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Why do climate change scenarios return to coal?

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ABSTRACT

The following article conducts a meta-analysis to systematically investigate why Representative Concentration Pathways (RCPs) in the Fifth IPCC Assessment are illustrated with energy system reference cases dominated by coal. These scenarios of 21st-century climate change span many decades, requiring a consideration of potential developments in future society, technology, and energy systems. To understand possibilities for energy resources in this context, the research community draws from Rogner (1997) which proposes a theory of learning-by-extracting (LBE). The LBE hypothesis conceptualizes total geologic occurrences of oil, gas, and coal with a learning model of productivity that has yet to be empirically assessed.

This paper finds climate change scenarios anticipate a transition toward coal because of systematic errors in fossil production outlooks based on total geologic assessments like the LBE model. Such blind spots have distorted uncertainty ranges for long-run primary energy since the 1970s and continue to influence the levels of future climate change selected for the SSP-RCP scenario framework. Accounting for this bias indicates RCP8.5 and other 'business-*as*-usual scenarios' consistent with high CO_2 forcing from vast future coal combustion are exceptionally unlikely. Therefore, SSP5-RCP8.5 should not be a priority for future scientific research or a benchmark for policy studies.

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1. Introduction

Since 1870, more than 70% of anthropogenic greenhouse gas (GHG) emissions have resulted from the combustion of fossil fuels [1]. Constructing projections of future fossil fuel emissions for studies of future climate change is a challenging task. Workers in 19th-century mines could have scarcely imagined the technologies used by today's coal industry. The same context is faced today when pondering an outlook for coal in the global energy system of the 21st-century.

To understand possibilities for future climate change, the research community uses sets of scenarios produced by integrated assessment models (IAMs) as a landscape for exploring the socioeconomic and energy system developments that lead to various levels of GHG emissions [2–4]. Each generation of climate change scenarios has drawn from IAMs to provide long-term production outlooks for oil, gas, and coal consistent with these GHG emission pathways. IAM scenarios of energy use establish a plausible uncertainty range for climate model inputs, shaping a context that influences all studies of climate change.

In preparation for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) the research community designed a new framework for future scenarios [3,5–11]. Each final scenario is defined using independent projections of future radiative forcing (representative concentration pathways — RCPs) and socioeconomic storylines (shared socioeconomic pathways — SSPs) [7,8].

Radiative forcing (RF) measures the change in Earth's energy balance with units of watts per square meter (W/m^2) [12]. In research on anthropogenic climate change, RF indicates the net magnitude of the greenhouse effect from all GHGs emitted by humans. The IPCC best estimate for total anthropogenic RF in 2011 relative to 1750 was 2.3 W/m^2, with an uncertainty span ranging from 1.1 to 3.3 W/m^2 [13]. Total RF includes positive components that lead to warming (e.g. GHGs) as well as negative components that lead to cooling (e.g. aerosols, land use change). A recent estimate places the GHG component of RF from GHGs at 3.0 W/m^2 where carbon dioxide contributes 2.0 W/m^2 [14].

The RCPs were primarily designed to serve as time-series of future RF. A combination of RCPs that lead to high and low levels of year-2100 RF intend to capture the full plausible uncertainty range for research on future climate change (Fig. 1). The initial RCP

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Nomenclature

Units

RF	Radiative forcing [W/m^2]
CO_2	Carbon dioxide – atmospheric concentration [parts per million - ppm]
EJ	Exajoules
Mtoe	Million tons oil equivalent
Mbd	Million barrels of oil equivalent per day
Bcm	Billion cubic meters
ZJ	Zettajoules
GJ	Gigajoules
Boe	Barrel of oil equivalent
USD	United States Dollar
Gtoe	Gigatons oil equivalent
URR	Ultimately recoverable resource

Abbreviations

IAMs	Integrated assessment models
GHGs	Greenhouse gas emissions
IPCC	Intergovernmental Panel on Climate Change
AR5	Fifth Assessment Report
RCP	Representative Concentration Pathway
SSP	Shared Socioeconomic Pathway
WGIII	Working Group III
BAU	Business-*as*-usual
LBE	Learning-by-extracting
TPES	Total primary energy supply
CTL	Coal-to-liquids
R-P	Reserves-to-production ratio

publications include underlying reference case scenarios of primary energy supply consistent with the internal logic of each level of forcing [15–18]. However, the RCPs could represent many different trajectories of future society and energy resource use. This allows modeling teams to independently develop detailed socioeconomic scenarios which map to each end-of-century value [7,19,20].

The decoupling of forcing and socioeconomic components in the new scenario framework provides flexibility to physical climate modelers and researchers in other disciplines, enabling experiments on future outcomes without the need to specify explicit sources of multi-decade GHG emissions [for example 21–26]. Therefore, each RCP should not be interpreted as presenting a description of *how* each pathway occurs, or whether certain levels of atmospheric GHG concentrations are inherently plausible. The SSPs and independent IAM scenarios describe how each RF trajectory results from future developments in the global energy system.

The RCPs derive their labels from values of total RF in 2100. AR5 Working Group III (WGIII) scenarios contribute detailed socioeconomic and energy system reference cases that illustrate how the RCPs could result [27]. These WGIII reference case scenarios reach an average of 7.1 W/m^2 in year 2100, between RCP6.0 and RCP8.5. As of late 2016, a series of five SSPs are available for continued research [3]. The SSPs provide detailed narratives explaining socioeconomic conditions consistent with each RCP. In essence, an SSP is a big picture description of the future which can downscale the larger story, guiding the development of IAM scenarios of energy resource use [28].

The SSPs intend to represent a space of uncertainties primarily defined by the nature of their outcomes rather than their inputs so that the chosen end-state is backcasted to the present using an inverse process of scenario construction [10,29–34]. This *backwards* technique enables the end state of key variables for each pathway to be in mind while they are developed [10,31]. Table 1 provides descriptions of the end-points IAM scenarios should achieve to illustrate an RCP or SSP, alongside key references for associated scenarios.

This paper argues SSP5-RCP8.5 is an exceptionally unlikely end-point of future CO_2 forcing because it is biased by a return to coal hypothesis that distorts the future energy scenarios produced by IAMs. This return to coal hypothesis: (i) represents a significant discontinuity in historical primary energy development trends (Section 2), (ii) is assessed for plausibility with an untested and empirically unverified model of technological change in resource extraction technology (Section 3), (iii) results from a temporal information asymmetry between fossil resource assessments (Section 4.1) and (iv) repeats the pattern and rationale of historical projections that dramatically overestimated future coal use

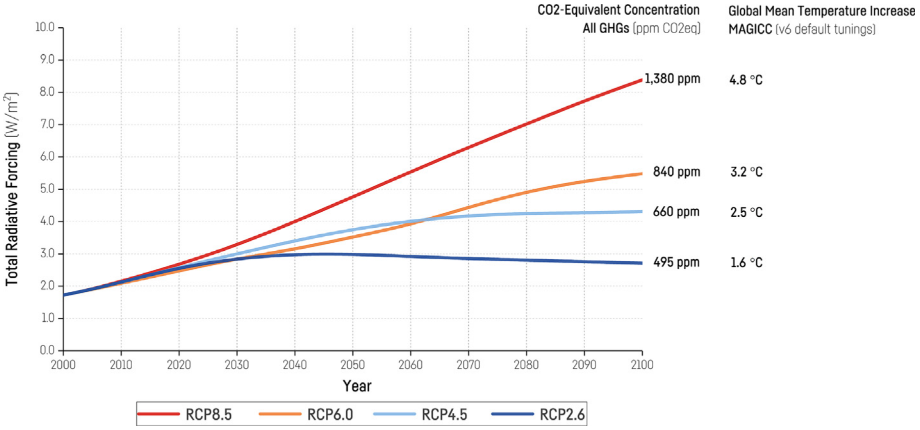

Fig. 1. The four representative concentration pathways (RCPs) - RCPs correspond to a specific value for total radiative forcing in 2100 *(left)* and CO_2-equivalent atmospheric concentrations *(right-y axis)*; when each RCP scenario is applied to the MAGICC model of climate change with default tunings *(right column)* corresponding projections result for a 21st-century increase in global mean temperature over pre-industrial levels [7,20].

Table 1
IAM marker models and scenarios for climate change pathways: Representative Concentration Pathways [7] and Shared Socioeconomic Pathways [3].

Pathway – Intended Representation/Narrative (end-point)	Marker IAM (Relevant Precursor Scenario)	Underlying Model and Scenario Documentation
RCP8.5 – Rising radiative forcing pathway – (~1370 ppm CO2eq) – no intervention, i.e. 'business as usual'	MESSAGE (A2r)	[15,35–37]
RCP6.0 – Stabilization without overshoot (~850 ppm CO2eq) – intervention for stabilization (high)	AIM (SRES B2)	[16,38]
RCP4.5 – Stabilization without overshoot (~650 ppm CO2eq) – intervention for stabilization (medium)	GCAM (CCSP 2.1)	[17,39]
RCP2.6 – Peak in radiative forcing before 2100 and then decline (peak at 490 ppm CO2eq) – intervention for stabilization (low)	IMAGE	[18,40,41]
SSP5 – Fossil-fueled development – 'taking the highway'	REMIND	[42]
SSP4 – Inequality – 'a road divided'	GCAM	[43,44]
SSP3 – Regional rivalry – 'a rocky road'	AIM	[45–47]
SSP2 – Middle of the road – 'dynamics as usual'	MESSAGE	[48]
SSP1 – Sustainability – 'taking the green road'	IMAGE	[49]

(Section 4.2).

These four lines of evidence (i-iv) collectively indicate that RCP8.5 no longer offers a trajectory of 21st-century climate change with physically relevant information for continued emphasis in scientific studies or policy assessments. Though IAMs could possibly re-imagine pathways that achieve RCP8.5 in the context of modern coal economics, this level of forcing was chosen as an SSP-RCP end-point based on scenarios that applied the most extreme version of the return to coal hypothesis [2,7,15,35]: an implausible outlook for a vast coal backstop [50,51].

To develop this case, Section 2 conducts a meta-analysis of the global energy system reference cases which illustrate the SSP-RCP scenario framework end-points. In AR5 and the newly developed SSPs, each *reference case* describes expected baseline or *business-as-usual* (BAU) future developments of global energy resource production during the 21st-century without any explicit or concerted steps to reduce GHG emissions through climate policy.[1]

Such multi-decade fossil energy reference cases inherently address anticipated future developments in energy resources, beyond the limitations of today's knowledge. IAMs understand this dynamic frontier with the theory of long-run fossil energy resources developed by Rogner [52]. Rogner proposes a framework for seeing beyond the horizon of today's short-term oil, gas and coal resource outlooks with techniques of perfect foresight, compounding productivity increases, optimal investment and certain recovery to formulate a model of *learning-by-extracting* (LBE).

The conceptual basis of this LBE theory anticipates that ongoing fossil energy extraction induces a learning effect which increases the availability of lower-grade resources. A compounding learning effect applied over decades depicts the totality of geologic oil, gas, and coal deposits as a viable fuel source for economic production. Section 3 argues this formulation of technical change for 'time-less' energy resource stocks leads long-term energy scenarios to rely on coal when the horizon of information for other energy resources expires - a problem of using the LBE theory as the plausible basis for future energy system scenarios that return to coal (Section 4). Section 5 concludes by summarizing the lines of evidence that indicate RCP8.5 should not be a priority for future scientific research.

2. Energy system reference cases in the SSP-RCP framework: a brief meta-analysis illustrates the return to coal hypothesis applied by IAMs

To define the way IAMs illustrate future climate change with a return to coal hypothesis, this section examines AR5 WGIII 21st-century reference cases of fossil energy production in Fig. 2a–d. These are framed by corresponding end-point ranges from the RCP and SSP marker scenarios [15–18,53,54].[2] Primary energy describes the energy embodied in natural resources before any conversion that enables end-use [55]. An annual measure of TPES accounts for the sum of primary energy consumed from all resources during a given year.[3]

Fig. 2 depicts the full set of AR5 energy system reference case time-series (transparent gray lines) with their corresponding uncertainty ranges illustrated by overlays to indicate minimum and maximum (black lines), 80th-percentile (green lines), median (blue lines) and 20th-percentile (orange lines) values. The right side of each plot provides year-2100 end-points for annual resource production from SSP marker scenarios and the original RCP reference cases. Axes are standardized in two common units for primary energy: (left) exajoules per year (EJ/yr) and (right) million tons oil equivalent per year (Mtoe/yr).[4] Oil and gas production profiles are also noted with common industry units of million barrels per day (mbd) and billion cubic meters (Bcm). These pathways result in levels of total RF that exceed 6.0 W/m^2 and thus define an uncertainty range for energy system reference cases spanning RCP6.0 to RCP8.5 [27,53].

Marker scenarios depicted here for RCP6.0, 4.5 and 2.6 are the original baselines from their corresponding IAMs, preceding the intervention steps applied to produce final RCP reference cases, and

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[1] The phrase 'BAU' carries several different meanings throughout the climate change research community which are important to clarify in the context of this paper. BAU is commonly applied to describe a trajectory of atmospheric CO$_2$ concentration, GHG emissions or RF which continues a post-1950 trend of increase or acceleration. This usage implies a passive momentum of global trends which are an unclear and unrefined description of possible developments in society, technology and energy systems. The IAM community tends to use the more precise term *reference case* for describing non-intervention scenarios or outlooks for a possible future society with no explicit steps to control GHG emissions. However, BAU is still common among physical climate modelers and other users of the RCPs.

[2] Analysis includes all AR5 WGIII reference case scenario (n = 200) projections for primary energy through the full 21st-century. These scenarios are from 14 IAMs: BET, EC-IAM, FARM, GCAM, GRAPE, ISGM, IMACLIM, IMAGE, MERGE, MESSAGE, POLES, REMIND, TIAM and WITCH.

[3] There are important differences to acknowledge in the methods and accounting procedures used by various energy agencies to develop long-term outlooks for primary energy, particularly from nuclear, hydro, wind, solar and biomass [55]. For example, the BP data applied in this work does not account for non-marketed traditional biomass in TPES. No harmonization procedure is applied, as this study focuses on oil, gas, and coal, and there is more general agreement among energy agencies for primary energy from these sources. The many IAM generated scenarios do not have a complete set of available documentation, which would make any harmonization factor suspect.

[4] All conversion factors in this article apply values from the Global Energy Assessment Table 1.B.1 [56].

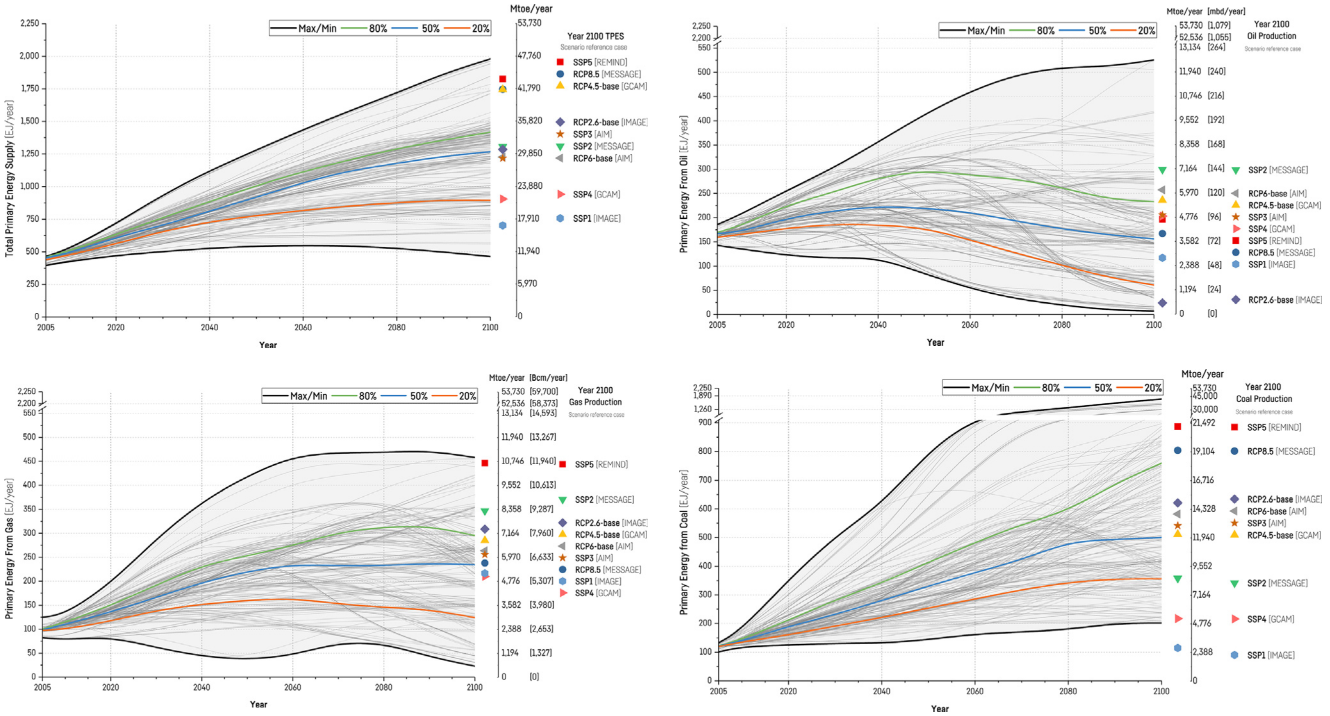

Fig. 2. IAM uncertainty ranges for 21st-century (2005–2100) fossil resource production outlooks from IPCC AR5 (time-series) with SSP marker scenarios and RCP reference cases (*right*): total primary energy supply (TPES), oil, gas, and coal with EJ/year (*left*) and Mtoe/year (*right*); note axis breaks for consistency - a) TPES scenarios; b) annual oil production scenarios *(right axis includes units of Mtoe/year and mbd/year)*; c) annual gas production scenarios *(right axis includes units of Mtoe/year and Bcm/year);*d) annual coal production scenarios.

are denoted with ‘base’ [15–18].[5] Extensive detail on the primary, secondary, and final energy supply cases for the full set of SSP marker scenarios are available in Bauer et al. [58].

Outlooks for total primary energy supply

TPES (Fig. 2a) outlooks in AR5 cluster at century's end between a median level of 1260 EJ/yr (30,200 Mtoe/yr) and a high level of 1420 EJ/yr (34,000 Mtoe/yr) with the 20th-percentile (low) level at 900 EJ/yr (21,400 Mtoe/yr).[6] Global TPES was estimated at 560 EJ/yr (13,280 Mtoe) in 2016, and so these projections envision a global energy system 1.6 to 2.5 times larger than today [59].

Outlooks for oil production

Oil production trajectories in AR5 (Fig. 2b) lead to mid-century maxima at high (140 mbd), medium (105 mbd) and low (86 mbd) levels. However, there are considerable variations between distinct individual scenario trajectories: some depict steady oil use *(steady-state)*, others a growth, peak, and decline *(peak-decline)*, or a late-century boost in oil after an earlier decline *(resurgence)*, generally after development in unconventional extraction technologies enable a return to production rates from preceding decades.

High levels of oil production in later decades draw heavily on sources presently considered unconventional, as in the RCP8.5 marker scenario which estimates 21 zettajoules (ZJ) of energy from unconventional oil this century [15], equivalent to approximately 100 mbd of sustained production from 2000 to 2100. Total oil production was reported at an average of 92 mbd in 2016 with approximately 8 mbd from unconventional sources [59,60].

Outlooks for gas production

Scenarios of gas production in AR5 (Fig. 2c) reach a median level of 230 EJ/yr (5600 Mtoe/yr) with high and low levels at 300 EJ/yr (7000 Mtoe/yr) and 120 EJ/yr (3000 Mtoe/yr) respectively. In 2016 global gas output was estimated at 134 EJ/yr (3200 Mtoe) [59].

Outlooks for coal production

AR5 projections for year-2100 coal production (Fig. 2d) illustrate a low level of 360 EJ/yr (8,500 Mtoe/yr), median of 500 EJ/yr (12,000 Mtoe/yr), and high of 760 EJ/yr (18,150 Mtoe/yr). Maximum and minimum reach 1,760 EJ/yr (42,000 Mtoe/yr) and 200 EJ/yr (4,800 Mtoe/yr) respectively. With coal production in 2016 reported at 150 EJ/yr (3,660 Mtoe/yr) (BP, 2017), these AR5 scenarios collectively envision continued expansion in global coal output, growing 140% (20th-percentile range) to 400% (80th-percentile range) from today.

2.1. AR5, RCP and SSP primary energy profiles in the context of historical development

Historical development trends in energy use per-capita can assist with interpreting the uncertainty ranges provided by the AR5 and SSP resource production outlooks [59]. Fig. 3a–d plots historical trajectories of TPES, oil, gas, and coal per-capita (green line) alongside those from AR5 and the SSPs. The left axis of each plot shows primary energy per-capita in gigajoules per global person (GJ/capita) and the right axes index these time-series to their level in 2016. A shaded light gray range in the figures highlight AR5 minimum and maximum levels, while the darker gray range depicts the space between 80th and 20th percentile boundaries. Dotted lines illustrate SSP marker scenarios and the average of the original RCP reference cases. The SSP scenarios vary in their projection for world population in year-2100, with SSP3 the highest

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[5] Though the RCPs are generally considered independent of their underlying IAM generated marker scenarios, each reference case was chosen by the research community to illustrate a set of energy system characteristics consistent with expectations for the archetype of a world without climate policy. Thus, because these underlying marker scenarios are reported in the literature with sufficient detail for analysis, they are an important focal point for understanding how IAMs project future energy system developments [42,57].

[6] ***Note:*** throughout the text, *high* levels correspond to 80th-percentile trajectories, *medium* to 50th-percentile trajectories, and *low* to 20th-percentile trajectories.

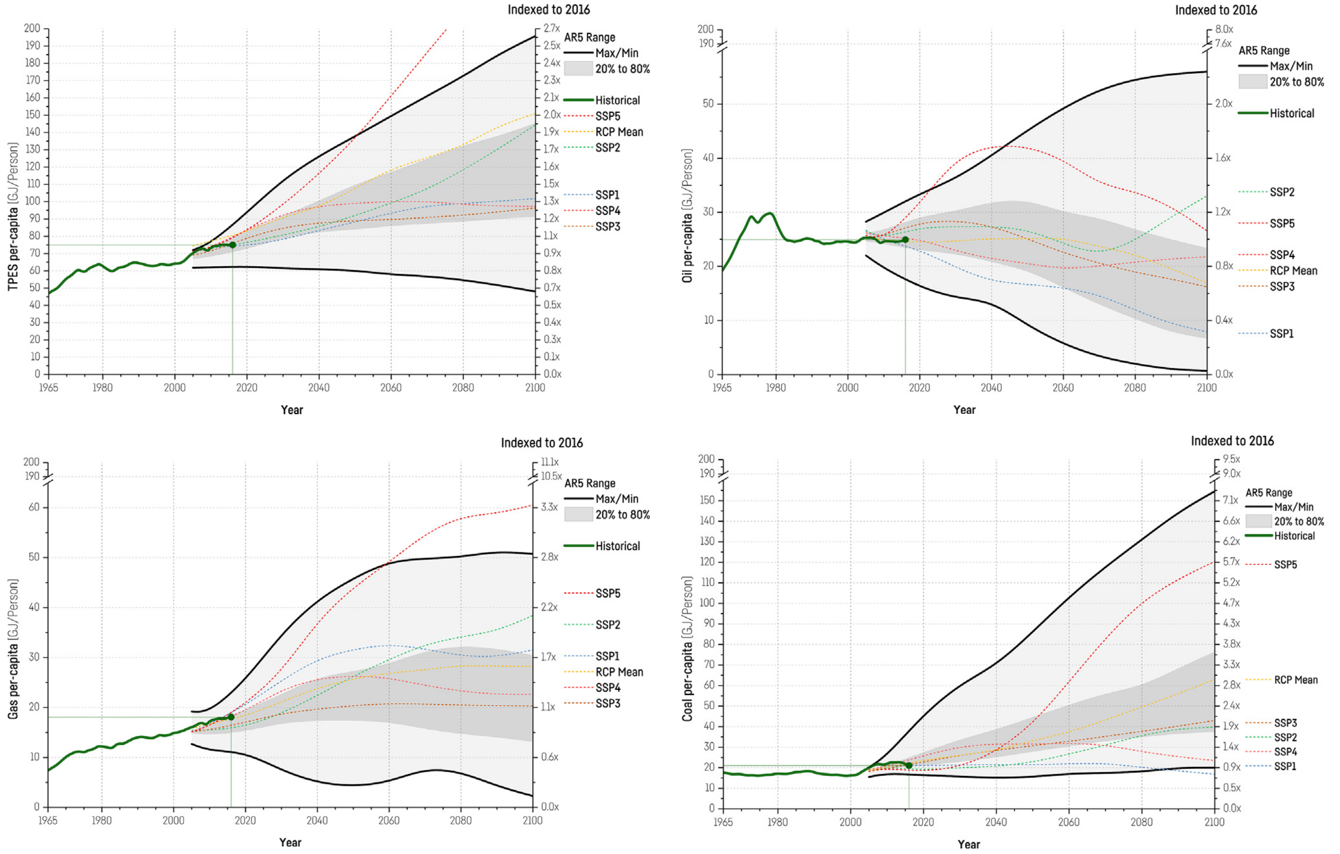

Fig. 3. Historical trends in per-capita energy resource use (1965–2016) compared to the IPCC AR5 range with SSP marker scenarios and RCP reference case average (2005–2100): comparisons between historical trend *(green)* with AR5 range full range *(light gray)*, and 20th-to-80th percentile range *(dark gray)*, indexed to 2016 *(right axis);* SSP1 *(light blue dotted line)*, SSP2 *(light green dotted line)*, SSP3 *(brown dotted line)*, SSP4 *(light red dotted line)*, SSP5 *(dark red dotted line)* and RCP reference case average *(yellow dotted line)* a) total primary energy per capita; b) oil per capita; c) gas per capita; d) coal per capita. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(12.6 billion), SSP1 and SSP5 with low populations (6.9–7.4 billion), while SSP2 and SSP4 end the century around 9 billion.

Since the mid-1970s global primary energy per-capita held relatively steady at approximately 65 GJ/person before growing 15% during 2003–2008 to the current level (Fig. 3a). The AR5 scenario range captures this recent trend by projecting similar rates of expansion, establishing the 20th and 80th-percentile boundaries with an additional 20–200% growth. SSP1, 3 and 4 end the century at the low end of this range, while SSP2 and the RCPs are consistent with the high trajectory. The low population and high energy use storyline of SSP5 describes an outlier case, significantly exceeding the maximum AR5 scenario to reach 250 GJ/capita by year-2100 - 3.3-times more energy resources per global person than today.

Despite a wide range of divergent AR5 scenario pathways, oil consumption has remained remarkably consistent at 25 GJ/capita since the 1980s (Fig. 3b). The SSP narratives lead to scenarios of 21st-century per-capita oil use that rapidly grow and decline after 2050 (SSP5), remain steady through mid-century before a decline and acceleration (SSP2), or gradually decline at compound annual rates of 0.2% (SSP4), 0.5% (SSP3) or 1.3% (SSP1). Natural gas per-capita has followed a steady growth rate of 1.2%/yr since the late 1970s (Fig. 3c). A growth trend in gas use is projected to continue or accelerate over the next few decades in the SSP scenarios before plateauing at varied points later in the century.

Historical trends in global coal since 1965 have shown more stability than oil, averaging 18 GJ/capita over this period (Fig. 3d). Extended data indicate this relative level of per-capita coal use has remained in relative steady-state since the 1920s, establishing a strong reference case baseline signal [61]. Over the last decade, China's unprecedented expansion in coal production drove an increase to 21 GJ/person.[7] A further rise in global per-capita coal use must overcome the policy and technical factors framing China's coal-intensive development pattern as a one-time secular trend that has matured, leaving limited anticipation of additional growth [60,62–64]. Yet, AR5 scenarios consider an even more dramatic change in coal use is on the horizon, which leads to as much as a 640% increase in per-capita coal consumption from recent levels by 2100.

In many long-run energy system outlooks, accelerating coal use results from adoption of coal-to-liquids (CTL) technologies as a backstop liquid energy supply in the second half of the century. Multi-decade energy studies have often projected a rapid scale-up of coal liquefaction once demand for liquid fuels outstrips oil supply available from known oil resources [51,65]. CTL deployment increases coal use after the maximum year of oil supply in several RCP and SSP scenario reference cases such as RCP8.5 and SSP5. Today, CTL provides much less than 1% of global liquids.[8]

High levels of coal use throughout the economy are characterized

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[7] China's coal production recently peaked in 2013 at a level 2.8-times higher than in the year 1999 [59].

[8] Though coal is not a major source of liquid fuel supply in 2017, a small level of production today does not inherently invalidate an outlook for CTL expansion. IAM scenarios must consider the possibility of major technological transitions. For example, renewables may be expected to play a larger role in the future global energy supply despite a lower contribution today.

by scenarios that consider slow progress in non-coal energy technologies such as in the RCP8.5 marker scenario. The original RCP8.5 reference case inherits the narrative of the A2r scenario where coal increasingly dominates global energy supply as slower rates of economic growth limits technological progress in other energy technologies [15,35]. A coal-dominant energy system in RCP8.5 results from coal investment costs that continually decline, while the learning curve for solar, wind and nuclear power remain static.

2.2. *Summary of how IAM primary energy profiles define the return to coal hypothesis*

The SSP storylines lead their marker scenarios to follow several trajectories of primary energy use. SSP1 represents 'green growth' and a narrative of sustainable development, but merely continues the post-1920s trend of per-capita coal use. SSP2 illustrates 'dynamics-*as*-usual' with growing per-capita primary energy and coal use more consistent with the decades following WWII than the late 20th-century. SSP5 'fossil-fueled development' has arguably occurred since the 19th-century, but per-capita primary energy, oil, and coal use in this storyline exceed historical development patterns by a significant margin to achieve 8.5 W/m^2 of RF by the year 2100.

The aggregate resource production and per-capita energy development trends analyzed in this section highlight that the IAMs used in AR5 and for SSP marker scenarios construct a 21st-century fossil fuel combustion uncertainty range summarized by (i) projections for rising energy demand met with continued growth in TPES, (ii) oil supply that reaches a mid-century maximum, and (iii) increasing per-capita coal use. These three factors lead the research community to characterize future climate change with a return to coal that dramatically breaks from the 1920–2016 trend in per-capita coal use. This discontinuity in reference case scenarios represents an explicit transition away from the current technological structure and composition of the global energy system toward increasing levels of coal combustion.

All of the original RCP baselines, 98% of the AR5 WGIII database reference cases, and all SSP marker scenarios but SSP1 project an extended period of moderate or rapid growth in per-capita coal use. For the remainder of the paper, this theory of global energy system development is labeled the *return to coal hypothesis*: long-run growth in future world energy demand must rely on increasing levels of per-capita coal use.

Although such a transition toward coal leaves the scenarios labeled BAU with an incoherent nomenclature, it may be justified if a compelling case vindicates this collective outlook. Thus, the plausibility of using a return to coal to represent the next century's global energy reference case must rest on a rigorously articulated and strong rationale. The remainder of this paper presents evidence that these scenarios result from a theory of technological change in resource extraction which provides significant motivation to question the credibility of coal dominant future energy supply projections.

3. Enough coal for the end of time: the learning-by-extracting theory of fossil energy resource supply

IAMs develop the energy system reference cases in the previous section from future oil, gas, and coal resource supply potentials determined by placing total geologic assessments within a common theoretical framework.[9] Rogner (1997) describes this theory of learning-by-extracting (LBE) and applies it to unify a range of assessments from various agencies for use in long-term studies [52].

Reliable energy data is difficult to procure and validate: it is of proprietary industry value and often reflective of short-term trends. Therefore, many recent studies still build from the resource assessment methodology articulated by Rogner's highly influential and important paper because it describes a process for seeing beyond the frontiers of available information with a dynamic boundary characterized by increasing knowledge that accumulates from learning-by-doing.

The IAMs providing marker scenarios for RCPs and SSPs use resource supply curves uniformly derived from this LBE methodology.[10] McCollum et al. (2014) review the various implementations of LBE applied to generate future energy system reference cases for IPCC AR5 as part of the Energy Modeling Forum 27 study [57].[11]

Though this section focuses on the theory of primary energy resources used by many IAMs, it is important to note that technical oil, gas, and coal extraction costs are the first layer of energy supply costs in each model. IAMs use different methods to simulate prices for additional aspects of energy service demand through technology choices that convert resources into secondary and final energy. Primary energy costs are not entirely independent of the assumptions in an IAM scenario, as in the series of fossil supply curves developed for each of the five SSP narratives [66]. Costs of energy supply in various IAMs can span a broad range due to assumptions about the cost of transportation, subsidies, rent, and taxes [44,57].

IAM fossil resource supply curves are regularly updated with new resource information, and their application and assumptions vary between models and scenarios. However, the general conceptual framework has remained consistent for decades [71,72]. Several papers have argued the original Rogner [52] fossil availability curve is overly optimistic on its assumptions for oil, gas and coal recoverability [73,74], but these perspectives place limited emphasis on the economic determinants of reserve assessments and resource recovery. Bauer et al. [58] make a significant contribution toward updating LBE supply curves for IAMs by integrating many factors independent of climate change mitigation policies that may influence the amount of extractable fossil fuels within SSP narratives [66]. Prototypes of similar total geologic assessments were used by earlier studies before Rogner's theory rooted them in a conventional economic understanding of learning-by-doing [75].

Since the LBE theory provides the plausible basis for the oil, gas and coal production outlooks developed by IAMs, this section reviews its foundational assumptions and context.

3.1. *Learning to blur resources into reserves: a theory of long-run fossil fuel supply economics*

Governments, agencies and the energy industry assess the economic availability of oil, gas and coal deposits by distinguishing reserves from resources. *Reserves* are the oil, gas or coal deposits that are explored, defined and determined available for extraction with varying degrees of techno-economic certainty. For oil, these broader categories are further distinguished by estimating

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[9] Bauer et al. [58] describe equivalent LBE supply curves as Cumulative Extraction Cost Curves (CECC) [66].

[10] Published descriptions of the original RCP8.5 [15] and RCP6.0 [16] scenarios cite that their underlying fossil energy resource assessments either directly apply the supply curve developed by Rogner [52] or its theory. Further descriptions of the IAMs used for RCP and SSP marker scenarios explain how their resource supply curves derive from the LBE approach as with GCAM (RCP4.5, SSP4) [67], IMAGE (RCP2.6, SSP1) [68,69] and REMIND (SSP5) [70].

[11] The LBE model is implemented differently by each IAM [57]: declining fossil resource extraction costs from technological progress due to ongoing production may be represented with an exogenous learning parameter (GCAM), a learning curve (IMAGE), or the influence of labor and technological progress (MESSAGE).

probabilities of recovery: proved reserves (1P) indicate a production threshold with a 90% probability of being exceeded, while the larger number of proved and probable (2P) reserves designate a 50% confidence level in an upper bound [76]. The oil, gas, and coal classified as *resources* represent the totality of their geologic deposits in the Earth's crust [77,78].[12]

Rogner (1997) argues that studies on long-term energy futures would be short-sighted to only focus on distinctions of recovery probabilities and the current boundary between reserves and resources [52]. He suggests that when assessing the costs and quantities of resources across the span of an entire century, it is insufficient to calculate reserve and resource volumes based on a static concept of present technology and cost regimes, since the total amount of reserves at any point in time are in-part drawn from deposits formerly classified as resources.

In Rogner's view, a current reserves-to-production ratio (R-P) - how long it takes to deplete reserves at recent production levels with current technologies - is not a suitable guide for multi-decade energy studies. R-P ratios for oil and gas are typically on the order of 20–50 years. By definition, any current R-P ratio does not embody future technological possibilities or hypothetical trends in energy prices.

As the range of R-P ratios for coal, oil, and gas had remained relatively static for decades, the LBE theory considers that reserves can be viewed as stocks continuously replenished by flows from the total resource base. Because the R-P ratio for many energy resources tends to maintain an equilibrium range [e.g. 79–84], Rogner argues all known resources are effectively ‘reserves-in-waiting’ - characterizing the future of fossil energy production with a *dynamic resource concept*. This dynamic resource concept anticipates that the R-P ratio is passively maintained over the long-run, presenting a theory that future technologies and undetermined breakthroughs will emerge to provide a backstop resource which induce a long-term energy price-capping effect on the cost of fossil fuel production.

Rogner applies this theory to develop an initial LBE supply curve for future fossil energy resources. He estimates the historical influence of technology on reducing costs of conventional oil and gas extraction by applying an instantly derived rate of productivity to aggregate fossil resource assessments from a range of agencies. This annual productivity gain is determined to be 1%, expected to result from learning-by-doing that accumulates from ongoing production of fossil fuels, e.g. learning-by-extracting.[13] In doing so, he highlights this annual productivity gain compounds over time, meaning a resource which costs $40 per barrel of oil equivalent (boe) to extract would, over a period of 50 years, drop gradually to $24.

3.2. *Developing a conventional view of unconventional resources: the methodology of the LBE theory for resource supply curves*

Building from this perspective, Rogner calculates an initial LBE supply curve from reported amounts of oil, gas, and coal where: (1) the reported resource base quantities represent the maximum occurrences derived from the literature. Where ranges of estimates were found, the highest plausible value is adopted; (2) hydrocarbon resource exploration, development and production is subject to the hypothetical compounding productivity gain of 1% per year to provide a condensed representation of 'dynamics as usual' for technological change in fossil energy extraction; (3) all conventional and unconventional resource categories are valued as if the full extent of future productivity gains are realized immediately.

From the quantity-cost relations calculated with these three steps, a single aggregate resource cost curve per source and region is developed, where “the dimension of time is taken out of the resource quantity-cost representations.” This approach values all conventional oil reserves identified at the time of his study at production costs of less than $12 per boe (USD 1990). This low-cost band combines categories of production from cheap unconventional resources, as well as high-cost production from conventional resources. The supply curve resulting from this process is reproduced in Fig. 4a.

The method developed in Ref. [52] structures LBE supply curves to report fossil fuel availability with a gradient of costs based primarily on assumptions regarding the pace of technical change, allowing IAMs to condense the uncertainties inherent in fossil resource extraction to a chosen learning rate. This simplifies the scenario development process by enabling the selection of learning rates based on chosen narrative end-points [66].

Final cost ranges calculated in this way intend to represent the impact of technical change on the economics of a resource as expressed through perfect foresight of: recovery rates, investments, and knowledge of future technology to derive “time-less” quantities of available energy. This instant application of future compounded productivity gains means that resources used in earlier periods reflect technological change expected to occur far into the future. Thus, it is unclear when the technology enabling each certain price band is achieved. Production outlooks that adopt such supply curves directly inherit a logical inconsistency that becomes increasingly distorted as more of the supply curve is extracted (as resources are produced left-to-right along the supply curve). However, Rogner explains that compared to the fossil reserve assessments and estimates of production costs performed by governments and the energy industry, the quantities identified through this methodology are, “gigantic” with costs that are not significantly higher than market prices in the mid-1990s.

When an IAM applies LBE supply curves, generally the lowest cost resource is used first to account for depletion – this broadly introduces the element of time into the fossil fuel production process, even though today's resources may be produced from multiple cost bands in parallel. While some studies use ‘time-less’ resource supply curves directly and fully adopt the temporal inconsistency this section highlights, it is important to recognize that implementation is not homogeneous across all models. For example, the learning curve used by IMAGE/TIMER re-calculates fresh resource costs in every period, applying productivity gains from learning-by-doing that only result from prior cumulative extraction [41]. Some IAMs depict their cost-quantity curves as ‘static’ to simplify their presentation in the literature, despite a more dynamic application of learning driven productivity gains within the model [57].[14]

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[12] The term *resources* notes deposits that are identified but inaccessible with today's technologies, or hypothetical quantities that are geologically possible but yet undiscovered. Resources are not recoverable with current technologies but may or may not become recoverable with future technological change and sufficient market prices.

[13] Though Rogner [52] explains that the compounding productivity improvement results from ‘endogenous learning-by-doing’ it is applied as an autonomous exogenous parameter. Rogner also notes that 1% may be much too high or low an estimate for future productivity gains from technological change in resource extraction since the underlying year-to-year productivity estimates can be volatile.

[14] However, even if learning-driven productivity gains are applied dynamically within an IAM, the initial information on resource cost-quantity availability remains static, and the production schedule becomes distorted unless multiple price bands are used simultaneously (rather than just the lowest cost band in each period).

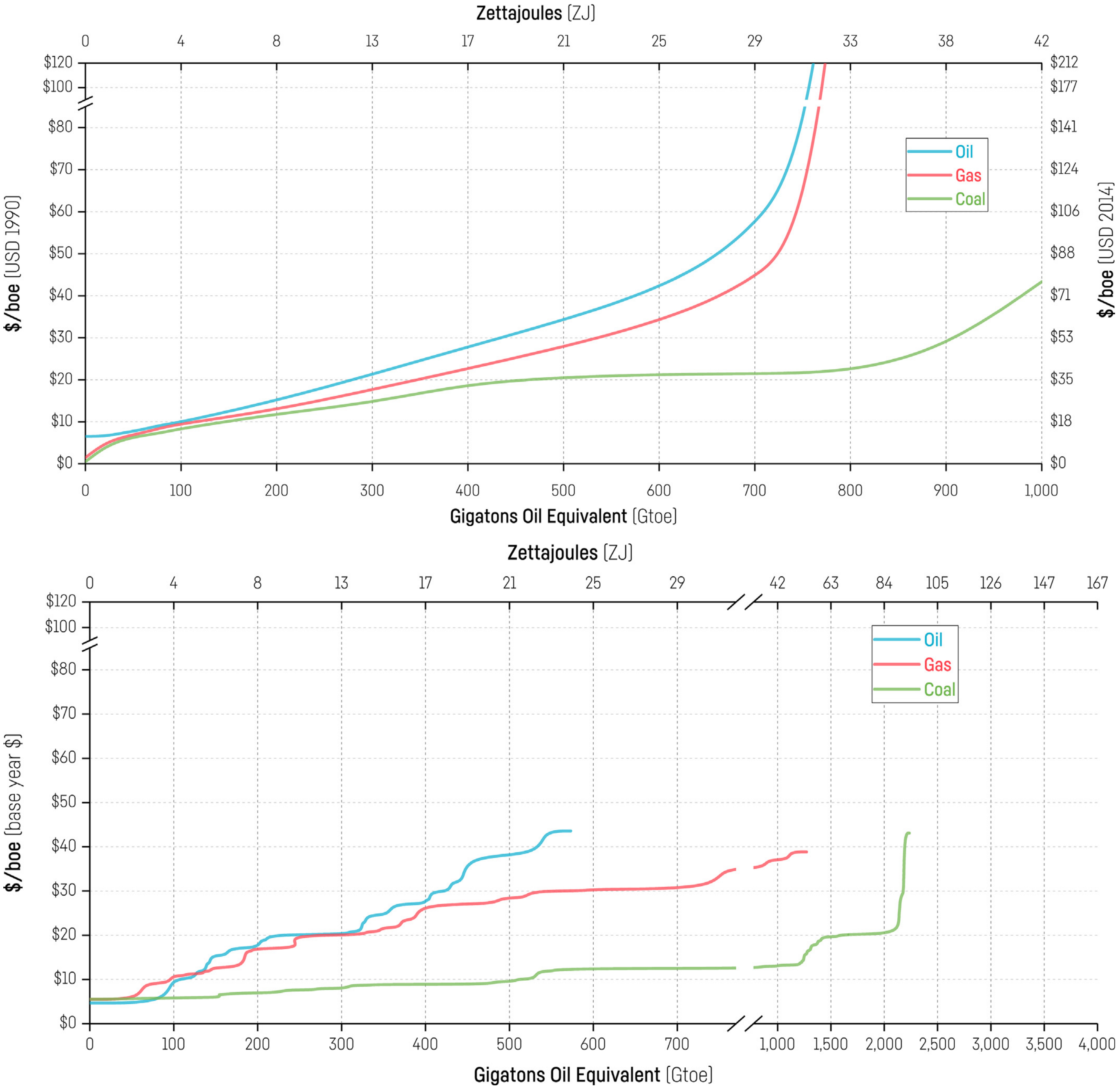

Fig. 4. Examples of learning-by-extracting (LBE) oil, gas and coal supply curves used in IAMs to structure energy supply projections for 21st-century climate change scenarios - a) The original LBE supply curve reproduced from Rogner [52]; b) The LBE fossil fuel supply curve reported for MESSAGE adapted from Ref. [85] for base year dollars (RCP8.5, SSP2); c) The LBE supply curve for oil, unconventional oil, gas and coal reported for GCAM (RCP4.5, SSP4) [44].

Though fossil fuel resource assessments based on the LBE theory are generally expressed as descriptive of likely developments in fossil fuel extraction, Rogner clarifies this approach to fossil fuel supply is both descriptive and normative. He explains this supply curve is descriptive of average productivity growth rates that represent historical trends in conventional oil and gas production, but the learning rate is normative because it projects a drastic pace of specific improvements in recovery technologies several times the historically observed average - especially in the case of coal and unconventional oil sands or shales.

As Bauer et al. [58] note, this learning parameter is widely used despite no empirical tests or calibrations available in the literature for any energy resource [66].[15] We evaluate this LBE model for oil, gas and coal resource economics in detail elsewhere, finding it: (i) provides a strong explanation for upstream operational expenditure trends in oil and gas production since the 1970s, (ii) did not anticipate oil industry capital expenditures which started to dominate production costs after the mid-1990s, and (iii) does not

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[15] The SI of [66] provides a valuable review of productivity in coal extraction for various regions, finding increases in some areas and declines in others.

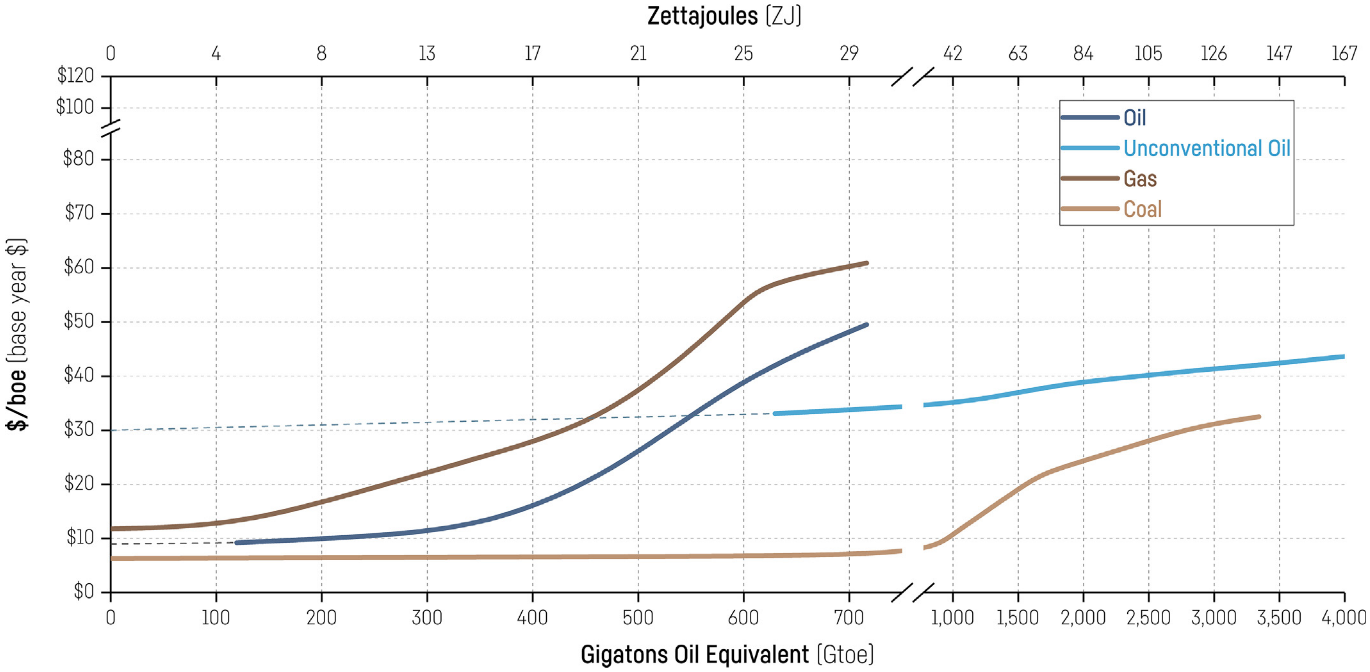

Fig. 4. (*continued*).

describe empirical developments in coal resources [75].

Fig. 4b and c plot the LBE supply curves reported for MESSAGE and GCAM, which provide marker scenarios for RCP8.5/SSP2 and RCP4.5/SSP4 respectively [67,85]. For example, GCAM reports a 0.75% per year cost decline to represent technological improvements that reduce the costs of resource extraction [67]. This compounded technological progress explains GCAM's consideration that 167.5 ZJ (4000 Gtoe) of unconventional oil is available at less than $45/boe (constant dollars), equivalent to 900 years of oil use at 2016 levels.

The LBE theory of a dynamic resource concept proposes that continuous compounding technical progress renders all hydrocarbon deposits on Earth available for economic extraction, enabling 21st-century energy system scenarios with much higher rates of fossil fuel production later in the century. When vast amounts of coal are modeled as a cheaply available backstop resource, IAM scenarios draw on this fuel extensively in reference cases.

In summary, an unverified theoretical projection of normative technology improvements in coal extraction underlies a broad array of long-run IAM energy system scenarios. The collection of scenarios based on this concept were used to determine the levels of forcing end-points for the SSP-RCP framework [7]. Section 4 considers whether this assumption continues to provide a plausible basis for the return to coal hypothesis that supports use of SSP5-RCP8.5.

4. Energy scenarios that return to coal: looking at the future with one eye on perfect foresight and no hindsight

Studies of climate change present a difficult challenge for the development of plausible long-run global energy scenarios. The SSP-RCP scenario framework specifies pre-determined levels of atmospheric RF and socioeconomic conditions in the year-2100 that extend far beyond the frontier of information available today. Because these scenarios must anticipate changes in technologies, energy resources, and social developments, they need to be viewed as hypotheses about the future.

A cautionary note about the way these hypotheses are interpreted relates to two specific issues: a) the scenario architects have steadfastly refused to place a probability on the relative likelihood of hypothesized future scenarios [3,86–88]; and, b) that hindsight, consistency and epistemological rigor in methodology suggests the different hypotheses do not have the same probabilities of being realized [89–91].[16]

Capellán-Pérez et al. [89] provide an important and timely study of issue (b) by conducting a probabilistic assessment of the RCPs [89]. These authors find uncertainties in coal production dominate the likelihood of realizing RF levels exceeding RCP6.0.[17] Scenarios that reach RCP8.5, RCP7.0 and RCP6.0 in GCAM are assigned probabilities of 12%, 25%, and 44% respectively by Ref. [89]. However, these probabilities are based interpreting ultimately recoverable coal (URR) outlooks published from 1913 to 2008 as equally likely.[18] Recent studies suggest coal resource estimates published during and after the early 21st-century coal bull market are more accurate, and so pre-1990 assessments of unlimited cheap coal should not be given equal weight [50,51,72]. Eliminating outdated legacy assessments from the methodology of [89] would constrain uncertainties for coal recoverability to a degree that implies an upper bound for 21st-century RF between RCP6.0-RCP7.0, and a probability of RCP8.5 that is virtually zero.

However, outside of [89] there are no other studies that apply formal techniques for uncertainty analysis to assess the relative

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[16] Though a full discussion of uncertainty in the context of emission scenario storylines exceeds the scope of this paper, van Vuuren et al. [92] provide an excellent dialogue on this topic in their development of conditional probabilistic projections for the Special Report on Emission Scenario narratives [2,92].

[17] Notably, Webster et al. [93] reach a similar conclusion about the role of coal in dominating reference case uncertainties for RF and cumulative CO_2 emissions [93].

[18] More than 30% of the database of coal estimates applied to determine these probabilities in Ref. [89] exceed the upper bound for today's recoverable coal [94]. Contemporary assessments place estimates of remaining recoverable coal on a spectrum of 8000 to 25,500 EJ [50], well below the mean of 35,000 ± 45,000 EJ applied to estimate a 12% likelihood of RCP8.5.

likelihood of climate change scenarios with an explicit focus on the context of resource recoverability factors. Studies of uncertainties in energy resources with IAMs have found that more expensive trajectories for oil and gas induce a return to coal earlier in the century, making a call on the high-carbon coal backstop sooner than later [92,95–97] – an outcome ensured by the supply curve structure of IAMs. Edmonds et al. [98] explored the reemergence of coal after 2050, and questioned its plausibility as a key uncertainty in earlier sets of emission scenarios [98]. However, this issue has not been explicitly addressed in the literature on more recent scenarios of 21st-century climate change. The LBE theory has contributed to this conceptual deficiency because it condenses the myriad factors determining economic resource recovery into a focus on technologies not yet in hand that will theoretically negate the relevance of any probabilistic elements related to oil, gas and coal extraction.

LBE simply states that knowledge of how to extract energy resources more economically increases with cumulative production. This theory does not require information on specific oil, gas or coal extraction technologies or empirical productivity trends. Resulting geologic outlooks are translated to production potentials through applying untested normative assumptions which unlock the full potential of extreme coal and unconventional oil and gas resources with costs virtually unchanged from today. Independent of the plausibility of these foundational assumptions, this theoretical approach carries a critical discontinuity which results from the asymmetric treatment of time applied to translate the total geologic stock of energy resources into a production outlook – leading to an issue particularly relevant to the case of coal.

4.1. The LBE theory leads to a temporal asymmetry in long-run fossil production outlooks

Rogner was wise to highlight that R-P ratios for oil and gas have maintained a steady equilibrium range of 30–50 years in the modern era (Fig. 5a - black line) [59]. However, this means the information available for oil is based on a horizon of plausible production outlooks that have only extended a few decades at most - no incentive exists to invest in additional information beyond that point [82,83]. Global R-P ratios for coal (Fig. 5a - red line) are regularly 100–900 years, many decades and centuries beyond that of oil & gas resources [51,99]. This R-P ratio asymmetry for oil, gas and coal resources is understood to result from differences in the geologic characteristics of each resource, information quality, and their assessment methods [51,100,101].

As examined in Section 2, IAMs develop scenarios of growing primary energy demand for the full 21st-century (Fig. 5b - green line), which pass several decades beyond the horizon of available information on most hydrocarbon and other resources (Fig. 5b - black line). By adopting the basic assumptions of Rogner [52] to characterize all geologic occurrences as reserves and production in-waiting independent of time, outlooks for growing primary energy demand run into a time-domain artificially dominated by coal resources, resulting from a logical inconsistency which treats coal and oil assessments as equivalent (Fig. 5b - red box). Illustrations of long-run TPES growth may readily project an artificial reliance on a coal backstop when passing through this domain (Fig. 5b - gray line).

A simple test can verify whether this dynamic is reflected in the AR5 IAM production outlooks: if scenarios of a return to coal primarily reflect a modeling artifact based on an information asymmetry, inflection points in long-run scenarios will tend to align with the R-P information boundaries identified.[19]

To examine this dynamic Fig. 5c plots a measure of the return to coal from AR5 database reference case scenarios, quantifying whether primary energy substitution of coal for oil changes at the points where R-P discontinuities are expected to occur (Fig. 5c): $\frac{EJ\ coal}{EJ\ coal + EJ\ oil}$, i.e. the primary energy from coal (EJ coal) as a proportion of primary energy from oil and coal (EJ coal + EJ oil).

In Fig. 5c lines marking the 80th-percentile (green), median (blue) and 20th-percentile (orange) express broader trends in the individual AR5 reference case time-series (gray lines). The inflection points notable in the 20th-percentile range and the 80th-percentile range for 2050, and the median range for 2030 are consistent with the proposed explanation: perceived future dominance of primary energy from coal begins in this range as an artifact from resource assessments adopted at face value, independent of their key uncertainties, information asymmetries, and data vintages.

This dynamic is enabled by the LBE theory, which provides a model of technological change that envisions resource potentials with 'only one eye' focused on a quantitative information bus, neglecting the social relevance and temporal dynamics of how data are gathered to produce these assessments. This is not a unique problem for today's scenarios of climate change, and the energy models that produce them. The same issue has faced multi-decade assessments of primary energy since the 1970s. Briefly revisiting the rationale of past studies which shared similar outlooks provides further confidence that a large-scale return to coal is not a plausible hypothesis for the 21st-century global energy system.

4.2. Systematic errors of past outlooks for future coal dominance: a global and national example

Projections of future primary energy dominated by coal have been used in the energy modeling literature for many decades. This section revisits several studies that developed return to coal scenarios with similar integrated modeling efforts. Global energy system reference cases in AR5 and the SSPs follow a tradition that took shape during the 1970s with the IIASA Energy Program which lead to the publication of *Energy in a Finite World* (EFW).

The EFW study used an earlier version of MESSAGE with total geologic assessments that were a precursor to the LBE model [102]. MESSAGE developed two scenarios of global primary energy use: *IIASA-High* and *IIASA-Low* [103]. The High scenario mirrors primary energy use trajectories and narratives of RCP8.5 and SSP5, while the Low scenario is more consistent with the world envisioned by the spectrum between SSP2 and SSP1.

Fig. 6a compares projections of annual TPES, oil, and coal (EJ/year) from IIASA-High (blue) and IIASA-Low (red) against the historical outcome (green). Though the trajectory of IIASA-Low closely anticipated growth in TPES, China's historic early 21st-century expansion in coal production was required to catch up with this outlook. Conversely, while the scenarios produced by MESSAGE in the 1970s overestimated coal use, they underestimated the contribution from oil (Fig. 6a - middle plot). Corresponding liquids production outlooks from EFW anticipated the same result as AR5 scenarios - expanding primary energy supply continued beyond the information horizon for oil, leading to a surge of coal-based liquids that started around the year 2000, reaching 30 mbd in IIASA-High and 10 mbd in IIASA-Low by 2030. Studies undertaken in the

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[19] These inflection points could also indicate points where oil production costs are expected to increase, however these cost profiles are often structured around reserve-resource boundaries which are influenced by their corresponding assessment process [52,72].

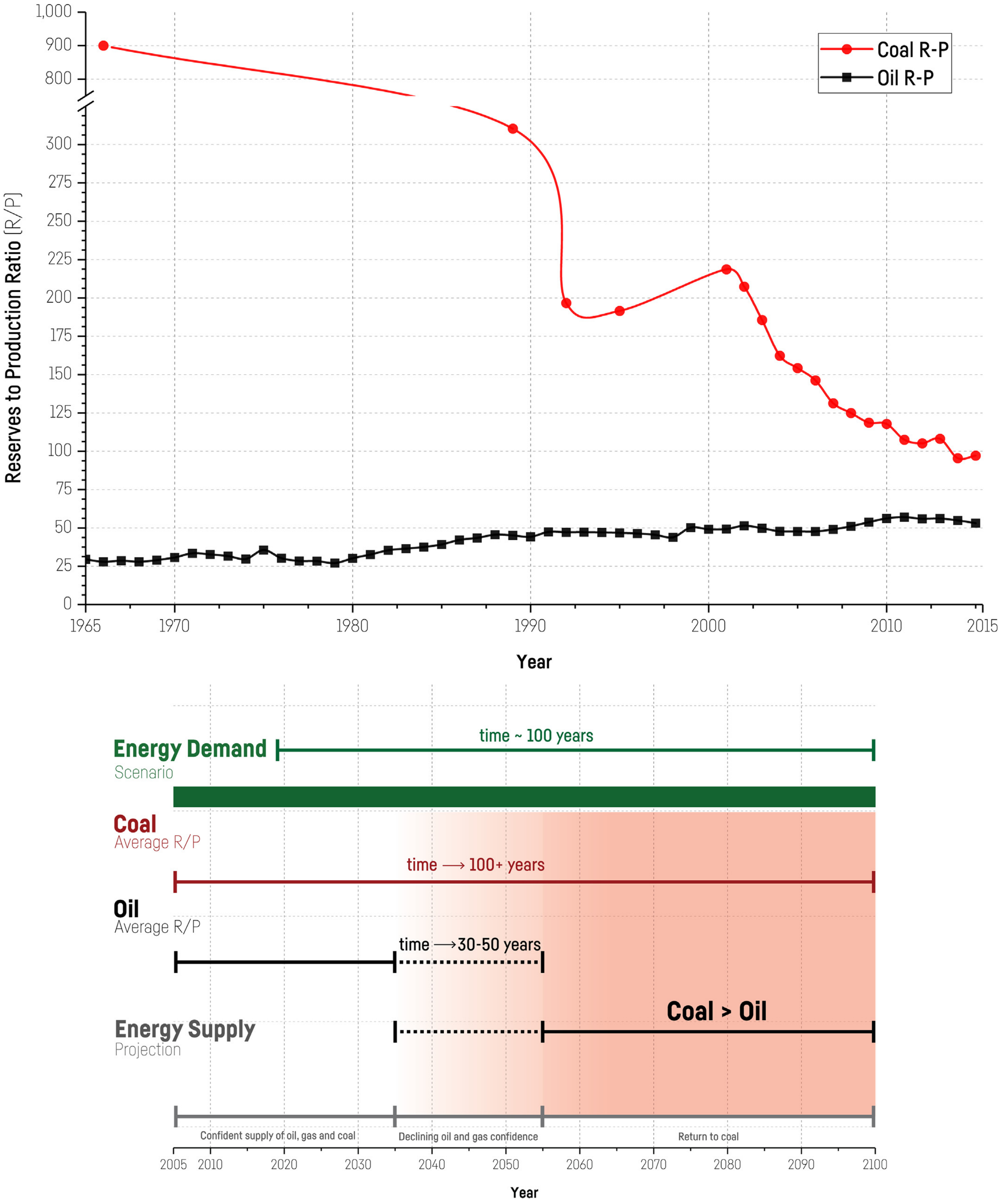

Fig. 5. The horizon of information for global oil and coal resource assessments, implications for coal in AR5 scenarios — a) reserves-to-production (R—P) ratio for oil *(black line)* and coal *(red-line)* from 1965 to 2015 [51,59]; b) horizon of information for 21st-century energy demand projections *(green line)* compared with data vintages of coal *(red line)* and oil *(black line);* c) ratio of coal substitution in AR5 scenarios per year with 80th-percentile *(green line)*, median *(blue line)* and 20th-percentile *(orange line)* highlighted; The right axis indexes this ratio of coal to oil to the year-2016 level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

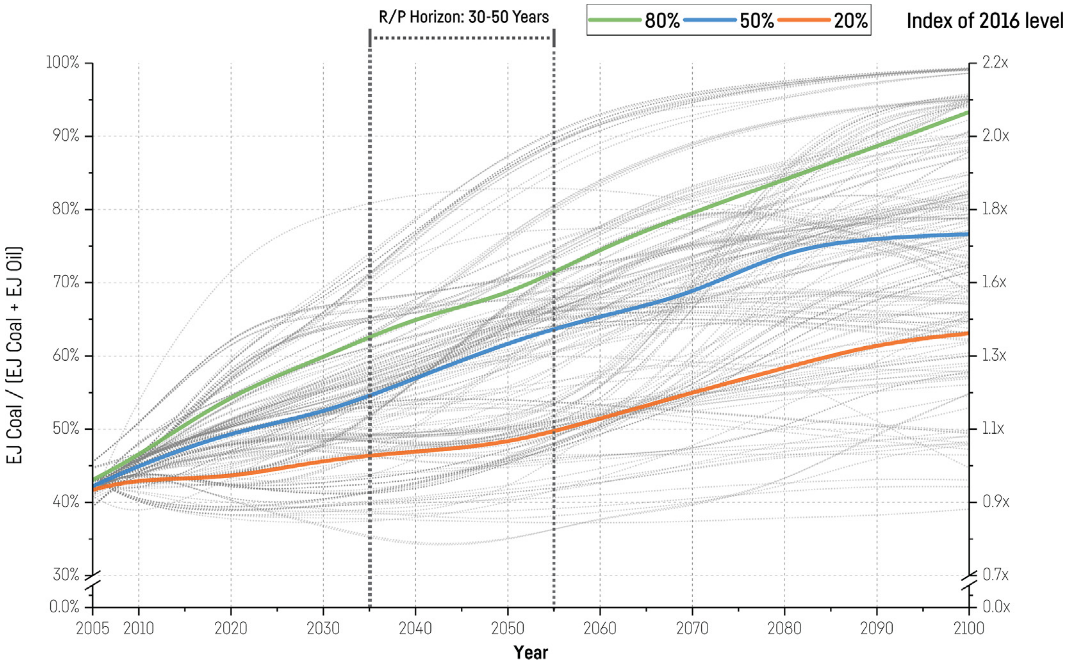

Fig. 5. (*continued*).

United States during this same period provide further illustration.

The 1973 & ’79 oil crises sparked an interest in long-term global perspectives, and many highly-detailed projections of primary energy were developed for the United States in parallel to the EFW study. Fig. 6b–e provides a retrospective on these outlooks for US TPES from a series of integrated models, reports, and agencies [59,104–108].

The Solar Energy in America's Future (SEAF) [107] and Ford Foundation Energy Policy Project (1974) [104] produced uncertainty ranges for future energy use outlined by several scenarios based on (i) reference cases of historical trends (*reference*/*historical growth*), (ii) the implementation of new technologies (*solar emphasis*/*technical fix*) and (iii) low primary energy growth (*low demand*/*zero energy growth*). In Fig. 6b these energy system trajectories (dotted lines) frame estimates for primary energy use at the end of the 20th-century from other reports [105,106,108]. Each study overestimated annual primary energy for the United States, and only the low demand/zero energy growth scenarios came close to providing accurate guidance.[20]

Of relevant note to narrative based energy scenarios, not only were outlooks for the year 2000 quantitatively inaccurate, the storylines associated with each pathway were dramatically inconsistent. Trajectories labeled 'Low Demand' and 'Zero Energy Growth' were closest to anticipating actual 'Business-*as*-Usual' developments - far from the Historical Growth, 'Reference' and 'Technical Fix' scenario descriptions.

Highly detailed fuel mix projections reported by the SEAF and Ford Foundation studies allow comparison of their outlooks for per-capita TPES, oil, and coal (Fig. 6c–e). As with the IIASA EFW study, each model produced scenarios that significantly overestimated coal and primary energy. Notably, the SEAF pathway designed to emphasize diffusion of solar technology overestimated recent per-capita coal use by five times.

The systematic upward bias of the uncertainty range across these studies is attributable to assuming an early end for oil production and consequently a high price that would allow a vast coal backstop to meet the presumed yawning gap in energy demand should economies grow as they had since WWII – by relying on ever greater use of primary energy resources for industrial manufacturing and consumerism. Revisiting these global and national energy projections from earlier iterations of the integrated modeling approaches used today do not provide confidence in scenarios that proscribe future possibilities with the same pattern of high growth in primary energy demand met with an ever-increasing use of coal. Past tests of the return to coal hypothesis have only produced a null result.

5. Summary and conclusion

This paper has described how IAMs produce upwardly biased scenarios of future RF with a return to coal hypothesis - an unlikely reference case for the 21st-century global energy system. Accounting for this bias provides motivation to question why RCP8.5 was chosen as the upper boundary for the SSP-RCP framework. At the time of the original RCP development process, an upper benchmark level of 8.5 W/m^2 was selected based on the high forcing scenarios available in the literature which relied on a return to coal [2,7,15,35,109,110]. Continued use of RCP8.5 without a return to coal *ex-post* would proceed despite this inconsistency with the original logic of the SSP-RCP architecture design.

Though the extensive SSP development process found RCP8.5 may only result under a narrow set of possibilities, namely the rapid return to coal depicted by SSP5, perhaps updated scenarios consistent with this level of RF could draw from accelerated development of unconventional oil and gas. In this context, the high levels of coal use in today's published scenarios may simply

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[20] While this paper emphasizes the uncertainty ranges produced by these scenarios, it is important to further highlight that scenarios in the field of energy research are usually not intended as predictions of the future. These scenarios were produced as 'reflective exercises of the imagination' with internal consistency between the supply and demand side of each equation to outline expected results based on 'more or less plausible assumptions about future events' [105]. The same philosophy applies to Section 2 reference energy scenarios developed by IAMs.

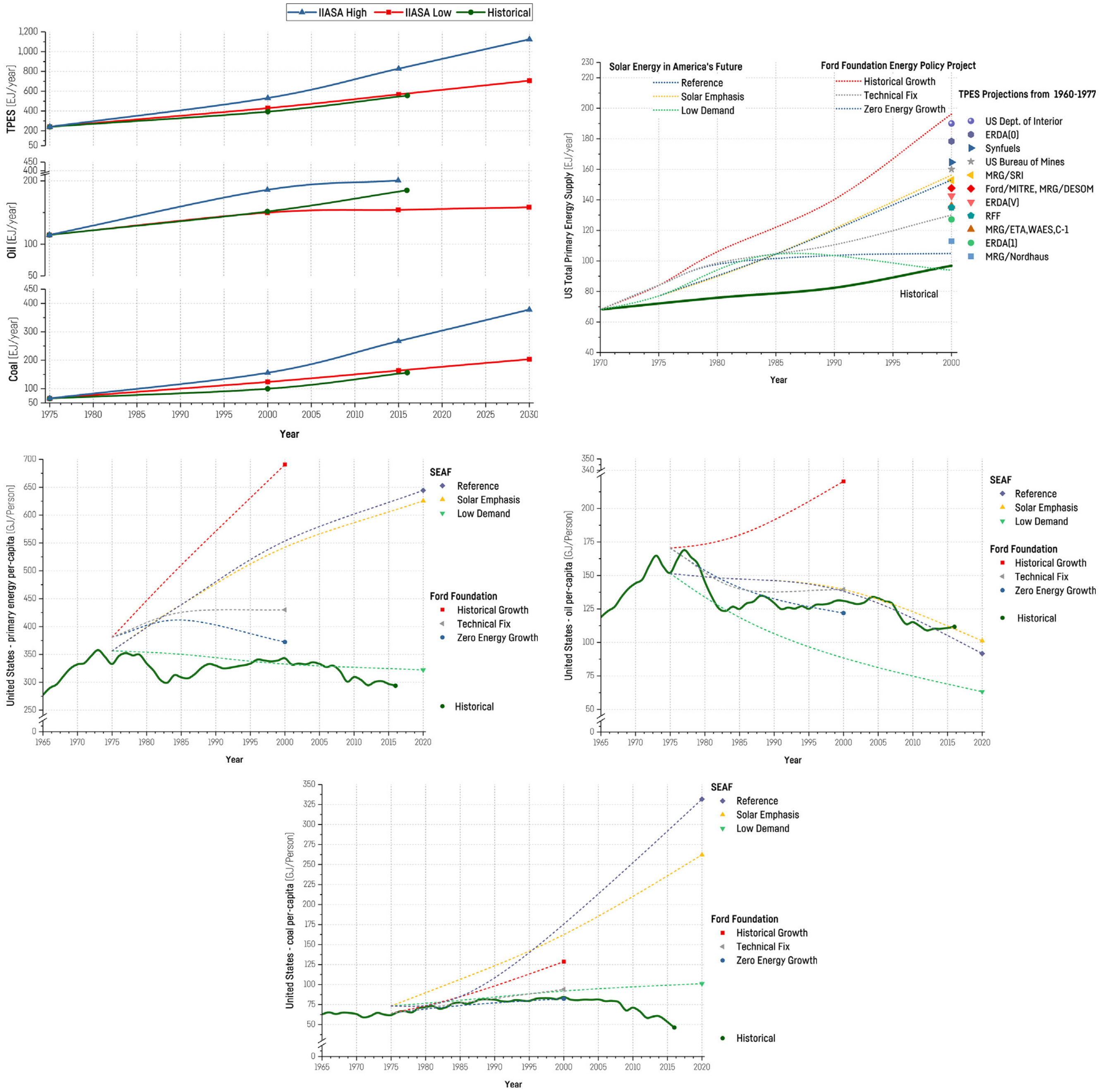

Fig. 6. Multi-decade projections of primary energy from IIASA *Energy in a Finite World* and a range of US energy policy studies — a) time-series multi-plot of TPES, oil and coal developed by MESSAGE for EFW with the IIASA-High scenario *(blue line)*, IIASA-Low *(red line)* and historical trajectory *(green line)*; b) annual US TPES (EJ/yr) from a range of studies through the year 2000 [104–108]; c) scenarios of US primary energy per-capita developed for SEAF and Ford Foundation studies; d) scenarios of US primary energy from oil per-capita developed for SEAF and Ford Foundation studies; e) scenarios of US primary energy from coal per-capita developed for SEAF and Ford Foundation studies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

represent a proxy for faster than expected growth in combustion of other high-carbon resources like oil sands and shales.

Yet, the original RCP8.5 scenario already uses 21 ZJ of unconventional oil and 17 ZJ of unconventional gas production, equivalent to 180 mbd of unconventional oil and gas throughout the 21st-century. It is unclear whether unconventional oil and gas production could plausibly exceed these levels given many recent upper bound estimates [50,76,111,112]. Further, the demand for end-use energy services formerly fulfilled by coal may be moderated by price elasticities that would account for higher primary energy costs without a coal backstop.

Therefore, SSP5-RCP8.5 is an exceptionally unlikely trajectory of climate change based on the four main arguments presented in this paper:

1. IAMs depict future energy scenarios with a return to coal that is a significant discontinuity in historical primary energy development trends (Section 2). This return to coal hypothesis dominates the scenarios of CO_2 forcing used in AR5 and RCP8.5 represents its most extreme implementation.

2. The plausibility of coal production outlooks in IPCC AR5, RCP, and SSP reference cases rely on the LBE theory: an untested and empirically unverified model of technological change in resource extraction technology with normative assumptions for coal (Section 3).
3. The LBE theory is applied to structure resource availability curves for future oil, gas and coal resources with a temporal information asymmetry between the assessment process for each fuel source, creating artificial confidence in a coal backstop (Section 4.1).
4. Projections of high primary energy growth dominated by coal repeat the pattern of scenarios from the 1970s that significantly overestimated coal use through the present (Section 4.2). All previous tests of the return to coal hypothesis have produced a null result.

This evidence indicates RCP8.5 does not provide a physically consistent worst case BAU trajectory that warrants continued emphasis in scientific research. Accordingly, it does not provide a useful benchmark for policy studies [e.g. 113].

Even if there remains sufficient rationale for selective application of RCP8.5 in future research, this work contributes to the body of work which frames it as an exceptionally unlikely scenario [50,89,114]. The RCP8.5-Ext scenario which uses simple rules to extend its forcing components through the year 2300 is equally improbable [115]. The Extended Concentration Pathway 8.5 (ECP8.5) scenario projects total future emissions of 5000 gigatons carbon, equating to the full extent of the original Rogner [52] carbon supply curve – a resource outlook dominated by prognostic and hypothetical coal resources in extreme locations for which the discussions in Sections 2–4 of this paper apply.

Perhaps 8.5 W/m^2 of atmospheric RF could result from factors other than fossil fuel combustion, but should that be the baseline for studies of climate change? Scenarios of extreme outcomes can be useful for assessments of risk, but they are explicitly different from BAU. Extreme futures may be possible, but there is an implicit suggestion of high probability when a scenario is labeled as “baseline”, “business-*as*-usual” or “fossil”, while lower pathways are depicted to result from mitigation steps [7]. Since the RCP scenarios play an important role in constituting the scientific evidence base for future climate change [116], their further development should refrain from needlessly constraining IAM scenarios to achieve high forcing baselines with an unlikely return to coal because of scenario architecture considerations for general circulation and earth system models.

An upper ceiling for plausible 21st-century RF from CO$_2$ and other GHGs can be based on well-articulated evidence for trajectories of future social and technological change, labeled according to likelihood, realization and underlying hypotheses. If research focused on likely energy system pathways may also have the potential to ameliorate concerns about the achievability of ambitious climate mitigation targets, why shouldn't future studies focus on plausible outlooks for BAU?

Acknowledgements

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