] at 94.6 $MtCO_2$/EJ. However, our conversion of mass to energy units is a simplification of the carbon content in hard coal, which ranges from 50 to 86%. A detailed estimation of the harmonized mass-unit, energy and carbon contained in global coal reserves is ready context for a further detailed study that captures relevant uncertainty in regional estimates and the stochastic factors influencing recovery rates.

Therefore, empirically constrained coal supply curves should stop within a moving average range of modern reserve figures, such as the BGR (2015) line of Fig. 5b. Otherwise the nearly 440,000 EJ of total geologic coal resources suggested by BGR (2015) appear as eventual reserves, which as we argue in Section 2 is not plausible, based on a detailed understanding of the varied definitions of reserves among energy resources.

The plausible theoretical maximum for a 21st-century global energy reference case coal supply curve is established by assuming that all hard coal reserves are recoverable. 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 question is answerable by analysis of reserve recovery rates per region, and it avoids the nullified assumptions that (i) all reserves are recoverable and (ii) all resources are eventual reserves.

Further, the use of an R-P ratio can actively inform projections, rather than providing a passive equilibrium which predisposes "vast" potential coal reserves and their eventual production from the outset. Using all modern coal reserves as the upper bound for long-term studies implies access of some marginal resources since not all reserves are recoverable.

4.1. Prototype 21st-century reference case for theoretical maximum coal use

Fig. 5c provides a prototype scenario to illustrate the concepts covered in this section. It adopts two features of 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.

Because the R-P trend in coal supply provides confidence for multidecade investments in capital equipment for mining, transportation, and combustion, a feasible R-P value must be maintained to secure

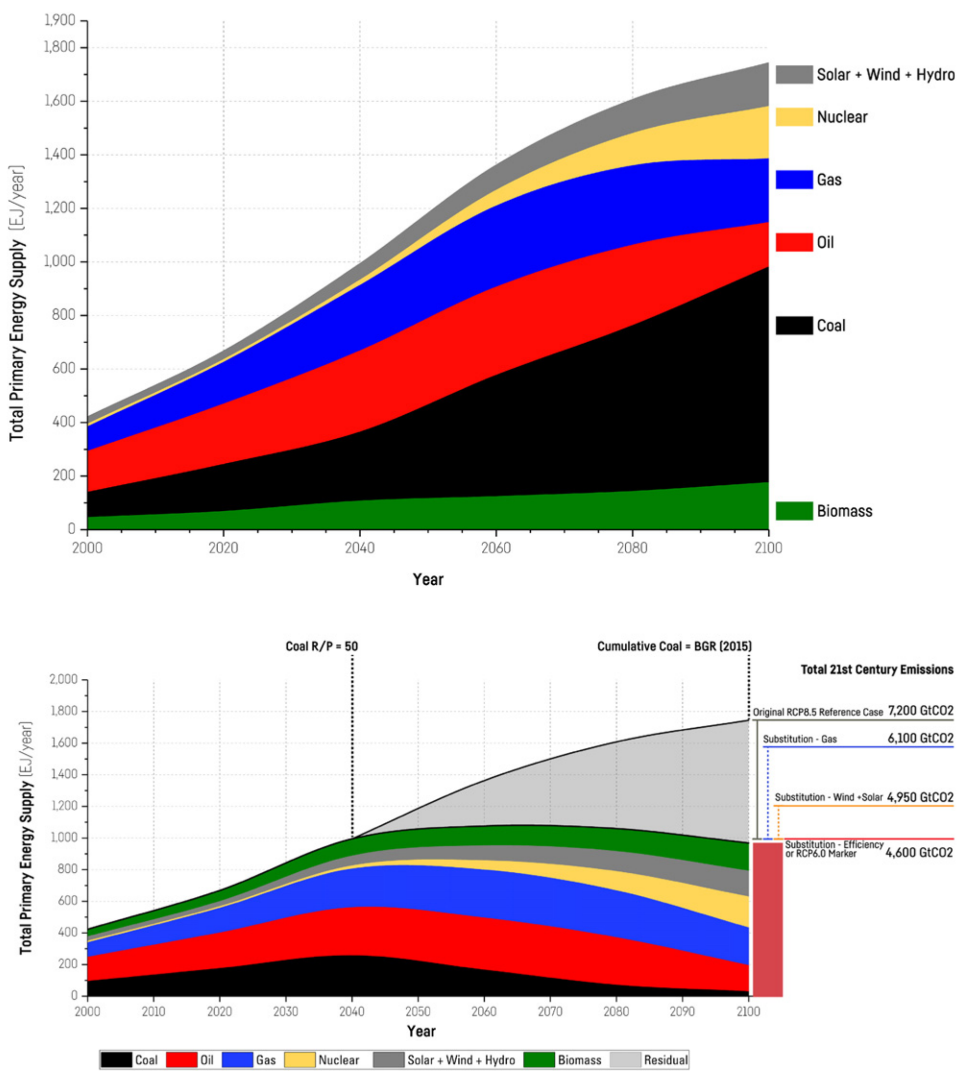

Fig. 5c. [above] original RCP8.5 total primary energy supply designed to illustrate 21st-century primary energy production consistent with the extent of theoretically extractable occurrences from the literature (Riahi et al., 2011); [below] a prototype long-run energy supply outlook based on modern coal assessments: the RCP8.5 marker scenario of Riahi et al. (2011) is amended to provide a stylized representation of an energy future with empirically constrained boundary conditions of BGR (2015). This case maintains the original RCP8.5 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 in 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 baseline GHG emission scenarios. A reduced contribution from coal leaves a 27,000 EJ residual from the original RCP8.5 TPES. On the right column, total 21st-century emissions from energy for various substitution cases for the residual are considered: the original RCP8.5 marker projects a total of 7200 $GtCO_2$ [gray], while direct substitution with gas leads to 6100 $GtCO_2$ [blue], renewables to 4950 $GtCO_2$ [orange] and efficiency to 4600 $GtCO_2$ [red]. The efficiency case is equivalent to the amount of 2000–2100 cumulative FF&I CO_2 emissions illustrated by the RCP6.0 marker scenario from mitigation efforts.

continued capital investments at each point in time.[17] A high R-P ratio for coal is commonly cited as the reason to invest in large-scale synfuel deployment (Yanarella and Green, 1987). 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 Fig. 5c – lower adapts the RCP8.5 marker scenario 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 RCP8.5 TPES (Fig. 5c – upper) designed to illustrate combustion of all theoretically extractable occurrences from the literature. Since the original projection drew from a misidentified upper boundary for coal reserves, the original RCP8.5 marker anticipates around 40,000 EJ from coal in the 21st-century. The prototype scenario for a modern coal reference case results in a residual demand for 27,000 EJ of primary energy, depicted with gray shading (Fig. 5c – lower).

In Fig. 5c - *lower* as coal production accelerates through 2040, eventually the coal R-P reaches a value of 50. At this point, investment in future coal consumption becomes risky, leading demand to seek other sources of supply, and investment in coal discovery and production declines, creating a negative coal demand–supply feedback. All modern coal reserves are used by year 2100 to maintain consistency with the convention of GHG emission scenario baselines in Section 3.

Though a portfolio of energy supply strategies could substitute for the demand formerly met by coal in the original RCP8.5 reference case, direct substitution of primary energy (EJ-for-EJ) with gas, renewables, and efficiency measures are considered on the right column of the figure. If gas is substituted for the coal residual, the original RCP8.5 total of 21st-century cumulative emissions would decline 15%. 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% reduction.[18] If energy efficiency measures are used to address the 27,000 EJ shortfall, total CO_2 emissions would replicate those illustrated by the original RCP6.0 marker scenario from mitigation steps.

Further, if we accept lower coal R-P values, because this resource commonly provides the lowest cost primary energy in baseline scenarios, the overall price of end-use energy may rise. Assumptions of high demand for primary energy post-2050 in scenarios like the RCP8.5 reference case may largely result as an artifact of virtually boundless cheap coal that suppresses any incentive for adoption of energy efficient technologies. However, integrated modeling with updated coal resource information can fully explore the energy system implications of modern coal reference cases and their implications for feasible energy capital investments to meet projections of primary energy demand.[19]

5. Summary and recommendations for a recalibrated 21st-century coal reference case

All recoverable coal is counted as 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 can be recovered. The answers to these questions extend beyond geology to include economic factors determined by technology, demand and trajectories of socioeconomic development. 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, requiring a dynamic consideration of energy resources that captures possible evolutions in the meaning of 'reserves' beyond today's limited knowledge. To address this challenge, scenarios of future energy supply have adopted the convention of projecting R-P equilibrium conditions for the totality of geologic resources as a way to estimate possibilities for expanded coal production. The knowledge of global coal which has accumulated over the last three decades shows that such dynamic considerations have been applied to produce scenarios which are inconsistent with actual reserve trends since 1990.

Modern trends in coal production, consumption, markets, and technology have pushed the global R-P ratio to ever-lower values, so the conditions predicted by a dynamic equilibrium framework that continually expands assessed reserves have not been observed. Thus, future scenarios using legacy estimates and understandings of coal reserve potentials and recovery rates lack a conceptual basis. The reference case 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 reference cases used in Section 3. This inconsistency poses an opportunity to revise the theoretical basis for treating coal reserves as a stock, continually replenished by drawing from total resources.

By relying on vintage assessments and assuming 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 assessed coal *reserves* are the reasonable upper bound for today's long-term energy studies. Application of regional recovery factors can further refine and provide confidence in this boundary.

Geologic coal resources are vast, but they do not constitute a viable industrial fuel source because these deposits are not recoverable with any technology suitable for inclusion in a 21st-century reference case. Thus, the total geologic coal resource base cannot be assumed as available for combustion in future energy scenarios. The reasoning we offer rests on the observation that today's reserves are now more costly and less abundant than assumed thirty years ago. This is likely to be further exacerbated if coal extraction were to proceed toward the extreme deposits and geographies required to realize coal supply curves presently used by IAMs.

Considering all geologic coal resources as eventual reserves equates 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 decision making and distorts any subsequent analytical framing if we assume from the outset that all saltwater is equivalent to fresh water.

We acknowledge that coal has been found in huge quantities throughout the Earth's crust. As noted at the outset, there is a poor record of guessing what technological breakthroughs may unlock economic access to this energy source. It would be foolish to suggest that such a cascade of technological innovations is impossible. However, to assume them as constituting a plausible reference case is a tall ask.

Though unforeseen, hypothetical and speculative developments in extraction technologies can provide a virtually boundless fuel for imagining scenarios which access the full extent of geologically present coal,

[17] Otherwise, a long-term projection could show coal production with an R-P value too small to secure further investment in capital equipment for resource extraction and use.

[18] This estimate of substituting renewables for the 27 ZJ residual applies the median lifecycle emission value for utility-scale solar from Schlömer et al. (2014) of 50 g/kWh. As with the estimate for gas substitution, this is also a high value because utility-scale solar is the most carbon-intensive renewable energy technology reported by the IPCC's Fifth Assessment Report.

[19] This prototype scenario is a very static illustration of an amended coal reference case which is not intended to substitute for results consistent with a fully integrated scenario. It merely serves to provide comparison with upper boundary primary energy use scenarios like the original RCP8.5 scenario of Riahi et al. (2011) which intend to depict use of all theoretically extractable occurrences from the literature.

IAMs must consider the full potential inventory of any energy resource within a realistic accounting basis for an upper bound. A plausible horizon for 21st-century coal is established by assuming that all reserves are fully recoverable. Adopting modern reserve figures as the empirically constrained supply curve for coal serves to harmonize definitions with those used to identify ultimately recoverable portions of oil and gas occurrences.

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 that tap into the global coal classified as resources. 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 hypothetical. 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 which determine an equilibrium market price. The trajectories of technological change that could result from a lower coal R-P may not inherently lead to innovations focused on mining technology that aims to recover the vast coal resource base.

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. This has reiterated the observation of Zwartendyk (1974) that, “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.” The greatest misconception is that assessed reserves for coal are equivalent to reserves for oil and gas. Expanding reserve and production trends of oil and gas are not an appropriate analogue for coal resources. Data on coal reserves provide fundamentally different information from the reserves of other energy resources because of a distinct assessment process that results from unique geologic characteristics, industrial composition and nature of reporting.

As demonstrated in Section 3, models of projected energy futures have applied pathways of vastly expanded coal production in long-run outlooks which assume full use of total reserves and partial access of resources. The underlying assumptions now significantly deviate from actual trends in coal prices (underprojected) and reserves recoverable (overestimated). Persisting with upwardly biased projected levels of coal combustion requires corroborative evidence for reasoning that supports dramatic upward revisions in reserve estimates and recovery factors with technology suitable for inclusion in a reference case.

Tapping into the vast geologic resource base to significantly increase assessed reserves will require breakthroughs in coal recovery that greatly outpace technologies for other energy supply strategies. Underground coal gasification 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 in-seam coal to gas, severe environmental harms, and curtailed production due to uncontrollable subsidence. Furthermore, UCG's broad adoption will need to outcompete improvements in the economics and availability of renewables, nuclear power, unconventional fossil sources and end-use efficiency.

The observed dynamics which distinguish modern coal reserve assessments from those of the past pose an opportunity to recalibrate outlooks for 21st-century global energy supply. Further research has the potential to update long-run studies with integrated modeling efforts, as a means of determining whether empirically consistent coal costs and availability provide a plausible backstop for oil and gas depletion in a way that is more than an anachronism.

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