Long-run energy resource economics: reconciling uncertain carbon signals for integrated assessments of global environmental change

by

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Abstract

Studies of global environmental change require a long-term perspective that must contend with uncertain future human and Earth system processes. In this context, the scientific community frames possibilities for energy resource use with integrated assessment models (IAMs). IAMs combine various threads of scientific knowledge to allow systematic studies of hypothetical socioeconomic and technological developments.

Engineering-focused IAMs maintain economic concepts of energy use initiated by studies which responded to the 1970s energy crises by anticipating that growing demand for energy could rely on a coal backstop supply. Thus, many scenarios of vast coal combustion were produced to illustrate this outlook, where humanity had no choice but to become “the intelligent mole”. Such coal backstop scenarios played an important role in early climate model development because they provided a strong carbon signal.

Initial economic models of climate policy costs were based on assuming that the high-carbon backstop would always be cheaper than the low-carbon backstop. These ideas anchored expectations for future climate change as the IPCC assessment process was established, and continue to shape the uncertainty range considered by today’s studies.

This thesis examines modeling concepts used to structure uncertain energy resource developments for long-term studies of global environmental change with a special focus on coal. The concept of a vast coal backstop energy supply is evaluated and these findings are applied to develop empirical constraints for an IAM coal supply curve. In the example considered by this thesis, an empirically consistent coal backstop scenario produces climate policy costs for a 1.5°C target equivalent to those for a 2°C goal that must overcome a vast coal backstop supply: the default configuration of many IAMs. An energy system phase space method is developed to map whether these long-run scenarios provide sufficient coverage of future uncertainties. It is found that IAM scenarios are needlessly constrained to produce outlooks for transitions toward a global energy supply with increasing carbon intensity. When these energy system scenarios are combined with socioeconomic projections for global per-capita income convergence, they serve to reproduce a style of reasoning that links aspirational equity goals with worst-case environmental consequences.
Lay Summary

Studies of global environmental change involve processes that require a multi-decade perspective on developments in future society. To frame uncertain future possibilities, the scientific community uses models that combine hypothetical concepts for long-run socioeconomics and energy technologies. These models have their conceptual origin in the aftermath of the 1970s energy crises, where securing oil and gas supplies seemed precarious. At that time, coal was thought to be the most reliable energy source for ever growing demand, and many future scenarios were created to illustrate how coal was the best option to substitute for oil and gas. These outlooks became the template for the worst-case climate change scenarios still used by the scientific community today. This thesis studies the way energy resources are conceptualized for research on climate change, with a focus on calibrating the range of future energy system developments that could result from an updated understanding of coal’s potential role.
Preface

The research program underlying this thesis addresses the context of global change research which extends over the course of many decades. Subsequent chapters contribute concepts to aid in studies of the future global energy system by using methods that can be broadly classified under the field of energy economics and data science.

I am primarily responsible for writing and conducting this work. My PhD supervisor Hadi Dowlatabadi was very helpful in shaping these concepts, verifying my analysis, tolerating my incoherent first drafts and drawing attention to the conceptual shortfalls they contained.


Chapters 2, 4 and 7 are in various stages of reviews and revision.
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x
List of Key Abbreviations

Alphabetical

Proved reserves ................................................................................................................................................ 1P
Proved and possible reserves ................................................................................................................................. 2P
Intergovernmental Panel on Climate Change Fifth Assessment Report ......................................................... AR5
Business-as-usual ......................................................................................................................................... BAU
Billion cubic meters ......................................................................................................................................... bcm
Bundesanstalt für Geowissenschaften und Rohstoffe (German Ministry of Natural Resources) ............ BGR
Barrel of oil equivalent ..................................................................................................................................... boe
Biomass energy carbon capture sequestration ............................................................................................... BECCS
Biomass-to-liquids .......................................................................................................................................... BTL
Compound annual growth rate ....................................................................................................................... CAGR
Capital expenditures .............................................................................................................................................. capex
Carbon capture sequestration .......................................................................................................................... CCS
Coupled model intercomparison project ....................................................................................................... CMIP
Carbon dioxide emissions ................................................................................................................................. CO2
Coal-to-liquids ................................................................................................................................................... CTL
Energy Information Administration ................................................................................................................. EIA
Economies in Transition ................................................................................................................................ EIT
Exajoule ............................................................................................................................................................ EJ
Energy modeling forum ................................................................................................................................... EMF
Earth systems models ....................................................................................................................................... ESMs
Fischer-Tropsch ................................................................................................................................................ FT
Fossil fuels and industry ................................................................................................................................. FF&I
General circulation models ............................................................................................................................. GCMs
Gross domestic product .................................................................................................................................. GDP
Greenhouse gas emissions ................................................................................................................................. GHGs
Gigajoule ............................................................................................................................................................. GJ
Global mean surface temperature increase above pre-industrial levels ....................................................... ΔGMST
Gigatons carbon emissions ............................................................................................................................... GtC
Gas-to-liquids .................................................................................................................................................... GTL
Gigatons of oil equivalent ................................................................................................................................. Gtoe
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<td>Integrated assessment models</td>
<td>IAMs</td>
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<tr>
<td>International Energy Agency</td>
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<td>International Institute for Applied Systems Analysis</td>
<td>IIASA</td>
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<td>Intergovernmental Panel on Climate Change</td>
<td>IPCC</td>
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<tr>
<td>Kilowatt-hours</td>
<td>kWh</td>
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<td>Latin America</td>
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<td>Learning-by-extracting</td>
<td>LBE</td>
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<td>Middle East and Africa</td>
<td>MAF</td>
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<tr>
<td>Millions of barrels per day (of oil)</td>
<td>mbd or mbdoe</td>
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<td>Monte Carlo simulation</td>
<td>MC</td>
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<tr>
<td>Market exchange rates</td>
<td>MER</td>
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<tr>
<td>Million tons of oil equivalent</td>
<td>Mtoe</td>
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<td>NGLs</td>
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<td>Organisation for Economic Co-operation and Development</td>
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<td>Organization of the Petroleum Exporting Countries</td>
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<td>Representative concentration pathways</td>
<td>RCPs</td>
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<td>Reforming economies</td>
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<td>Shared socioeconomic pathways</td>
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<td>Total primary energy supply</td>
<td>TPES</td>
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<td>Underground coal gasification</td>
<td>UCG</td>
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<tr>
<td>United Nations Framework Convention on Climate Change</td>
<td>UNFCCC</td>
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<td>Ultimately recoverable resource</td>
<td>URR</td>
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<td>United States Dollar</td>
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<td>United States Geological Survey</td>
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I thank my parents, Bill and Trish Ritchie for instilling the value of education from an early age, and for their continual encouragement as I’ve pursued that path. My wife Jane has been an incredible partner in this work, and so I dedicate this thesis to her.
For Jane.
Chapter 1: Introduction to studies of energy system uncertainties relevant for global environmental change research

Studies of global environmental change investigate human interactions with the Earth system on time scales of many decades (Camill, 2010; Munn, 2002; Schellnhuber et al., 1997). This context extends beyond the frontiers of today’s knowledge, calling for a consideration of possible developments in future society and technology.

Such a long-range approach inherently enters domains of deep uncertainty, defined by Lempert et al. (2003) as situations where scientists, analysts, and decision-makers do not know or cannot agree on: (i) the appropriate conceptual and mathematical models for understanding dynamics of the major driving forces that will shape the future, (ii) the probability distributions of key variables or parameters, or (iii) the way to value desirability of alternative outcomes.

These three characteristics aptly describe research on the economics of energy resources in the long-run. Processes of fossil resource extraction and combustion are recognized as a key driver of global environmental change (Alcamo et al., 1996; Dincer, 1999; Grubler, 2012; IPCC, 2014; Quéré et al., 2016; Vitousek et al., 1997). Therefore, it is important to understand possibilities for energy demand and supply given hypotheses of future development.

The field of global change research frames uncertainties relevant for the future global energy system by drawing from a tradition of integrated assessment models (IAMs). Accordingly, these models and the theories they apply to structure their economic understanding of energy resources are naturally a key focus of this thesis. Therefore, the following chapters examine energy-economy modeling within the world of IAMs.

1.1 How to study energy-economy models? A world in the model that can be examined in stages

This study draws motivation and inspiration from work on economic and energy models conducted by Mary Morgan (2012) and Martin Greenberger (1983).

Through providing quantitative frameworks that mediate both social and physical processes, IAMs are distinct from the models developed by economists. Yet, they are used in analogous ways to the autonomous epistemic genre of economic modelling investigated by Morgan (2012). Morgan’s work eloquently describes how economists craft their models as research tools to study the context of the world, but also as a means of enquiring into a world within the model. IAMs find equivalent treatment in global environmental change research by making disciplinary intuitions explicit. Therefore, any study of IAMs can draw insights from Morgan’s approach to economists and their use of models.

Further to the specific context of energy-economy modeling, Greenberger (1983) studies the research program that arose from combined efforts of engineers and economists during the 1970s.

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1 This thesis does not provide a detailed comparison of economic models and the economic world of IAMs. Though IAMs intend to capture world dynamics, so they include at least a stylized representation of some economic theory at a global scale. Some IAMs are certainly economic models, such as the Nordhaus DICE model (Nordhaus, 1992; 1977; Nordhaus and Sztorc, 2013). Many IAMs simply have exogenous GDP growth that calibrates energy demand based on economic theories of productivity and production functions, elasticities of substitution, learning-by-doing, and equilibrium solutions (partial or general).
In doing so, he identifies three distinct phases of formal modelling efforts that provide a useful structure for positioning ideas analyzed and developed in the following thesis:

I. **Ideation:** The initial *ideation* phase is primarily informal, where ideas are generated to structure and define the focus of resulting work. Ideation proceeds with exploratory efforts, shaping ideas, establishing a hierarchy for proposing questions and outlining terms of reference. For Greenberger, ideation is the critical phase of modelling: an art shaped by wisdom, oriented by an intention to be, "approximately right, rather than precisely wrong." It is important to note that disciplinary intuition plays a major role in the ideation phase.

II. **Classification:** The second phase of *classification*, establishes an accounting scheme, allowing formal models to describe the relationships at hand. This specification allows for precise numerical work, and an, "effective quantitative structure for exercising judgment and setting priorities."

III. **Codification:** The final phase of *codification* forms explicit rules for interactions between system elements. These rules record hypothesized relationships between variables and parameters, maintaining internal consistency between assumptions, data, and results. Greenberger sees codification as the stage which facilitates communication beyond the horizon of the modeler's cognition and intuition.

This introductory chapter proceeds by recounting the prevailing theories applied to structure uncertainty in studies of global environmental change. Then, we proceed by briefly understanding the history and context of the energy-economy models applied to this task.

1.2 Structuring deep uncertainty in future energy scenarios: two theories

Outlooks for the global energy future are influenced by two contemporary schools of thought on how to address deep uncertainty in scenarios of global environmental change: (i) an approach using alternative storylines (de Vries, 2006; Robinson, 1990; 1982; Schwartz, 1991; Vergragt and Quist, 2011), and (ii) a focus on fully probabilistic scenarios (Casman et al., 1999; Dowlatabadi, 2002; Dowlatbadi and G. Morgan, 1993; Sokolov et al., 2009; Webster et al., 2003).

1.2.1 Alternative scenario method: uncertainties structured by storyline narratives

The alternative scenario method acknowledges that possible future developments can result from a wide range of unknown and unknowable outcomes (Grübler and Nakićenović, 2001). In this sense, assigning subjective distributions using probability concepts drawn from natural sciences is interpreted as a distortion on further analysis.

This view is based on an understanding that verification of any distribution would require repeated experiments and measured outcomes that are impossible in the context of long-range future social development. van Vuuren et al. (2008) point out that energy models may only address a limited scope of complex relationships, so adopting a narrative approach can provide consistency for the aspects that cannot be captured within the world of the model.

Davidson (1991) outlines an economic perspective for this theory building from the understanding Keynes (1937; 1921) applies to the situations where probability distributions are not helpful in understanding real world uncertainty. For Davidson there are three distinct environments for decision-making under uncertainty: (i) the *objective probability environment* where the past is
considered a statistically reliable guide to the future; (ii) the subjective probability environment in which prospects for future outcomes can be weighted at the moment of choice; and (iii) a true uncertainty environment that exists when a decision-maker believes unforeseeable changes will occur between choices made today and future outcomes, even if there is significant evidence to support the existence of objective frequencies and/or subjective probabilities.

True uncertainty in the Keynesian sense is often referred to as irreducible uncertainty (O'Donnell, 2013; 1989), or as Knightian uncertainty in reference to the distinction made by Knight (1921):

But Uncertainty must be taken in a sense radically distinct from the familiar notion of Risk, from which it has never been properly separated. The term "risk," as loosely used in everyday speech and in economic discussion, really covers two things which, functionally at least, in their causal relations to the phenomena of economic organization, are categorically different... The essential fact is that "risk" means in some cases a quantity susceptible of measurement, while at other times it is something distinctly not of this character; and there are far-reaching and crucial differences in the bearings of the phenomenon depending on which of the two is really present and operating. There are other ambiguities in the term "risk" as well, which will be pointed out; but this is the most important. It will appear that a measurable uncertainty, or "risk" proper, as we shall use the term, is so far different from an immeasurable one that it is not in effect an uncertainty at all. We shall accordingly restrict the term "uncertainty" to cases of the non-quantitative type. It is this "true" uncertainty, and not risk... which forms the basis of a valid theory of profit accounts for the divergence between actual and theoretical competition. (p.20)

Davidson (1996) further argues that economic modeling based on equilibrium microfoundations often proceeds by assuming or implying an ergodic reality - one that consists of essentially predetermined and immutable outcomes that result from hypothetical centers of gravity that stem from tendencies like 'equilibrium'. Thus, he concludes that sampling from past data to understand true uncertainty in economic futures is equivalent to an implausible "sampling from the future". Davidson contrasts this view with a nonergodic interpretation of the future economy, where decision makers recognize that they are dealing in-part with an uncertain but creative reality that may not occupy positions consistent with past states.

Grubler and Nakicenovic (2001) employ a similar 'creative reality' concept by arguing that since each future outcome is path-dependent due to a number of conditional 'what-if, then' assumptions, narratives are the way to determine an internally consistent structure for uncertainty. Schweizer and Kriegler (2012) describe internal consistency as a, “scenario’s ability to represent dynamics consistent with current knowledge regarding plausible trends.” In this sense, formulating long-run scenarios by starting with narratives aims to avoid arbitrary and implausible combinations of social conditions, such as prospective societies where 'high infant mortality' leads to 'low fertility rates' (Grübler and Nakicenović, 2001) or 'high levels of wealth' occurs alongside 'low educational attainment' (Schweizer and Kriegler, 2012). Such an uncertainty range of outcomes produced by storylines allow stylized facts to structure the relationships and underlying logic among variables for further quantitative exploration (van Vuuren et al., 2008).
1.2.2 Fully probabilistic scenarios: projecting energy system futures from distributions

The probabilistic approach to long-run global change understands inputs as distributions of possibilities. This partitions resulting scenarios into probabilistic intervals which denote median expected results and extreme outliers (Capellán-Pérez et al., 2016; Dowlatabadi and G. Morgan, 1993; Keppo et al., 2007; Schneider and Mastrandrea, 2005; Sokolov et al., 2009; Webster et al., 2003).

Schneider (2002; 2001) argues that subjectivity is fundamentally inherent in all future projections, regardless of discipline or research program, and so it should be addressed explicitly and with quantitative rigor. Probabilistic studies of the global energy system are important to Schneider because relevant uncertainties feed into other downstream aspects of global environmental change research, driving an ever-larger cascading range of uncertain impacts that complicate risk assessments.

This perspective from Schneider (2002) is illustrated in Figure 1.1 for uncertainties relevant to studies of climate change, segmented by each stage of the research process. Though the public and decision makers may be most interested in stage VI, the range of possible impacts are contingent on uncertainties within each individual stage from I-V. Any uncertainties in the initial input conditions (Stage I) become amplified throughout this chain. Thus, a comprehensive mapping of uncertainties relevant for the initial stages is viewed as an important undertaking.

Without any attempt at subjective probability assessments, Schneider (2001) argues there is a 'probability vacuum' which leads to arbitrary interpretations. Even if such use is unintended, some outcomes are perceived as implicitly more likely than others. Lempert et al. (2006) extend this argument, proposing that understanding this sequence of interdependent uncertainties with equally likely storylines compromises decision-making. In the view of these authors, developing scenarios of future outcomes with quantitative probabilities will aid in determining priorities for future investments since resources are not unlimited.

Gillingham et al. (2015) understand subjective probabilities as 'degrees of belief' regarding future uncertainties. This follows from Ramsey (1926) which recognized that while it is impossible to obtain objective measurements of psychological variables there is still an important distinction to be made:

I do not see how we can sharply divide beliefs into those which have a position in the numerical scale and those which have not. But I think beliefs do differ in measurability in the following two ways. First, some beliefs can be measured more accurately than others; and, secondly, the measurement of beliefs is almost certainly an ambiguous process leading to a variable answer depending on how exactly the measurement is conducted.

This interpretation of subjective probability is employed by Gillingham et al. (2015) as, "the odds informed scientists would take when wagering on the outcome of an uncertain event," where, "the 'wager' is understood to bound the calculation of probability."
Morgan and Henrion (1990) offer three arguments in support of explicitly representing uncertainty in studies relevant to global change because: (1) it aids in identifying the most or least important factors, the source of disagreement, and in anticipating the unexpected; (2) it clarifies the opinion of experts about how much they think they know and whether they disagree; (3) when the uncertainties of the past have been carefully articulated we can improve confidence in appropriate use of earlier work.

Though Morgan and Henrion provide these arguments in the context of policy analysis and decision making, their perspectives also apply to research in the physical and social sciences: why should any global change researcher focus significant research time on future outcomes beyond the range of possibilities?

**1.2.3 Structuring uncertainty in global change research: juxtaposing these two theoretical approaches**

An ongoing debate has addressed the meaning and adequacy of uncertainty in each of these contrasting theories, framing their ability to serve robustly guide broader scientific research on what to expect from the global energy future (Allen et al., 2001; Cooke, 2013; Dessai and Hulme, 2004; Grübler and Nakićenović, 2001; Grübler et al., 2006; Kandlikar et al., 2005; G. Morgan and Keith, 2008; Parson, 2008; Parson et al., 2007; Patt and Dessai, 2005; Pittock et al., 2001; Reilly, 2001; Trutnevyte et al., 2016; Webster et al., 2002).

van Vuuren et al. (2008) position these two traditions by relating them to disciplinary approaches in the ideation phase of study. These authors argue the fully probabilistic approach can represent a ‘positivist control systems engineering’ paradigm (where the system is well-known enough to make meaningful estimates of probabilities). The alternative storyline framework for future scenarios is
understood as within the ‘constructivist social science tradition’ (where alternative visions are created without assigning likelihood) (de Vries, 2006; Dreborg, 1996; Robinson, 2003; 1990; 1982).

Narratives and quantitative probabilities are seen complimentary efforts by van Vuuren et al. (2008) because they can address multiple dimensions of uncertainty in long-term studies which include: ontic uncertainty (natural randomness), epistemic uncertainty (incomplete knowledge), disagreement among experts (pluralism or disciplinary), and human reflexivity (unknowns in response to change).

Dessai and Hulme (2004) interpret this bifurcation as representing biophysical and social approaches to risk. They highlight that studies of biophysical impacts tend to be more comfortable with probabilistic studies and often use a long-term perspective to examine physical changes to ecosystems and geologic features. Social approaches are more focused on the shorter-term horizon and the human element of change, which is much harder to anticipate and thus tend to resist rigid probabilistic uncertainty analysis.

Walker et al. (2003a) synthesize both definitions, characterizing uncertainty as, “any departure from the unachievable ideal of completely deterministic knowledge.” This is a broader definition of uncertainty than one focused on situations defined by inadequate information because it recognizes that phenomena under study may be non-deterministic.

Several studies have developed conditional probability estimates of population and other factors of global change scenarios by embedding probability distribution functions (PDFs) within narrative storylines (O’Neill, 2005; 2004; van Vuuren et al., 2008). However, the broader research community has tended to follow from the philosophical position outlined by Grübler et al. (2006) which argues there are simply too many uncertainties relevant to important questions for global change research without narratives. Thus, storylines are developed that provide a structure which captures, “how future societies will operate, how fast the population will grow, and how technological progress will change things.” In this view, simply focusing a few ‘best guess’ scenarios ignores the important lessons of history regarding technological change, i.e. simply relying on subjective probability assessments of experts from the past would mean nuclear power is still expected to be too cheap to meter. Therefore, equally probable storylines have provided the most widely applied method for addressing uncertainty in global change research.

Two prominent examples of energy scenarios developed with this approach include the storyline based IPCC Special Report on Emission Scenarios (SRES) (Nakicenovic et al., 2000) and Shared Socioeconomic Pathways (van Vuuren et al., 2017). Much of the dialogue between the two schools of uncertainty took place in response to the SRES (Grübler and Nakićenović, 2001; Schneider, 2001).

Parson et al. (2007) address the controversy that arose from the six SRES storyline scenarios when the narrative developers argued that all storylines of future global change were ‘equally sound’. The rationale for treating each storyline scenario as equally likely stems from arguments that: (i) the multivariate possibilities which vaguely define boundaries of the outcome space leave no coherent way to distinguish whether a probability is attributed to the interval between scenarios or if it addresses the probabilities within a scenario, (ii) quantitative probabilities may induce reflexivity that influences the behaviors driving the scenarios, so that the storylines become ‘self-fulfilling’ or ‘self-
(iii) it is not the role of scenario developers to make judgements of likelihood but the users, especially when scenarios are used to inform high-stakes decisions and (iv) that the joint distributions of underlying drivers are simply too complex on the global scale to convey meaningful information in a way that isn’t ‘spurious’ or ‘arbitrary’. Parson et al. further note that while the SRES scenarios began their life as ‘equally likely’ storylines, they finished their use more like probabilistic scenarios, as many quantitative likelihood assessments followed in their wake.

The more recent Shared Socioeconomic Pathways (SSPs) eschew any focus on assessing the likelihood of storylines, drawing mainly from the arguments used to support the initial release of the SRES. A common concern is that focusing on a few ‘spuriously’ selected ‘most likely’ scenarios could lead to disregard for low-probability high-impact scenarios, which may be the most relevant for approaches to risk management (Riahi et al., 2017; Rozenberg et al., 2014). For studies of climate change policies, inclusion of low probability scenarios is considered essential (Rozenberg et al., 2014; Wagner and Weitzman, 2015).

Both the SRES and SSPs structure uncertainty with narrative-based approaches, and expand these concepts using extensive quantitative modeling efforts. These narrative and quantitative methods play a major role in constructing long-run scenarios of the global energy system. However, questions of uncertainty in global change take on additional dimensions within the world of a quantitative model.

1.2.4 Uncertainty in global change codified by the world of the model

Models abstract from the world to give ideas an explicit form, allowing further inquiry to proceed within a structure and style for reasoning (M. S. Morgan, 2012). A model can be conceptual (a line and box diagram) or a mathematical formulation, structured by equations and coded into a computer (Walker et al., 2003).

Modelling is said to become 'formalized' as it moves from vague ideas about the world toward more explicit and exact rule bound interactions between system components (M. S. Morgan, 2012). Moving from the ideation phase of a formal modeling effort, into stages of classification and codification, introduces additional dimensions of uncertainty.

Explicit to the context of global change modelling, van Vuuren et al. (2008) identify uncertainties in three forms: (a) conceptual theories, (b) structures, and (c) parameterizations. These three issues are analogous to each stage of the model development process identified by Greenberger (1983) for uncertainty in stages of ideation, classification and codification.

Walker et al. (2003) provide a parallel logic, defining a three-dimensional taxonomy for uncertainty in a model based on axes of:

- **Location**: Location refers to the position of uncertainty within a modeling exercise. This refers to uncertainty in model (i) boundaries, (ii) structural components, (iii) technical implementation, (iv) inputs (v) parameters and (vi) outcomes (prediction error).
- **Level**: This dimension of uncertainty captures the spectrum between knowledge and ignorance, i.e. the difference between myopia and perfect foresight. This is the dimension of uncertainty addressed by work that follows from Knight (1921) and Keynes (1921).
• **Nature:** The *nature* of uncertainty distinguishes between epistemic and natural variability. Walker et al. (2003) highlight that natural variability can result from the inherent randomness of nature, human behavior (micro-scale), society (macro scale), and technological change (new developments, breakthroughs or side-effects) – e.g. ‘ontic uncertainty’ as termed by van Vuuren et al.

**Chapter 2** of this thesis focuses on a single key parameter used by IAMs to represent the global energy future, so it is useful to address parametric uncertainty with more detail in this section. Parameters define constant relationships within a model. They are contingent on the chosen context and scenario (Walker et al., 2003). Parameters can be exact (universal constants), fixed (well defined by previous investigations), *a priori* (difficult to identify and are chosen to be invariant based on experience), and calibrated (unknown values determined by comparison of model outcomes for historical data series). Uncertainty in *a priori* and calibrated parameters can be difficult to constrain, e.g. know the plausible scope, such as upper or lower boundaries of their possible values.

Large ensembles of global change models are applied to address uncertainty in outcomes through multi-model comparisons (e.g. Clarke et al., 2014; O’Neill et al., 2016a). Studies on the macroeconomics of the long-run global energy system are commonly conducted through multi-model comparisons of IAMs (Kriegler et al., 2014a). These intercomparison exercises intend to provide uncertainty ranges for outcomes by running similar scenarios across a range of different models, producing an ensemble based on measuring *model uncertainty*. This is equivalent to asking the same question to a range of different oracles, with their responses forming the range of expected outcomes.

With the theories applied to structure uncertainty in global change research defined and structured, we can now focus on the specific context of IAMs.

### 1.3 Quantitative studies of global change: integrated assessment models

Today’s IAMs build from a discipline of global systems modelling efforts that started in 1960s, following from the World 3 model used by the 1972 *Limits to Growth* (LTG) study (de Vries, 2006; Forrester, 1971; 1969; Martens and Rotmans, 1999; Donella Meadows et al., 1972; 1982). The World 3 model faced criticisms that it did not sufficiently address regional dynamics, the process of resource discovery, behaviors in response to price (substitution, elasticities) or technological change (Donella H Meadows and Dennis Meadows, 2007; Nordhaus, 1973; Nørgaard et al., 2010; Vieille Blanchard, 2010). Further critiques focused on data calibration and whether the trajectory of human society presented in the LTG study was overly constrained by poor modelling choices (Cole, 1973).

This discourse inspired economists, engineers, physicists, geologists, mathematicians, psychologists and other disciplines to seek an integrated approach toward a new suite of global change models (Costanza et al., 2006; de Vries, 2006). The International Institute for Applied Systems Analysis (IIASA) served as a nexus for many these initial steps toward a discipline of integrated assessment modelling of the world system (Häfele, 1976; Häfele and Buerk, 1976; Häfele et al., 1974; Donella Meadows et al., 1982).
1.3.1 The IIASA Approach establishes foundations for the discipline of world energy modelling

IIASA was founded in late 1972 by the Soviet Union, the United States, and ten other countries to cultivate scientific research on global challenges across the divide of the Cold War. Against the backdrop of energy challenges during the 1970s, namely the 1973 OPEC oil embargo, world modelling of energy systems became an important research thrust for IIASA. The First IIASA Energy Program (1973-1979) aimed to study possible developments in global long-range energy systems through the year 2030.

The IIASA Approach to integrated global energy modelling combined a set of models to examine energy use and supply in seven world regions. Population and economic growth were specified exogenously for the MEDEE model of final energy demand, after which the MESSAGE supply model determined the optimal supply-cost combination of environmental, technological and resource constraints. The IMPACT model evaluated economic impacts of the MESSAGE supply strategies, and the MACRO model illustrated consequent investment and consumption. Each region was evaluated iteratively until an internally consistent set of results emerged to produce two scenarios of global energy use from 1975 to 2030: IIASA-High and IIASA-Low (Figure 1.2).

Results from the IIASA energy models led to the publication of the IIASA Energy in a Finite World (EFW) study (Häfele, 1981; 1980a; 1980b; Häfele et al., 1981). Work conducted at IIASA in preparation for EFW convened scientists from around the world, helping to establish important conventions in integrated modelling of long-range developments in world energy economics. These efforts motivated the next generation of energy studies conducted with integrated models of the global economy (Edmonds and Reilly, 1985; Nordhaus, 1979).

![Figure 1.2 IIASA Energy in a Finite World – two global energy supply scenarios and historical](image)

**Figure 1.2** IIASA Energy in a Finite World – two global energy supply scenarios and historical – the MESSAGE energy model led to the (a) IIASA-low and (b) IIASA-high scenarios, compared to (c) historical developments in global primary energy from BP (2017); historical data 2016-2030 trend based on extrapolated decadal growth rate per source; oil (red), gas (blue), coal (yellow), nuclear (green), hydro (purple), solar (grey), other (pink)

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2 There is a parallel strand of national and regional energy-economy modelling with roots in the World 3 and IIASA approach (Greenberger, 1983; Donella Meadows et al., 1982), however this section is focused on global energy models and so these are left unaddressed. Chapter 5 of this thesis touches on some examples from the United States.
1.3.2 World energy models focus on climate change: integrated assessment models grow in scope and scale

Analogous approaches to energy modelling formed the basis for a new class of IAMs focused on global climate change (Dowlatabadi, 1995; Edmonds and Reilly, 1983a; 1983b; Lashof and Tirpak, 1990; Mintzer, 1987; Nordhaus, 1993; 1992; Rotmans, 1990). Early methods of integrating climate change simply extended the energy models of the 1970s and 1980s with fuel-specific emission coefficients to produce scenarios of greenhouse gas (GHG) emissions from energy system projections (Häfele, 1980b).

IAMs study climate change by linking developments in macroeconomics, the global energy system, demographics, land-use and their influence on the climate. Integrating so many complex factors leads IAMs to include reduced form representations of each underlying system as a way to maintain numerical tractability (Casan et al., 1999; Parson and Fisher-Vanden, 1997; van Vuuren et al., 2009). IAMs inform assessments of economics and policy relevant for climate change research by connecting socioeconomic and energy system projections with simple climate models that emulate the physical system response of full climate models (Clarke et al., 2014; van Vuuren et al., 2009).

More detailed studies of physical climate processes use general circulation models (GCMs) and earth system models (ESMs). GCMs divide the atmosphere into vertical layers of grid-cells coupled with ocean layers, allowing for calculations of the mass-energy balance within this hierarchy of tiers (Flato et al., 2013; IPCC, 2013; Wilby and Wigley, 2016). ESMs add further comprehensive detail by providing explicit representations of atmospheric exchange with the global carbon cycle, including ocean and plant ecology, land use and biogeochemistry (Heavens et al., 2013). Studies conducted with GCMs and ESMs draw from IAMs for relevant detail on their input scenarios of future GHG emissions (Nakicenovic et al., 2000; O’Neill et al., 2016b; van Vuuren et al., 2011).

Throughout the 1990s a growing number of IAMs were developed to address the challenge of climate change (Dowlatabadi and G. Morgan, 1993; Edmonds et al., 1997; Hope et al., 1993; Janssen, 1998; Martens and Rotmans, 1999; Nordhaus 1993, Rotmans and Dowlatabadi, 1998; Schneider, 1997; Tol, 1995; 1997). Surveying this generation of IAMs Weyant et al. (1996) describe two types of IA model: (i) policy optimization models that produce projections of climate change in the context of optimal policy for emission control rates or carbon taxes based on goals that could include maximizing welfare or minimizing costs and (ii) policy evaluation models which assess environmental, economic and social consequences of specific policies, or inform strategies on how to achieve them.

Rotmans and van Asselt (1999) and Dowlatabadi and Rotmans (1998) classify IAMs along a spectrum of: (i) macroeconomic oriented models – simple parameterized decision-analytic formulations of complex problems, and (ii) biosphere-oriented models – process-oriented descriptions of complex problems with a responsive environment.

The macro and microeconomic world in many IAMs draw from a neo-classical ideation (Rotmans and van Asselt, 1999; Weintraub, 2005) which informs a partial or general equilibrium structure (classification) with conventional approaches to optimization for utility, capital accumulation, savings, investment, productivity and economic growth (Manne et al., 1995; Nordhaus, 1992). Major engineering-economic IAMs include the Global Change Assessment Model (GCAM) (Edmonds et
al., 1997), the MIT Integrated Global Systems Model (IGSM) (Prinn et al., 1999), the IIASA MESSAGE (Messner and Schrattenholzer, 2000) and the Asia-Pacific Integrated Modeling (AIM) group (Fujimori et al., 2012). These employ neoclassical concepts in a more general way, and are less identifiable as pure economic models, representing hybrids of various degrees between the macroeconomic and biosphere oriented IAM approaches.

The diversity of IAMs available to the global environmental change research community has grown in recent years. Many of these are either direct or tangential descendants of the models developed during the 1990s. Twenty-nine IAMs took part in the scenario intercomparison exercises which provided data to the Intergovernmental Panel on Climate Change (IPCC) Working Group III (WGIII) database (IPCC WGIII, 2014). These included the Energy Modelling Forum (EMF) 27 study which included 18 energy-economy IAMs originating from the European Union (IMAGE, MESSAGE, POLES, REMIND, WITCH), the United States (GCAM, MERGE, FARM, Phoenix), Canada (EC-IAM, TIAM-WORLD), Japan (AIM, BET, DNE, GRAPE), India (GCAM-IIM) and the OECD (ENV-Linkages) (Kriegler et al., 2014b).

IAMs are developed with distinctly heterogeneous approaches and adapted for studies of various scopes and scale. Therefore, it is important to draw clear boundaries for analysis and to avoid lumping all models together. Accordingly, this thesis focuses on evaluating concepts used in the engineering-economy models traditionally applied to develop outlooks for energy macroeconomics in Energy Modelling Forum (EMF) studies and for Intergovernmental Panel on Climate Change (IPCC) assessments (Blanford et al., 2014; Clarke et al., 2009; Krey et al., 2014; Kriegler et al., 2014a).

1.3.3 Understanding the meaning of the world in the model: evaluating the performance of IAMs and large global models more generally

Today’s global energy-economy modeling efforts benefit from much greater overall technical and conceptual sophistication than the world models developed during the 1970s. However, processes of global change are complex and human knowledge is inherently limited. Even if we could fully capture and understand the world as it is today with perfect information, such a snapshot would be bounded by time and human comprehension. Though separate modeling sciences have distinct approaches, the process of modelling leads to endemic challenges in assessing the meaning of the world in the model, and how its epistemological resonance can be interpreted.

Simon (1996) suggests many complex structures are redundant, so we can use this repetition to simplify our description of planetary phenomena. This process of simplification in the development of models sharpens their focus during the ideation phase of development. However, ideation necessarily leads to subjective assumptions regarding structure and interactions between system components.

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3 If we imagine a complete implementation of a big data fantasy, wide-scale diffusion of quantum computing with server farms would capture and process data while 8 billion distinct agents represent human behavior analyzed by an artificial intelligence. Such a research program would still be dominated by uncertainties that result from theoretical interpretation of data over long time-frames, and unknown environmental responses in an open system and the depth of the human psyche. Reducing these uncertainties would therefore proceed in the form of making the human world more like the model, rather than vice versa.
Macroeconomist Robert Lucas describes this process of ideation in Spencer and Macpherson (2014) as one of enabling focus on the inquiry at hand:

The construction of theoretical models is our way to bring order to the way we think about the world, but the process necessarily involves ignoring some evidence or alternative theories – setting them aside. That can be hard to do – facts are facts – and sometimes my unconscious mind carries out the abstraction for me: I simply fail to see some of the data or some alternative theory. This failing can be costly and embarrassing… but I don’t think it has any effect on the advance of knowledge. Others will see the blind spot… keep what is good, and correct what is not.

In other words, modelling sciences proceed by requesting simplified abstract representations of the world, which require subjective evaluations to determine where phenomena are condensed or expounded.

IAMs intend to capture a far grander scope than macroeconomic modelling. And with this challenge, there arises the question of how to evaluate and interpret theories, concepts, parameters, variables and their technical implementation in IAMs given 'what gets left out' and 'what gets put in' (Risbey et al., 1996).

1.3.3.1 Framing archetypes of model evaluation

Computer-based mathematical models have long been influenced by Newtonian concepts of mechanistic, deterministic, reductionist and equilibrium-based explanations of the world (Mirowski, 2002; 1989) After World War II, conventional economic concepts fused with this modeling paradigm during a period of stable growth, favorable demographics for a consumer economy, and technical engineering successes at ever larger scales (Erickson et al., 2013; Janssen, 2002; M. S. Morgan, 2012).

The archetype for evaluating models consistent with this philosophy draws from creating simulations of reality that cannot be rejected (Janssen, 2002). Therefore, a 'successful' model represents a physical (or human) process that leads to some form of accurate predictive power, validated by the ex post testing and observation of its subcomponents. For example, validation of an econometric time-series model can proceed by looking for similar autocorrelation functions and residuals that are random or 'close to zero' (Chatfield, 2005; Hamilton, 1994; Pindyck and Rubinfield, 1991), even if many parameters have no clear physical representation. In early econometrics, data could be rejected but not theory: if results were suspect, it was interpreted as a problem in the data because the theory could not be wrong (M. S. Morgan, 1990).

However studies of global environmental change involve non-equilibrium states of ecosystems and biological processes, and so many traditional disciplinary model validation techniques do not apply to such a context (Janssen, 2002; Risbey et al., 1996). Models developed within this archetype must face a system structure that is constantly evolving and adapting to change. Accordingly, Oreskes (1998; 1994) argues that verification and validation of mathematical models of natural systems is impossible because, "natural systems are never closed and model results are always non-unique."

In the view of Oreskes, models of earth systems can be evaluated for relative performance but that validation cannot proceed in absolute terms. Her perspective is that models can corroborate
hypotheses, or elucidate discrepancies in other models, but that their most important contribution is heuristic - as a guide for areas of further study. This is comparable to a work of fiction that tells a story which is a combination of objective, subjective and imaginative experience. She sees models as useful when they challenge existing formulations, rather than as tools verify or validate.

1.3.3.2 Subjective evaluation and testing of hypotheses in global change modelling

Reflecting on the first major decade of global change modelling, Meadows, Richardson and Bruckmann (1982) recount a survey of large-scale multi-decade modeling teams conducted before the Sixth IIASA Symposium on Global Modelling, conveying insights on how the issue of evaluation is approached. Meadows responds about her own experience developing the LTG model stating that the, "purpose of a model is not to dictate the truth, but to put forward a hypothesis for discussion and for attempts at disproof." In her view, the purpose of modeling is to simplify the system until it can be understood. She sees validation as a subjective concept and that it is, "best to admit that validity is a purely subjective concept and that each modelling school has its own unique approach to establishing confidence in its models."

Morgan and Henrion (1990) draw attention to this subjective model validation concept in Mar (1974) which suggested that modelers consider a model as validated when, "all variables they feel are important are included and none of the relationships between variables are incorrect by the modeler's standards." This subjective interpretation can inform a "uniform wince" criterion, where a critical look at one part of a model with its application in mind, one should not wince any more than looking critically at any other part (Howard and Matheson, 1984).

The Latin American World Model (LAWM) team from Candido Mendes University in Brazil provided a detailed response to the IIASA Symposium Global Model survey (D Meadows et al., 1982), sharing their understanding of model evaluation from the perspective of one of the first major global modelling teams from the 1970s:

[A] global model is a structured discourse... this means that it should never be understood as a 'reflection', or a 'synthesis' of reality. Rigorously speaking, a global model does not necessarily discourse about reality.

The LAWM team argue that every formal model (codification) is a discourse about a theoretical model (ideation) and that a homology is simply, "assumed to exist between the theoretical model and reality." In other words, the theoretical model is thought to 'resonate' with reality. When the formal model is built, another homology is assumed to exist with the theoretical model. Therefore, work conducted in a formal model is interpreted by the LAWM group as a discourse about the world in the model, but that may not include the theoretical model or representations of reality.

They highlight this distinction because structural resonance is 'passed through' with a priori and tacit assumptions, so that variables in the model are interpreted as faithful representations of the real historical process by default. Therefore, the lack of epistemological rigor in communication and presentation leads to confused interpretations of mathematical simulations as forecasts of the future.
They conclude that the descriptive dimension of a model only allows us to study what would happen \textit{if certain hypotheses are valid}.

Despite many improvements in today’s generation of IAMs, there are intractable challenges in producing multi-decade outlooks with large-scale models. Thus, it is helpful to reflect on perspectives from Ayres (1984) who candidly assessed the difficulty of evaluating and interpreting the meaning of long-range models of human society.

1.3.3.3 Evaluating large-scale societal models – insights from Ayres (1984)

Ayres (1984) argues that the epistemology of long-range general equilibrium and systems dynamics models draw from a Leibnitzian philosophy of ‘trust derived from formal structure’. This is distinctly different from short-range econometric model evaluations based on empirical content. Therefore, he focuses on the formal structure of large-scale long-range models, identifying four key problems:

1. \textbf{Applicability of economic theories for characterizing long-range historical development:} Long-run models are often oriented around concepts of GDP, aggregate production functions and productivity that extend recent expectations for stylized relationships. For example, technological change is exogenous in neoclassical theory, leading modelers to specify constant rates of productivity increase. Ayres argues such formulations are likely to be misleading, e.g. external constant productivity increases compound over decades and lose analytical meaning. Though this critique is most applicable to the macroeconomic modelling school of IAMs, many IAMs are still influenced by neoclassical and conventional economic concepts by using constant productivity formulations. Here, Ayres echoes the concern of the ‘humbug production function’ which fit a Cobb-Douglas production function to data points that spelled out the word ‘HUMBUG’ (Shaikh, 1974).

2. \textbf{Limitations of the statistical methods used in time-series analysis:} Ayres suggests that best-fit methods from econometric time-series analysis only identify ‘strong’ relationships. This automatically limits models to a short-term perspective because more important ‘weak’ relationships may only appear as ‘noise’, even though their cumulative effect may be important. His examples include links between: energy prices and long-run productivity, resource scarcity that induces technological innovation, and demographics.

3. \textbf{Ubiquitous nonlinearity of global processes:} Since linear models do not apply to long-range phenomena, Ayres emphasizes the importance of nonlinear models. However, nonlinear models are extremely sensitive to parametric assumptions, and can be adapted to show essentially any dynamic behavior. Thus, he suggests their form is less important than their parameters.

4. \textbf{Preoccupations with determinism (the Selden Paradox):} Ayres explains the Selden Paradox (drawn from Isaac Asimov’s \textit{Foundation} novel) as the belief that ‘human behavior on the macro-scale is absolutely predictable, while on the other hand, this course of history can be altered by a single intervention.’ Thus, the Selden Paradox forms an irreducible uncertainty for energy modeling, exemplified by the 1970s: historical GDP rates were projected by modelers to the end of the century, and the ratio of GDP to oil use was considered roughly constant, however these outlooks were completely decimated by the 1973 oil embargo which were contingent on choices of individual actors in OPEC.

Given these issues, Ayres concludes long-run global change models are most useful at communicating the extreme sensitivity of outcomes to small changes in the choice of control
variables. He sees them as useful accounting meta-frameworks, where the final uncertainty range of possibilities are their most important contribution.

1.3.3.4 Defining an evaluation concept for today’s generation of IAMs

Work conducted with IAMs face a persistent existential dilemma that results from combining models of physical and social processes in ways that create a challenging epistemic discourse. Ackerman et al. (2009) contest that IAMs should be recognized as fundamentally different from physical science models because they combine descriptive analysis of physical and engineering systems with value judgments stemming from conventions in economics. These economic ideas can be opaque because they are couched within the same technical framework, or are simply exogenous in the form of productivity and GDP (Millner and McDermott, 2016). Therefore, unwise use of IAMs could imbue normative economic inputs or values with undue physical meaning.

Though models are useful tools for formalizing and communicating one’s disciplinary intuition, the longevity of large-scale global models introduce a unique problem. IIASA’s MESSAGE model has been used in studies since the 1970s, and despite ongoing code revisions and updates, many aspects of the structure and its objective functions for cost minimization have been maintained (according to the available documentation). Modeling teams may develop and work on a single IAM for many years, allowing the model to gradually supplant one’s intuition on energy-economy interactions.

Pindyck (2015) takes a more combative tone, arguing IAMs may do little more than provide a technical means of legitimizing subjective opinion. He sees economic models as means to organize thinking in logically consistent way, improving understanding of relationships among variables. However, from his view, developing elaborate economic and physical models, “might let us think that we are approaching the climate problem more scientifically, but like the Wizard of Oz, we would just be drawing a curtain around our lack of understanding.”

While Pindyck’s critique certainly applies to explicitly ‘macroeconomic’ IAMs, DICE is a model of this class which takes great effort to maintain simplicity and provide transparency. For example, Nordhaus has long provided code for DICE in the readily accessible format of Excel alongside detailed manuals to enable relatively seamless testing of alternative assumptions, even if end-users may be inclined to interpret results with limited sophistication. Pindyck’s arguments become more concrete when models like DICE are applied as key policy inputs for national and regional regulation as in the case of the social cost of carbon (G. Morgan et al., 2017; National Academies of Sciences, Engineering, and Medicine, 2016).

Although engineering and biosphere oriented models of the global energy system face their own distinct set of challenges, developers generally provide enough documentation to understand the operational meaning of parameters and variables (Bridgman, 1927). That is, every term in a model has an operational meaning that develops from a description of how it would be measured, given sufficient means and license (Cooke, 2013). Even if comprehensive measurement is impossible, or imbued with deep uncertainty, an internally consistent operational meaning provides a cohesive
means of evaluation for IAMs because it takes a model at its word, aiding in an ability to distinguish the physical from the metaphysical. 4

1.3.3.5 Why use large-scale IAMs? Evaluating an appropriate use with a perspective from Morgan and Henrion (1990)

The discussion developed in this introductory chapter has highlighted the importance of avoiding the “run once for the answer mode” and the need to understand broader philosophical implications of modeling that stem from the integration of physical concepts with those of human systems (G. Morgan and Henrion, 1990). This warning is strengthened when large complex models can have their results replicated by simple pen, paper and calculator techniques (Keepin, 1984; Keepin and Wynne, 1984). However, healthy skepticism does not have to fuel pure cynicism (e.g. Pindyck, 2013).

As emphasized by the developers of early large-scale long-range models, today’s IAMs are analogous in their ability to provide a common basis for structuring and organizing strands of scientific knowledge in ways that allow for testing hypotheses of the future (Rotmans and van Asselt Marjolein, 2001; van Asselt Marjolein and Rotmans, 2002). The array of large-scale energy system models which have been built and maintained with considerable effort can be applied as a testing bed for ideas and a valuable tool for characterizing uncertainty as suggested throughout this section by Ayres, Oreskes and Meadows.

An insight in this vein is provided by Morgan and Henrion (1990) who suggest that once large research models are built and trusted, simplified analytical models can be developed to analyze specific domains of interest. Therefore, it is possible to distill them into surface response functions and phase space concepts to construct arguments for boundary conditions, scaling and other forms of more focused inquiry. This can allow for iterative development between a well-suited specific model which feeds back into the other realms of the world within the larger model. Chapter 6 revisits this idea with an example from IAM energy system outlooks in the development of a more general presentation of uncertainty in global change studies.

However, Morgan and Henrion (1990) emphasize that without thorough and systematic modeling and analysis of the uncertainty of the problem at hand, “we can not be sure that the results of a model, especially a very large and complex one, mean anything at all.” Therefore, these authors emphasize the importance of attention to model verification, input uncertainty, and clear definition of the modeling project objectives. These are all relevant considerations for studies of technological change in the future energy system.

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4 It is important to note that in defining the concept of operational meaning Bridgman (1927) does not intend to claim that physical knowledge obtained via measurement is inherently more valuable than metaphysical knowledge: “If the concept is physical, as of length, the operations are actual physical operations, namely, those by which length is measured; or if the concept is mental, as of mathematical continuity, the operations are mental operations, namely those by which we determine whether a given aggregate of magnitudes is continuous. It is not intended to imply that there is a hard and fast division between physical and mental concepts, or that one kind of concept does not always contain an element of the other.”
1.3.4  Formal studies of energy system uncertainty with IAMs

Uncertainties in future energy system developments are generally addressed with multi-model comparisons of deterministic scenarios, i.e. model runs of a single evaluation of a given state of the world. These comparison projects apply common scenarios to produce an ensemble uncertainty range for key energy system outcomes such as total primary energy supply (TPES) or carbon dioxide emissions (CO₂) based on the span generated by a range of models (Blanford et al., 2014; Calvin et al., 2012; 2013; Chen et al., 2013; Clarke et al., 2009; De Cian et al., 2013; Edenhofer et al., 2010; Energy Modeling Forum, 1995; Krey et al., 2014; Kriegler et al., 2014a; 2015; Luderer et al., 2013; 2011; Riahi et al., 2015).

Formal uncertainty analysis of the long-run global energy system is generally conducted with techniques for uncertainty propagation in IAMs – where probability distributions of input parameters are subject to Monte Carlo sampling, with each parameter combination run through a deterministic model (Manne and Richels, 1994; Reilly et al., 1987; Scott et al., 1999). Today’s IAMs used in the research community largely preserve the deterministic structure of earlier energy-economy models, and recent studies have employed these to conduct increasingly sophisticated formal uncertainty analyses (Bistline and Weyant, 2013; Bruckner et al., 1999; Capellán-Pérez et al., 2016; Gillingham et al., 2015; Kann and Weyant, 2000; Lemoine and McJeon, 2013; McJeon et al., 2011; Nordhaus, 2016; Rozenberg et al., 2014; Sokolov et al., 2009; van Vuuren et al., 2008; Webster et al., 2008; 2012). We now focus on a few of these papers to highlight their methods and key findings.

Nordhaus (2016) applies the DICE IAM to address parametric uncertainty in future climate change by developing probability density functions (PDFs) for equilibrium climate sensitivity, productivity growth, economic damages, the carbon cycle and the rate of decarbonization. These five PDFs are discretized into quintiles, creating 5⁵ combinations (3,125) of model parameters. This structure is applied to estimate a mean SCC of 36 $/tCO₂ (ton CO₂) for the year 2015, a value that increases the mean estimate from a fully deterministic analysis with DICE. Therefore, Nordhaus suggests that optimal policy does not suggest waiting for uncertainties to be resolved. Nordhaus emphasizes that uncertainty about physical parameters is ‘level’ (uncertainties remain roughly constant over time) but that economic variables are a ‘growth’ uncertainty (which tends to increase over time). Therefore, he concludes that outlooks for the year 2100 contend with greater uncertainty from economic variables than physical.

Webster et al. (2008) conduct a Monte Carlo (MC) simulation of 100 probabilistic parameters with the MIT Emissions Prediction and Policy Analysis (EPPA) model – the ‘human’ side of the IGSM. Relative contributions to uncertainty in baseline emissions are estimated for each parameter, and energy supply emerges as the dominant factor. ⁵ The authors note a surprising, and ‘puzzling’ result regarding the most important parameter that emerges: the elasticity of coal supply with respect to price, which explains nearly 25% of the variance in baseline emissions. They highlight that since coal is considered abundant, supply side factors were not traditionally thought to be important. However, this formal uncertainty analysis highlights varied rates of autonomous energy efficiency improvement (AEEI), and interfuel substitution that lead to higher-carbon emitting economies induce

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⁵ Variance explained by energy supply sums the effects of all parameters related to: technology costs, penetration rates, fossil resource availability and supply price elasticities.
a ‘call on coal’ that becomes a major influence on baseline emissions. In this study 2050 coal use
ranges from 220-480 exajoules (EJ) with a median estimate of 320 EJ. Annual global emissions in
the year 2100 reach a median level of 22 gigatonnes carbon (GtC) with an upper bound of 36.9 GtC
and lower bound of 14.5 GtC. While baseline emissions are dominated by uncertainties related to
energy supply (especially from coal), this study finds that uncertainties in carbon price trajectories
are dominated by demand-side factors.

Bistline and Weyant (2014) provide a sequential decision-making model of electricity generation
capacity technologies in the United States using multi-stage stochastic programming techniques with
the MARKAL IAM. Sequential decision-making frameworks consider policy decisions at multiple
time-periods, allowing for explicit discussion of hedging strategies in the face of uncertainty. 6 To
develop cost projections for a hedging scenario, Bistline and Weyant apply discrete random
variables for technological parameters in the context of policy decisions made during the period
2000-2025 under uncertainty regarding the strength of a CO2 cap in 2025 (no emissions cap,
moderate cap, tight cap). Their hedging strategy suggests installations of nuclear before 2025
provide a strong hedge against low CCS availability and stringent climate policy targets. 7 Though
this stochastic programming approach provides simulations of policy decision-making with somewhat
more realism regarding timing, the authors highlight that numerical tractability constrains the number
of scenarios that can be considered.

van Vuuren (2008) conduct a ‘conditional probabilistic’ analysis with the IMAGE/TIMER energy
model using the Special Report on Emission Scenario (SRES) storylines to inform sampled ranges
of parameter values PDFs for key CO2 emission driving forces. For example, in the A2 storyline of
regionalization and low technology diffusion, the median AEEI is 50% lower than in a B1 storyline of
higher sustainability, i.e. the A2 storyline has lower energy efficiency. Around the median range of
each storyline’s contingent PDF a default of +/- 15% is sampled. This method effectively develops +/-
40% ‘error bars’ for the main SRES marker scenarios by bounding potential 21st-century outcomes,
subject to the interpretation of each narrative’s influence on the global energy system. These authors
find an overlap range for 21st-century GHG emissions between 1,400 and 1,600 GtC across
storylines, smaller than the range of fully probabilistic studies of 1,100 to 1,700 GtC.

Gillingham et al. (2015) apply six IAMs (DICE, FUND, GCAM, MERGE, IGSM and WITCH) to study
the influence of parametric uncertainty in population, total factor productivity and equilibrium climate
sensitivity on estimates of CO2 emissions, climate change and the social cost of carbon. The authors
develop a ‘two-track’ MC method based on: (Stage 1) model runs are conducted over a set of grid
points to produce surface response functions that emulate model runs, then (Stage 2) input
parameter PDFs are developed and sampled using MC simulations for each parameter. The final
surface response functions for each model indicate the degree that outcomes deviate from a set of
parameters which are different from the model’s baseline values. Based on this study, the authors
estimate the relative contributions of parametric uncertainty vs. structural uncertainty to the final MC-

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6 This multi-stage approach rather than policies imposed ‘all at once’ as with approaches to uncertainty that conduct
MC simulation for parameters with IAMs.

7 The electricity generation technology portfolio in this study focuses on coal with CCS, unabated coal, natural gas,
nuclear and wind. Regarding solar, the authors state, “Solar technologies are rarely deployed due to the high
assumed investment costs in the database and lower conventional technology costs, which make the marginal
abatement costs for solar higher than competing low-carbon technologies. The lowest-cost solar technology has
investment costs that increase over time to $2.33/W by 2050.”
simulation results. Analysis of variance for each parameter indicates that parametric uncertainties overwhelm structural model uncertainties. The authors conclude this result is a 'sobering' indication that the technique of multi-model ensembles to develop uncertainty ranges is highly deficient, and underestimates overall uncertainty by a significant amount. 8

Since this thesis is focused on the long-run macroeconomics of energy resources, we now direct our focus toward IAM studies on this topic.

1.3.4.1 Studying hypotheses of energy resources in IAMs: alternate dimensions of uncertainty

Multi-decade studies of the global energy system must anticipate how our knowledge of oil, gas and coal resources will change over time. As covered earlier in this chapter, a major criticism leveled at the World 3 model used in the LTG study was that it considered a fixed resource base which did not evolve with technological change (Cole, 1973; Nordhaus, 1973), therefore any scenario with an outlook for 'running out of resources' was classified from the start.

Since then, studies with IAMs have adopted a more dynamic approach to energy resources by considering the full extent of their geologic availability and by developing hypotheses of technological change which could lead to their eventual economic production (Bauer et al., 2016; e.g Gregory and Rogner, 1998; Rogner et al., 2012; Rogner, 1997). However, deposits of energy (and other mineral) resources lie beneath the surface of the Earth, and are challenging to characterize in a way that provides accurate knowledge of their quality and extent (McKelvey, 1972). Therefore, studies sensitive to future energy resource production face key uncertainties along three dimensions:

1. How much is geologically available? (reserves v. resources vs. total abundance in the Earth's crust);
2. What determines economic production? (demand, production technology, technological change, fuel conversion processes, end-use potentials, substitution); and
3. Is this information reliable? (classification schemes, data quality, economic vs. physical accounting, incentives for knowledge production, exploration techniques, regulatory regimes, political factors).

Research focused only on the first dimension can lead to outlooks that are overly pessimistic or optimistic: oil, gas and coal accounted as 'reserves' are but a fraction of the total amount of geologic resources; yet the total amount of resources are unlikely to ever be producible because of dimensions (2) and (3). Projections of end-use energy demand based solely on technologies (electric cars, hydrogen fuel cells, internal combustion engine) may extend beyond feasibility if they are not coupled with considerations of dimensions (1) and (3). Energy resources are commonly characterized with degrees of uncertainty such as proved, probable, possible; or measured, indicated, inferred. 9 Yet the application of these terms is often inconsistent across national boundaries, data vintages and resources (3), leading to confused outlooks, unclear future

8 However, model structure was found to lead to vastly different SCC estimates – more than 80% of the difference between SCC values were explained by the model uncertainty, compared to 0.052 (CO2 concentrations), 0.062 (temperature), economic output (0.016), radiative forcing (0.020) and population (0.109).
9 So far in this literature review, we have touched on the concept of 'subjective probability distributions', these categories are excellent examples of widely-used subjective probabilities.
possibilities and overconfidence in decision-making. Thus, any study on long-run energy supply and demand must be conducted within an explicit framework that accounts for the influence of these three dimensions.

1.3.4.2 Classifying energy resources: reserves, resources and occurrences

A widely used system for classifying the economic and geologic factors inherent in assessments of energy resources draws from McKelvey (1972). McKelvey develops a horizontal axis for geologic factors and a vertical axis for degrees of economic recovery (Figure 1.3) based on general definitions (Rogner et al. 2012) of:

- **Reserves** (dark blue) are the quantities indicated by geologic and engineering information that are likely to be recovered with reasonable certainty in the future from known reservoirs under existing economic and operating conditions.
- **Resources** (lighter blue) are the detected quantities that cannot be profitably recovered with current technology, but may be recoverable in the future, and quantities that are geologically possible but undiscovered.
- **Occurrences** (light blue) are the total amount of a mineral contained in the Earth’s crust in some recognizable form.

Further muddling this picture, the lowest box of Figure 1.3 includes *unconventional* resources. The distinction between conventional and unconventional resources is often confusing, based on various combinations of geological characteristics and production technologies. Authors tend to apply preferred definitions which can change depending on industry conventions and developments in technology.

*Conventional* generally refers to oil and gas produced from reservoirs using traditional drilling, pumping and compression techniques. *Unconventional* oil and gas is present in different geologic formations, requiring advanced production methods. Unconventional oils include shale oil (hydraulic fracturing), oil sands (bitumen), oil shale (kerogen), or extra heavy oils – these deposits may involve *in situ* heating or treatment before they can be extracted (McGlade, 2012). Unconventional gas refers to shale gas, tight gas or coal bed methane (McGlade et al., 2013).
1.3.4.3 Energy resources in IAMs: assessing plausible oil, gas and coal production outlooks in the world of the model

Multi-decade studies conducted with IAMs understand the potential for future energy resource production by looking at the full extent of this McKelvey diagram. An example of the fossil energy potentials used by IAMs in the EMF 27 study is included in Table 1.1 (IEA, 2016; McCollum et al., 2014; Rogner et al., 2012).

As noted in Table 1.1, during 2014 production of conventional oil was 170 EJ/year. With reserves of 4,900-7,600 EJ, the reserve-to-production (R-P) ratio for oil is 30-45 years. However, some of the oil produced today was formerly classified as ‘resources’ meaning that a long-term study must consider the additional 4,200-6,200 EJ in oil resources, establishing a resources+reserves-to-production (R+R/P) ratio of 50-80 years.  

Many engineering-economic IAMs apply a dynamic resource concept to characterize the boundary between today’s reserves and the resources that could be re-assessed as reserves in the future. IAMs translate this concept into supply curves that include reserves and resources, structured by their potential extraction cost and the influence of technological change on improving their economic value.

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10 Geologists commonly frame production potentials through accounting for a ultimately recoverable resource (URR) which is a theoretical approach to determining the amount that has been extracted already and the ultimate amount that can ever be extracted. There is a great volume of literature of suitability and applicability of URR which is outside the scope of this introductory chapter.
production (Bauer et al., 2016; Rogner, 1997). **Chapters 2 and 3** of this thesis examines this concept in detail.

Studies on uncertainties in these reserve and resource outlooks conducted with IAMs examine varied outlooks for oil, gas and coal by modifying the cost or quantity as presented in their supply-availability curves (Calvin et al., 2013; Capellán-Pérez et al., 2014; McCollum et al., 2014, 2016; McJeon et al., 2014; van Ruijven and van Vuuren, 2009). We can now revisit a few key insights from these studies.

McCollum et al. (2014) examine fossil energy resource production outlooks developed by 12 IAMs for the EMF 27 study. Though models employ varied cost-availability curves that lead to notable differences in reference scenarios, these collectively result in projections of future energy systems dominated by use of fossil fuels through year-2100 (58-80 ZJ - 3.1-4.3x historic use). Even though coal is massively deployed by several models (10-14x today's production rate by 2100), it is noted that the total resource base is extremely large and so these scenarios are considered plausible. Cumulative fossil fuel consumption across the range of model produced scenarios are well within the bounds of estimated reserves and resources, and so the authors interpret all of these outlooks as likely.

McJeon et al. (2014) analyze trajectories of GHG emissions under two scenarios: conventional gas (11,000 EJ of natural gas) and one of abundant gas (40,000 EJ) through the year 2050 in five IAMs (GCAM, MESSAGE, REMIND, WITCH and BAEDEM). The abundant gas scenario reduces the cost and increases the availability of natural gas, which then largely substitutes for coal, but also for lower carbon energy from nuclear and renewables. Natural gas releases about half as much carbon (56 kgCO₂/GJ) per unit of energy than coal (96 kgCO₂/GJ) so substitution of gas for coal is often thought to aid in decarbonizing the energy system. However, this multi-model study found that the abundant gas scenario had a limited impact on lowering CO₂ emissions because gas substitutes for both high and lower carbon energy. Further, cheaper gas reduces the cost of energy, expanding total global energy use.

### Table 1-1 - Oil, Gas and Coal: Production, Reserves and Resources as applied in EMF 27

<table>
<thead>
<tr>
<th>Type</th>
<th>Production* (2014)</th>
<th>Reserves (EJ)</th>
<th>Reserves-to-Production</th>
<th>Resources (EJ)</th>
<th>R+R-to-Production†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>170 EJ</td>
<td>4,900 - 7,600</td>
<td>30 - 45</td>
<td>4,200 - 6,200</td>
<td>50 - 80</td>
</tr>
<tr>
<td>Crude oil + NGL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unconventional</td>
<td>16 EJ</td>
<td>3,800 - 5,600</td>
<td>250 - 350</td>
<td>11,300 - 14,800</td>
<td>950 - 1,300</td>
</tr>
<tr>
<td>Natural Gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>110 EJ</td>
<td>5,000 - 7,100</td>
<td>45 - 65</td>
<td>7,200 - 8,900</td>
<td>110 - 150</td>
</tr>
<tr>
<td>Unconventional</td>
<td>27 EJ</td>
<td>20,100 - 67,100</td>
<td>755 - 2,520</td>
<td>40,200 - 121,900</td>
<td>2,260 - 7,100</td>
</tr>
<tr>
<td>Coal</td>
<td>170 EJ</td>
<td>17,300 - 21,000</td>
<td>100 - 125</td>
<td>291,000 - 435,000</td>
<td>1,850 - 2,740</td>
</tr>
</tbody>
</table>

* IEA World Energy Outlook 2016; All other data from McCollum et. al (2014); † R+R = Resources and Reserves
McCollum et al. (2016) conduct a similar study for oil, examining the sensitivity of CO₂ emission trajectories to oil prices, creating a high price ($120/barrel) and a low price ($40-50/barrel) scenario for the MESSAGE IAM. These two scenarios are assessed in the context of biomass energy, biofuels, fossil synfuels, couplings between oil and natural gas prices, alternative vehicle technologies (electric, natural gas, hydrogen) and climate policy. The difference in CO₂ emissions in the two scenarios is as much as 7 GtCO₂ per year by 2050, or about 10% of the difference from the initial reference case. In the high oil price case, more carbon intensive alternatives are used, such as coal-to-liquid based synthetic fuels (synfuels), unconventional oils and biomass. In the low-oil price case, demand is higher and fewer high carbon-intensity alternatives are deployed. In summary, it is unclear from this study whether oil prices have a significant influence on trajectories of GHG emissions in MESSAGE, or if outlooks for CO₂ emissions in MESSAGE are simply insensitive to energy prices.

van Ruijven and van Vuuren (2009) develop three price scenarios for the TIMER (IMAGE) energy model based on oil prices at low ($5/GJ), medium ($10/GJ) and high ($20/GJ) levels which are coupled to similar trajectories in natural gas markets. They introduce an exogenous price parameter for calculations of production costs to dynamics generally not presented in IAM supply curves. 11 Across all three of these scenarios, projections for primary energy supply in 2050 remains consistent, and coal provides the residual for lower or higher levels of oil or gas use. The high cost scenario in van Ruijven and van Vuuren (2009) leads to substitution away from oil over five decades, producing an outlook for transportation with biofuels and hydrogen. As most of the hydrogen is produced from electrolysis with coal-based electricity, a faster rate of coal production is projected. In the low-cost scenario, oil and natural gas is produced at a faster rate, and depletion raises the cost these fuels. Therefore, energy prices converge among all the scenarios. GHG emission projections for each of the scenarios also show little sensitivity, varying only as much as 15% after 2040.

Calvin et al. (2013) produce various combinations of high, medium and low scenarios for oil, gas and coal with the GCAM IAM. The high and medium scenarios assume a supply of 52 ZJ for oil, 56 ZJ for gas and 104 ZJ for coal. The low case assumes 30 ZJ of oil, 38 ZJ of gas and 39 ZJ of coal. These authors find that in scenarios with low oil availability, coal-to-liquids provides a significant portion of liquid fuels. In the high coal scenario, low cost coal substitutes for oil, leading to wide deployment of coal-to-liquids. The high fossil fuel scenario (high for all hydrocarbons) leads to the lowest deployment of coal-to-liquids by 2095 as abundant unconventional oil at 70 million barrels per day (mbd) reduces the 'call on coal' to only 23 mbd. Coal-to-liquids provides as much as 90 mbd of liquid fuels across all the scenarios. As with the other studies covered in this section, there is little change in CO₂ emissions across the GCAM scenarios by 2050. The baseline, high fossil and high coal scenarios follow the exact same emission trajectories through mid-century, while the low fossil scenario leads to an outlook for emissions 15% lower than these projections.

Capellan Perez et al. (2016) develop a probabilistic assessment of fossil resource outlooks, applied to the GCAM IAM. These authors propose use of a vast array of ultimately recoverable resource (URR) estimates to account for uncertainties in the information conveyed by resource estimates from

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11. These include (1) strategic behaviours of oil producing countries, (2) potential underinvestment in production and refining capacity, (3) market uncertainties in response to political uncertainties, (4) rapid increases in demand, (5) limitations in the production rate of low-cost fields, (6) energy security policies in oil consuming countries, and (7) limitations in the rate at which new oil resources can be brought into production.
different agencies. URR intends to estimate the sum of past and future production in the context of physical factors related to reserve growth, resource discoveries, field sizes, and depletion rates. The authors synthesize a range of URR estimates from agencies (USGS, WEC, BGR, IEA, IIASA) and industry (ESSO, Shell) (Dale, 2012). From this database of URR estimates, they develop a distribution with uniform probability for each fuel source. The reserve and resource estimates applied in EMF 27 map to the top range of this database. These URR estimates are randomly assigned cost-availability curves shaped as either logistic, exponential or inverse. Then, 1,000 MC iterations are applied to produce a range of scenarios in GCAM, producing cumulative distribution functions (CDF) for outputs. This process achieves an interquartile estimate for 21st-century emissions of 970-1,470 GtC which is lower than the 1,370-1,700 GtC range produced by the EMF27 study. The authors find that a large portion of variance in cumulative CO2 emissions (0.73) stems from the URR of global coal.

This section has summarized recent research on uncertainties in energy cost and availability with IAMs. Issues noted by each study are: (i) the relative convergence of carbon emissions and energy prices across scenarios within models, and (ii) the significant role of coal in dominating uncertainty for future CO2 emission reference cases. Coal as a key uncertainty in GHG emission projections was also noted by Webster et al. (2012; 2008). Therefore, a key focus of this thesis is on outlooks for energy resource production in the world of IAMs, with special attention to coal.

1.4 Summary

This introductory chapter has reviewed key literature relevant to a systematic inquiry on energy resource uncertainties in global change research. Accordingly, we can summarize that:

- Studies of global environmental change must address long-time horizons beyond the boundaries of today's knowledge, where the global energy system is a key source of uncertainty.
- Integrated assessment models (IAMs) are applied in global change research to understand possibilities for future fossil energy production in this context.
- IAMs are models of the global energy-economy system where it is useful to distinguish between the 'model in the world' and a 'world in the model' created through ideation, classification and codification (Section 1.1). IAMs are used in ways that are analogous to the process by which economists use and create models: they give form to disciplinary intuitions and communicate these perceptions to others.
- Studies of global change structure uncertainty with two distinct approaches: one focused on scenarios constructed by narratives (Section 1.2.1) and the other with input PDFs (objective, subjective) (Section 1.2.2). Both concepts draw on IAMs for quantitative rigor (Section 1.2.3), which leads to specific forms and concepts of uncertainty relevant for modelling sciences (Section 1.2.4).
- IAMs provide quantitative meta-accounting frameworks for global change research (Section 1.3). Today's IAMs continue a tradition of global energy-economy models developed from collaborations between economists, engineers, environmental scientists and other disciplines (Section 1.3.1). Through the 1990s, this discipline of energy-economy modelling was increasingly adapted to study climate change (Section 1.3.2).
- Research conducted with IAMs faces challenges endemic to modelling sciences (Section 1.3.3), namely that by creating a simplified abstraction of the world, complex processes are condensed in a way that requires epistemological rigor for evaluation and communication of model results.
• Because IAMs define boundaries for analysis within open systems, it is not useful to understand them with an absolutist concept of 'validation', but to 'evaluate' them based on their ability to corroborate hypotheses and provide useful heuristic tools for studies of global change (Section 1.3.3.1).

• Early large-scale global model developers viewed the issue of model evaluation as one that is deeply subjective, where they were understood as a structured discourse about the world of the model, rather than 'reality' (Section 1.3.3.2).

• Confidence in these models draws from formal structure, rather than empirical content. However, this leads to challenges that stem from structural uncertainties inherent in the: (i) applicability of economic theory over the long-run, (ii) limitations of time-series calibration methods to detect important relationships, (iii) ubiquitous nonlinearity of global change, and (iv) deterministic nature of models outlooks that create paradoxes for interventions to redirect their trajectories (Section 1.3.3.3).

• IAMs face a persistent existential dilemma that results from imbuing concepts from social science with explicit physical relevance. While this can lead to skepticism and cynicism regarding their usefulness, they are accompanied with operational definitions that provide a meaningful context for evaluations (Section 1.3.3.4).

• With careful evaluation and understanding of the world of the model, IAMs can be useful means of structuring and organizing strands of scientific knowledge in ways that test and communicate hypotheses of the future. However, large-scale IAMs are so complex, specific domains of interest are best explored with simple analytical models well suited for focused inquiry. This can take place with simple surface response functions that allow for bounding, scaling or calibration arguments that feed back into the larger model (Section 1.3.3.5).

• Studies of uncertainties in the future global energy system are conducted with IAMs through multi-model comparisons of deterministic scenarios, or through uncertainty propagation techniques that draw from input probability distributions (Section 1.3.4). Gillingham et al. (2015) conduct a multi-model study that combines both approaches, finding that parametric uncertainties overwhelm structural uncertainties. These authors indicate that IAMs can be redundant in their description of energy-economy systems, e.g. for some studies, running one large-scale IAM is equivalent to effectively running all models.

• Research on energy resources across the long-run must contend with uncertainty in dimensions that address supply, demand and information quality (Section 1.3.4.1). These must look beyond today's assessed reserves, to anticipate factors that could influence the recoverability of identified resources through conventional or unconventional techniques.

• IAMs approach such questions by varying their underlying oil, gas and coal input supply curves to analyze the influence of different assumptions on outlooks for primary energy production, key sectors of end-use energy and the influence on long-run CO2 emissions (Section 1.3.5.1). Two key insights can be distilled from these studies regarding trajectories of CO2 emissions produced by IAMs: (i) they are largely insensitive to significant changes in oil and gas costs or availability and (ii) are dominated by uncertainties regarding coal supply-side factors.

With this foundation established, the following thesis proceeds by evaluating the concepts applied to structure uncertainties relevant for fossil energy resource input supply curves in IAMs (Chapters 2-4). In Chapter 5, these ideas are synthesized to understand how they influence outlooks for scenarios used by the global environmental change research community. Chapter 6 proposes a method to address long-run outlooks for energy resources in a structure-neutral fashion, with the intent of contributing toward a more general discourse on uncertainty in studies of global change. Chapter 7 understands the socioeconomics
of these scenarios in the context of historical analogues. **Chapter 8** concludes by recounting the key contributions of this work within a concise summary.

The work leading to this thesis started with a simple research question: How did historical concepts of energy resources and technology in economic thought shape today’s models of how to achieve a future low carbon transition? Initially, there was no intention that coal would have much to do with this line of inquiry, since I wanted to focus on decarbonization rather than re-carbonization. Yet, since this fuel source was considered the ultimate backstop technology when today’s climate models were in their early stages of development, it was inevitable that coal would eventually play a leading role in the following chapters.
Chapter 2: Evaluating the learning-by-doing theory of long-run fossil energy economics

As addressed in Chapter 1, long-term studies of global change inherently extend beyond the scope of today’s knowledge, requiring a dynamic approach to future technological possibilities and the frontiers of currently available information. Understanding fossil energy resources in this context commonly begins with assessments of total geologic oil, gas and coal occurrences. After data limitations are acknowledged, hypotheses can be applied to anticipate future developments in the production technologies that could enable economic access to the full extent of these deposits.

Rogner (1997) addresses these questions of inherent long-run uncertainty with an innovative methodology by providing an approach to the ideation phase of energy modelling which grounds the total geologic presence of fossil energy resources in a theory of learning-by-doing. This seminal assessment combines diverse reports from governments and international agencies to formulate internally consistent cumulative availability curves for each hydrocarbon fuel (further referred to as the H-H-R Supply Curve).

Cumulative resource supply curves were originally proposed by Tilton and Skinner (1987) as a means of showing how the future availability of energy resources could vary according to price, and these build on the conceptual foundation established by Hotelling (1931). Aguilera (2014) discusses cumulative supply curves for global oil and gas, highlighting that they differ from the supply curves in microeconomics which are a static snapshot in time. Production cost-recoverable quantity (cost-quantity) curves, such as those covered in this chapter, intend to depict the general availability of energy resources over the long-run.

Rogner’s hypothesis is that continuous production will induce a learning curve effect independent of market prices, reducing the cost of accessing future resources. As more of the cost-quantity curve is produced, technological improvements accumulate as a compounding learning effect that leads to significant productivity gains in conventional and unconventional oil, gas and coal extraction technologies. In this theory, today’s reserves are understood as a "flow" continually replenished by the "stock" of total geologic occurrences, with a dynamic boundary characterized by learning that accumulates from increasing knowledge. The specific methodology applied by Rogner to structure resource cost-quantity curves is addressed with more detail in Chapter 5, as this chapter focuses primarily on the learning-by-doing element of their ideation.

Learning curves draw from a long history of studies on manufacturing, and in macroeconomics through endogenous modeling of technical change (Anzanello and Fogliatto, 2011; Arrow, 1962; Yelle, 1979). Since Wright (1936) observed productivity gains that resulted from repetitive tasks on airplane assembly lines, learning curves have provided effective and accurate mathematical accounts of performance improvements in continuing manufacturing processes when used in a relevant context (Yeh and Rubin, 2012).

Economic models of learning-by-doing anticipate productivity improvements that result from ongoing use of tools and techniques by workers, which lead to shortcuts and process optimizations that reduce the time, cost and materials involved in executing a specific task. Macroeconomic concepts of learning-by-doing have drawn from these strong microeconomic foundations, as in the work by
Arrow (1962) and Lucas (1988) which consider learning effects for an endogenous model of technical change in neoclassical growth theory. However, the remainder of this chapter focuses on the conceptualization of learning-by-doing for cumulative resource supply curves, and not on its implementation in growth theory and other areas of economic thought.

Rogner (1997) adapts the concept of learning-by-doing to cumulative resource supply curves, creating an elegant foundation for energy models by condensing the complex factors shaping hydrocarbon economics into a numerically tractable solution. This learning-by-extracting (LBE) theory calculates future fossil energy supply potentials with a non-price induced learning rate ($\rho$) – an expected outcome of ongoing production. The resulting cost-quantity curve for future supply is then simplified to focus on two dimensions: assumptions varying the rate of future learning and the total geologic stock of the resource.

IAMs regularly apply the LBE theory to develop fossil resource input supply curves (Clarke et al., 2014; IPCC, 2000; IPCC WGIII, 2014; Joint Global Change Research Institute, 2016; Luderer et al., 2013; Masui et al., 2011; McCollum et al., 2014; Riahi et al., 2011; van Vuuren, 2007). Detailed and publicly accessible global oil, gas and coal productivity data is often outside the budget of public and academic researchers, making the original H-H-R Supply Curve one of the very few available to the research community for more than a decade after its publication. Rogner et al. (2012) provide an updated outlook for energy resources within this conceptual framework of learning-by-doing.

Though each IAM applies unique variations of Rogner’s initial concept, the basic theoretical approach has remained consistent for decades. McCollum et al. (2014) review the details of learning driven fossil energy resource supply costs in a range of IAMs. Recent efforts by Bauer et al. (2016a) place this method within a framework that scales fossil availability curves based on scenario assumptions for trajectories of future socioeconomic development. However, this geologic learning model of productivity has yet to be empirically assessed for consistency with its operational definition by comparing against oil, gas and coal industry data (Bauer et al. 2016a). This gap in the literature leaves studies reliant on the LBE theory with an untested concept of technological change inherently sensitive to its key parameter: the chosen learning rate.

To illustrate the influence a selected learning rate can have on cost projections of future energy supply, Figure 2.1 reproduces the original H-H-R Supply Curve for oil with annual rates of learning driven productivity gains ($\rho$) that vary from +1.0% to -1.0%. Each cost-quantity curve for oil intersects with its equivalent amount of carbon dioxide emissions (top x-axis) at a common backstop price for low emission oil alternatives of roughly $120/barrel of oil equivalent (boe). Calculating the next century of oil economics with this 2% total variation in learning rates results in an 1,800 GtCO2 span of uncertainty across the supply curve, e.g. roughly a half-century of current annual total CO2 emissions from all fossil fuels. The total price effect contributed by learning ($\delta$) in this case estimates an aggregate productivity improvement for oil supply costs across the century as high as +170%, or as low as -60%.

12 Lucas (1988) articulated a case for learning-by-doing in macroeconomics where each good has a different potential for learning induced productivity gains.

13 Note: Each curve starts at a different place on the y-axis as it reflects the learning effect throughout the entire century.
Throughout this chapter the annual learning-by-extracting effect is denoted as $\rho$: the rate of learning driven productivity gain, or dollar value of upstream cost reduction. The cumulative productivity gain induced by learning over the duration of the projection is $P$.

Figure 2.1  Influence of learning rates on calculations of future oil supply costs – Rogner (1997) oil supply curve (bottom x-axis in gigatons oil equivalent) modeled with varied assumptions on the rate of productivity gains from learning (-1.0% ≤ $\rho$ ≤ +1.0%). The equivalent amount of emissions from carbon dioxide (GtCO2) are shown on the top x-axis; the range of GtCO2 spanning the variation in each learning driven supply curve is shown on the top bar (green).

Nordhaus (2009) argues that learning curve models of future energy technologies produce estimates of long-run productivity with a consistent upward bias. He suggests this is “dangerous” because costs for any energy supply strategy calculated with such a technique is highly sensitive to a chosen learning rate that is difficult to evaluate (and possibly indistinguishable from model or data artifacts, or normative preferences).

The following chapter considers LBE assessments of fossil energy resources as a specific illustration of Nordhaus’ argument. This is highlighted by extending Nordhaus’ theoretical formulation to account for the specific physical and geological factors related to oil, gas and coal recovery. Production of fossil energy resources occur under conditions distinct from other manufacturing processes, adding further complexity to the issue Nordhaus raises for robust determination of an appropriate learning rate.

This chapter evaluates the suitability of the Rogner (1997) hypothesis for long-run fossil resource economics in the context of contemporary data. As proposed in Chapter 1, this resource concept in IAMs can be evaluated based on the operational definition described by Rogner - namely that, "hydrocarbon resource exploration, development and production is subject to a compounded productivity gain of 1% per year. This 1% productivity growth rate approximates the average long-term historically observed rates in the hydrocarbon upstream sectors." (Rogner 1997, p.251) Though
IAM scenarios can apply different learning rates, this chapter evaluates the essential ideation of a long-run stable learning rate independent of price.

To conduct this evaluation, Section 2.1 revisits productivity trends in upstream oil and gas since the LBE model was developed in the mid-1990s, providing a first step in linking the theory proposed by Rogner (1997) to empirical evaluation. Section 2.2 extends the theoretical case of Nordhaus (2009) to the specific context of energy resources. With these issues articulated, Section 2.3 understands the conceptual influence of various empirically consistent learning rates on outlooks for oil production, economics and backstop resources with a simple conceptual model, and with the GCAM IAM. Section 2.4 concludes this chapter with a short summary, which establishes a background for evaluating the dynamic reserve-resource concept for coal (Chapter 3).

2.1 Empirical trends in upstream oil and gas (1978-2008): production costs, market dynamics and reserves

Rogner (1997) develops a cumulative fossil resource availability curve to understand the economics of oil, gas and coal through the 21st-century. We have now experienced more than 15% of this period, allowing us to revisit the basic tenets of the LBE theory for empirical evidence of its core assumptions regarding: (i) autonomous compounding upstream productivity driven by learning, (ii) long-term stable upstream costs independent of market price effects, and (iii) the relevance of a reserve-to-production (R-P) equilibrium range for framing the economics of future production.

2.1.1 Data on oil and gas upstream costs: evidence of compounding productivity driven by learning?

The US Energy Information Administration (EIA) conducted a regular survey of major US energy companies with its Financial Reporting System (FRS) through 2011. Subsequent FRS reports analyzed data on the financial performance of domestic and worldwide operations for companies that included ExxonMobil, Shell, ConocoPhillips, Chevron and BP. The latest EIA FRS publication provides an internally consistent time-series from 1977 through 2009 that allows for examination of aggregate industry productivity data (Bawks et al., 2011). Figure 2.2(a-b) displays these reported FRS company cost trends for two key elements of oil and gas production that map to the operational definition of Rogner (1997): total upstream expenditures per barrel of oil equivalent (boe) for oil and gas (Figure 2.2a) and production costs less royalties (Figure 2.2b).

Figure 2.2a overlays the upstream cost trends for each decade of available FRS data, calculated by compound annual growth rate (CAGR) with a 3-year moving average (top axis). Decadal trends in upstream costs indicated by these FRS data are: +0.9% (1978-1988), +0.5% (1988-1998) and +9.6% (1998-2008). Assuming a stable declining trend for total upstream costs would be inconsistent with the FRS data since the calculated productivity rate is negative in each ten-year period \(\rho < 0\). \textsuperscript{14}

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\textsuperscript{14} The resolution of trend analysis is of importance to note: while the 1978-1988 trend shows a slight increase in costs, a smoothed compound annual growth rate would miscalculate the costs in nearly every year during the decade, missing the extreme cost increase from 1979-1983 and decline from 1984-1987. This reflects price volatility in the market for a global commodity. Alternative supply strategies that compete with oil through demand for manufactured products (such as wind turbines or solar panels) may have price trends that more directly relate to the learning-by-doing model for manufacturing.
Across the full three decades in the FRS data, total upstream costs increased at a rate of +3.6% per year. The right-axis (dark purple) of Figure 2.2a overlays the Brent market price in constant dollars ($2009). Exploration costs show the highest stability, fluctuating between 10% and 30% of Brent crude. Production costs dominate throughout the early portion of the time-series (1978-1996) until development expenditures become the highest proportion of upstream spend from 1997 onward. Notably, the three-year moving average of upstream FRS expenditures exceed Brent market price for much of the period during 1997-2002 - signaling market prices that reached unsustainable levels for the industry long-term. Development costs increasingly dominated upstream costs from the late 1990s, indicating a growth trend in industry capital expenditures that contributed to the supply-side conditions for the following decade’s oil bull market. 15

Industry trends for production, development and exploration costs reported in the FRS (Figure 2.2a) align with the initial formulation of the LBE model in the period leading up to its original publication. From 1988-1996 total upstream costs per boe of oil and gas output experienced an average -1.1% annual cost decline ($\rho \approx +1\%$). Though these productivity gains did not translate to subsequent decades, this portion of the time-series shows gradual improvements in oil and gas production costs as a learning effect would expect for a homogenous product.

Cost ranges reported in the H-H-R Supply Curve show correspondence with industry metrics reported as direct lifting costs. 16 Lifting costs account for the expenditures required to extract developed reserves after they are found and acquired. EIA FRS data on direct lifting costs provided in Figure 2.2b indicate the technical cost of extracting oil and gas rose +0.7% p.a. from 1980 to 2009.

The three decadal cost trends range from negligible (1980-1990), to a sharp compound annual decline of -5.5% (1990-2000) and a rapid increase (+9.0%) in the first decade of the 21st-century. From 1980-1992 the trend indicates an annual cost decline from improving productivity at a rate of -1.0% per year. This sub-period appears to show the effect of learning from continuous production with conventional technologies in well-characterized geographic regions. This shaped the initial formulation of the LBE concept which anticipated these productivity gains would continue for all geologic oil and gas resources.

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15 **Note:** The FRS data report aggregate oil and gas production, so these values are not directly indicative of actual producer marginal cost, or useful for calculating profit margin. While providing an internally consistent data set for upstream costs and production, the aggregation of oil and gas data makes disaggregation dependent on a series of complex assumptions.

16 Though Rogner (1997) argues full upstream costs from exploration, development and production are captured in this model because of evidence suggested by development in the United States and North Sea production, the supply curves produced by the LBE approach more closely correspond to the direct lifting costs associated with production (e.g. operational expenditures). This case is argued throughout the following Section 2.1.2.
Figure 2.2a  Upstream productivity trends in oil & gas (1978-2008) – EIA FRS reporting on worldwide expenditures for exploration, development, and production of oil and gas output in barrel of oil equivalent (boe) with a 3-year moving average (MA); (right-axis) annual Brent crude benchmark price (purple line) in constant dollars ($2009); (top-axis) the decadal compound annual growth rate (CAGR) trend for upstream costs.

Figure 2.2b  Trends in direct lifting costs per barrel of oil equivalent for EIA FRS Companies (1980-2009) – domestic trends (blue) and rest of world (red); (right-axis) proportion of 2009 Brent benchmark price; (top axis) CAGR trends for each decade.
While the EIA is only one source for industry productivity indicators, these data on upstream cost trends mirror the general features of other academic studies (Fantazzini et al., 2011; J. V. Mitchell and B. Mitchell, 2014) financial institution publications (Citi Research, 2013; Deloitte, 2015; Goldman Sachs, 2014; 2013; JP Morgan Asset Management, 2015; Lewis, 2014) and reports from oil industry consulting agencies (e.g. Kopits, 2014; Rystad Energy, 2015). This chapter focuses on the EIA FRS data because it is the highest quality dataset we could find in the public domain and available to readers for additional scrutiny. Further efforts can harmonize these data with upstream trends from the most recent decade. Admittedly, while including worldwide measures for Canada, Europe, the Former Soviet Union, Africa, the Middle East and other parts of the world, these data are biased toward US operations. Therefore, an immediate question arises about the application of these upstream trends to studies of global oil and gas, where OPEC producers play a major role.

On that point, Watkins (2006) highlights that the deregulation of US oil prices in 1981 plugged the domestic market into the world, allowing information from the US to provide a window into reserve prices and costs in all regions open to new investment. As non-US companies develop and explore for oil in the US with operations around the world, the EIA FRS data series can be considered to generally represent the ‘shape’ of costs in many parts of the world. Global price trends have mirrored these upstream costs, suggesting they are generally representative of industry marginal cost and performance trends.

The LBE theory expected that compounding gains in performance would lead to ongoing upstream cost declines from accumulated learning. Yet, total upstream costs indicate an extended period of aggregate performance declines for total global oil supply. Despite specific performance increases in some regions and rapid diffusion of innovations in new upstream technologies (e.g. especially horizontal drilling post-2005), sustained long-run productivity trends from 1978-2009 break from those anticipated by the LBE theory. This discontinuity indicates a model of autonomous non-price induced learning for conventional oil and gas supply technologies does not capture relevant characteristics of the frontier between production technologies of the past and those of the future. A continuous learning effect applied to a heterogeneous resource base will thus face essential constraints in modeling the productivity of new technologies needed to access different types of resources in varied geologic formations. Cost-quantity curves can therefore present an inaccurate picture when combining multiple production technologies.

The analysis in this section suggests that specific manufacturing processes for future oil and gas production must be considered in models of long-run technological change to resolve contradictions between empirical trends and theoretical expectations for contributions from learning. The importance of introducing higher resolution modeling for extraction technologies is further illustrated by the context of capital expenditures.

2.1.2 The influence of market prices on productivity measures: distinct patterns for operational and capital expenditures

The LBE theory expects that a learning effect independent of market price is a suitable explanation for productivity improvements in upstream energy resource extraction costs. However, upstream

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17 Operations in the US are less subject to political instability than many regions, however, they may be more expensive due to concerns about litigation and social license.
costs are also contingent on a range of non-technical factors: taxes, royalties, land valuations, political intentions and business cycles.

Osmundsen and Roll (2016) explore evidence of industry cycles on upstream expenditures and provide evidence that bullish periods increase costs per unit of output, reducing measured productivity. In periods of rapid expansion, oil rigs and other oilfield service equipment experience a faster hike in wages and rig prices which reduce measured productivity, due to pressure from higher rates of capacity utilization. Conversely, in a market slump, equipment utilization rates decline, rig rates fall, and upstream productivity measures increase.

Rogner (1997) equates long-term price in LBE supply curves to marginal costs ($P = MC$) determined by technology that improves with learning to formulate cost projections dominated by supply-side factors. The FRS upstream costs we analyze mirror patterns in market price, but are these fluctuations in productivity more clearly shaped by demand or ‘supply driven’ gains from learning? If learning-by-doing dominates upstream costs, an autonomous stable productivity trend is an appropriate model, since the costs of investing in supply expansion are largely independent of demand. However, Osmundsen and Roll point to one important way that demand-led prices shape marginal cost profiles, suggesting upstream productivity modeled independent of market conditions may not be applicable.

Figure 2.3(a-b) examines the relationship between prices and productivity in the EIA FRS data. Production costs are summarized as operational expenditures (opex) and development plus exploration costs as capital expenditures (capex) (Aguilera, 2014). Figure 2.3a plots the year-to-year change in Brent price (top) alongside measured productivity gains for opex (middle) and capex (lower) from the FRS data in Section 2.1.1. Price declines visibly precede productivity gains through the early 1980s, suggesting much of the ‘learning effect’ measurable over this period resulted from industry consolidation. Parallel productivity gains in this series for opex are far less volatile than capex, and consistent with what a learning model would expect: 1991-1999 shows an eight-year stable improvement in operational productivity ($\rho \approx +3\%$). Because long-term models smooth trends to maintain numerical tractability, the histograms (right-side) superimpose empirically consistent normal distributions with mean values over the entire time-series for opex of $\rho = -4\%$ (dashed yellow line) and $\rho = -5\%$ for capex (dashed orange line).

To test for the relevance of price effects, Figure 2.3b shows the influence of market fluctuations with year-to-year marginal changes in productivity measured per dollar of market price ($\frac{dP}{ds}$). Once again, the theoretical framework of LBE corresponds to opex trends: production expenditures experience little sensitivity to market price throughout the time-series, as Rogner (1997) originally assumes for total hydrocarbon energy supply.

A simple time-series average for opex indicates the productivity of operational expenditures fell by 0.08% for every dollar increase in market price ($\frac{dP}{ds} = -0.08$), but an equilibrium value is close to zero. This supports further confidence in a non-price induced productivity model for opex. However, this assumption does not extend to capital expenditures where marginal productivity rates fluctuate significantly from 1979-2008.
The overall relationship between price and capex in this time-series is broadly negative \( \frac{d\rho}{ds} < 0 \), suggesting the industry tends to commit capital investments when market prices increase. The cyclical nature of this trend indicates that the industry adjusts expenditures based on what market outlooks allow over any multi-year period. Large positive values for capex in 1990, 1997 and 2003 may indicate points where the industry was temporarily starved for capital from underinvestment over the preceding period, and they are playing catch-up. Significant increases in amplitude during the latter half of the series correspond with the scale-up of capital investments needed to extend production into areas that required deepwater drilling and hydraulic fracturing, alongside boom times for the industry in the early 21st-century.

Since many oil and gas companies employ significant teams for forecasting and strategy, decisions to commit development costs are undoubtedly contingent on scenarios for market outlooks. This analysis supports the relevance of simulating market conditions in-step with projections for upstream productivity over the long-run. It seems difficult to harmonize an outlook for optimal investments that result in supply-led marginal costs determined by a 1% p.a. learning improvement with an industry that undertakes marginal capital investments under an expectation of higher market prices.

As visible in the FRS data from 1998-2008, development expenditures continue to accelerate in line with market prices (Figures 2.2a and 2.3a), indicating that the projects expanding marginal supply from the expensive end of the cost curve receive a green light under outlooks for continually increasing prices. If a 1% p.a. total upstream productivity improvement had occurred from 1988-2008, total upstream costs would have fallen from $24.50 per barrel to $20 per barrel by 2008, and expenditures on capex would have declined from $13 to $11 per barrel. Such a projection would have underestimated total upstream costs over these two decades by an average of 60% per year and capex by 100% per year. In this case, the LBE theory would have anticipated an equilibrium Brent market price of $26/bbl through the period from 2000-2008 over which Brent market prices averaged $60.\(^{18}\)

Overall, it is unlikely that year-to-year average productivity measures for capital would maintain such distinct volatility across the industry. We therefore interpret these fluctuations of measured annual productivity in capex as indicating the dominance of essential business cycle elements over a measurable level of pure endogenous learning in this time-series. These are the factors originally discussed by Schumpeter (1934; 1939): during an upturn, wages increase and labor productivity decreases, during downturns the opposite occurs, as companies throttle expenditures for production capacity based on market outlooks. \(^{19}\)

FRS data illustrate important and relevant macro-scale aspects of the trends explored at the micro-scale by Osmundsen et al. (2016): short and medium-run constraints on production equipment during booms drive up costs because limited supplies of oilfield capital and labor may command higher prices. Accounting for such demand-led marginal costs in a long-run supply model is

\(^{18}\) This projection of market prices maintains average mark-up per barrel in the FRS series of 30%.

\(^{19}\) These measures are further complicated because of the long-run outlooks required to develop new fields, i.e. market price outlooks for development expenditures must look beyond 3-year moving averages. However, this comparison is developed with 3-year MA market prices to make a one-to-one comparison with the original FRS data. In many regards, a year-to-year measure of capex productivity is limited but this is provided to match the annual point estimates in the LBE model.
necessary: socioeconomic conditions of many long-run policy models are predicated on a ‘long-boom’ of equilibrium growth in economic output (Clarke et al., 2014).

Total upstream costs per unit of production decline in a market bust, but resulting productivity measures are dominated by the expenditure reductions driven by responses to market conditions, and not the influence of learning. Capex productivity improvements in these data under such an economic environment seem to primarily reflect curtailed expansion of production to new areas and consolidation. Even though market pressures drive innovation, aggregate industry productivity data requires a careful analysis that accounts for explicit technological improvements alongside potential bear or bull market conditions - an insight particularly relevant for oil, gas and coal production data collected during the commodity bear market that started in 2014.

While short multi-year downturns merely constrain future output growth, extended periods of low capital investment will eventually lead to maturing production and well depletion, a 9% p.a. decline that sustained investment tends to reduce by 3% in aggregate. 20 Measured productivity gains due to a period of oversupply and falling oil prices do not inherently translate to increased long-run output potential because the production of oil resources is inherently different from manufacturing of a homogenous product: the production profile of specific wells and fields declines over time.

This analysis of FRS data indicates: (i) the LBE model accurately captures non-price induced secular trends for spending on operations and that (ii) the performance of energy sector capex is poorly represented in a homogenous formulation of marginal costs driven by the accumulation of learning.

Accordingly, some element of observable market price effects must inform a model of long-term industry productivity trends to overcome the bias introduced by aggregating operational and capital investment dynamics in the LBE theoretical approach to upstream cost. Plausible simulations of long-run oil and gas supply costs requires an explicit representation of the industry decision context for capital expenditures.

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20 The IEA World Energy Outlook 2016 highlights that depletion rates for global mature fields are around 9%, but sustained investment reduces decline of producing fields to 6% (IEA, 2016). Fustler et al. (2016) review the academic literature on decline rates, estimating a 6.2% p.a. rate post-peak.
Figure 2.3a  Market price and upstream productivity trends multi-plot (1978-2008) – time-series (left column) and histogram with superimposed normal distribution (right column) for 3-yr MA change in Brent market price (purple line - upper), measured productivity improvement for operational expenditures (yellow line - middle), and capital expenditures (orange line – lower); the original Rogner (1997) estimation of 1% annual productivity gain is overlaid on the time-series (dark blue dotted line - upper) along with the average productivity improvement for opex (dashed yellow line - middle) and capex (dashed orange line – lower); each plot includes gray lines for the other two data series out of focus.
2.1.3 How relevant is an equilibrium reserve-to-production range for calibrating future upstream cost profiles?

Reserves-to-production (R-P) ratios for oil and gas have maintained a relatively consistent range over the 20th century (Adelman and Watkins, 2008; BP, 2017; Watkins, 2006; Wellmer, 2008). The LBE theory draws from this data to expect that R-P values maintain an equilibrium range in the future, framing recoverable reserves as a continual flow from the total stock of geologic resources. In this sense, resources are continually reclassified as reserves with production at costs subject to productivity improvements driven by learning. The equilibrium R-P intends to represent the behavioral dynamic of producers who otherwise have little incentive to invest in knowledge at lower production rates. However, the last few decades of data challenge the relevance of this assumption for projections of upstream costs drawn from cumulative resource availability curves.

Even as R-P ratios for oil and gas can remain relatively stable, the expenditures necessary to develop reserves into production have varied. A growing reserve base doesn’t inherently ensure that oil is getting cheaper to produce, and can often mean the opposite. The costs of converting proven reserves into a producing well are accounted as development expenditures. The LBE theory conceptualizes a dynamic resource boundary, and development expenditures represent the costs of ‘moving’ this boundary which differentiates the total geologic stock of an energy resource from its reserves, and their eventual production. Figure 2.4(a-c) plots several relationships between development costs, reserves and production for oil and gas.
**Figure 2.4a** depicts the proportion of exploration, production and development costs in the EIA FRS. Development as a fraction of upstream costs remained relatively stable from 1978-1991 but grew steadily from 1992-2005. Data from EIA FRS companies indicate that total expenditures on development grew from $7.50/boe in the mid-1990s to $36.50/boe in the mid-2000s. Over this period, development costs grew 4.8%/year from 1978-2008, outpacing growth in operating costs by 56%.

As an aspect of total industry marginal cost, development costs will be reflected in market price. Over the last few decades, development costs have mirrored trends in market prices much closer than trends in exploration or production costs (Section 2.1.2). Based on this observation, we can suggest that the LBE supply curves applied thus far in the literature reflect only one-third of the marginal cost of oil and gas production by focusing on technical operating costs of producing wells. This has neglected the cost and performance dynamics of the boundary between resources, reserves and production – especially as significant unconventional resources were being developed. While the equilibrium R-P concept is useful for capturing basic features of producer exploration behavior, the development costs required to realize an equilibrium reserve base are highly sensitive to aspects of technical difficulty introduced by geology or geography at the boundary between today’s reserves and those of the future.

Adelman (1995) characterizes industry upstream behavior with a warehouse metaphor, where reserves are the dynamic inventory. This warehouse inventory is replenished from the resource base, depleted through production, and reserves are established by development expenditures. Adelman highlights that production capacity is likely to increase if development costs are below the equilibrium market price, but intensive periods of development raise the marginal cost per barrel of output, continually testing the equilibrium value. This interplay between supply and demand converts the marginal warehouse inventory of reserves into production as fast as the equilibrium market can rise. The dynamic described by Adelman implies a relationship between reserve development expenditures and demand that drives cycles of marginal cost and market price which effectively fluctuate around the base of proved reserves. In this case, an autonomous projection of an equilibrium R-P ratio provides little information on the availability of long-run supply if applied independently of development cost trends. 21

A ratio of proved reserves to market prices (R-to-Price) can illustrate a stylized version of these cycles in Adelman’s metaphor. 22 This plot of industry data (Figure 2.4b) suggest the realization of the reserve warehouse has fluctuated through two major cycles between 1955 and 2015. Each point on the curve in Figure 2.4b represents the size of the global oil reserve warehouse and the cost of converting it into production. A lower value indicates fewer reserves or higher costs (more expensive warehouse withdrawals) and vice-versa. In this series, peaks in the ratio of proved reserves-to-price

21 The snapshot of a reserve base at a point in time will include a portfolio of projects with a range of necessary development costs to realize production consistent with today’s output. The view of Adelman (1995) is that the stock of geologic oil resources is irrelevant, and what matters is the development cost needed to provide a regular flow of oil production.

22 Market prices are assumed to reflect some aspect of medium-run marginal costs related to mobilizing reserves – i.e. reserves anticipated to be economically viable are developed at expected market prices.
Costs in this cycle test the maximum threshold of market demand in each period. Once market equilibrium no longer supports further growth in development costs, pressure eases on the need to sustain high production growth rates. At this point, upstream cost consolidates around ongoing viable production at a lower market price level (the 1980s and 2014-2016). Regardless of the exact mechanism generating these two cycles, they indicate the industry conditions that lead to increasing reserves at lower cost characterize only part of each cycle since 1955. This suggests the initial formulation of the LBE theory is based on a convention that projects dynamics consistent with the most favorable portion of this cycle for producing low-cost oil and gas (1984-1999). 24

Though the LBE supply model as applied in Rogner (1997) and subsequent studies allows the total size of the warehouse to grow, development expenditures that would govern the rate and costs of ‘warehouse withdrawals’ are noticeably missing from these cost-quantity curves - such as Adelman’s (1995) observation that development costs increase rapidly during periods of high capacity use. Therefore, we can argue the LBE concept for a dynamic oil and gas resource base is a useful description of factors that add to the reserve warehouse’s possible inventory, but a poor model of the inventory’s potential for production.

The costs of oil and gas supply estimated by the LBE theory depict conditions unmoderated by the development costs and market prices that could diminish reserve growth, lower demand or decrease production in a competitive marketplace with a diversity of energy supply strategies. Hence, the long-term fossil supply curves shaped by the LBE theory describe prices and availability consistent with an ideal outlook for permanently optimal investment, where supply is expanded at the lowest possible cost in perfect foresight.

The projection of a learning effect point-estimate from any single state in this reserve-price cycle will result in an over-abundant or overly-scarce depiction of oil and gas supply - each point in the historic time-series of Figure 2.4b is a valid representation of the supply-demand balance for the reserve base at a snapshot in time. Projecting a learning trend that smooths this cycle by starting with a selected baseline period is likely to considerably miscalculate the cost of mobilizing reserves in all future periods by establishing overly-bearish or bullish conditions from the outset.

To illustrate how this distortion is likely to occur, a Monte Carlo (MC) simulation with 200 runs randomly selects a base year R-$ value from a uniform distribution of the underlying time-series data from Figure 2.4b for calculation of compounded learning across the 21st-century. Projections of this reserve-to-price ratio are overlaid on Figure 2.4c for 600 Gtoe of oil (~140 years of supply at 2016 levels) from Rogner (1997), GCAM (Joint Global Change Research Institute, 2016) and 570 Gtoe from MESSAGE (Riahi et al., 2012). Historical trends across a five-year moving average for proved reserves...

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23 Data for oil prices and reserves were collected from the BP Statistical Review (2017) and for 1948-1980 from the Oil Economists’ Handbook (Jenkins, 2005).

24 One possible interpretation of these cycles could build from the pattern of structural oil demand adoption that generates alternating states of pressure and release on the reserve base. As the reserves in the present become cheaper (upward ascent of each cycle), development costs accelerate to keep production capacity growing in-step with the demand that absorbs increased availability, e.g. as the rate of adoption increased from the 1990s through the early 2000s, development costs increased as a proportion of upstream spend (Figure 2.4a).
reserves (P1) to constant 2014 USD (R/$) are illustrated by the solid black line which re-produces Figure 2.4b.

The mean year-2100 value from the results of our MC simulation is R-to-$ = 70.43 billion barrels of reserves per dollar, which represents a steady-state reserve-base condition 55% higher than data indicate the industry has ever experienced. By mid-century, the mean value of all runs illustrates a sustained level that surpasses previous peaks in the late-1990s and before 1973.

Though the projections of Rogner (1997), GCAM and MESSAGE may appear like conservative median estimates when plotted against the full range of simulations, they are consistent with the MC runs which have already reached the most bullish observed industry conditions by 2050. Representing these states as the baseline for industry operation will significantly underestimate the cost and overstate net economic benefits of future supply. Future research on long-term energy resources must strike a balance in recognizing the nature of industry operations which are defined by distinctly bullish and bearish long-term cycles that operate on time-scales of one to two decades – these are not short-term fluctuations that should be smoothed out to enhance model numerical tractability. The boundary between reserves and resources can move in directions that allow production of more reserves at lower cost, and vice-versa.

This section has considered empirical upstream cost dynamics and profiles to evaluate the suitability of the LBE theory’s conceptual pillars. Though none of these assumptions have provided a particularly strong guide for multi-decade studies of oil and gas economics, they have attempted to specify a model of industry productivity that captures essential elements of long-run trends. Therefore, the question arises: if higher resolution data were available, would it be possible to identify and fully distinguish macro-level productivity gains attributable to learning?
Figure 2.4a  Development proportion of upstream costs (1978-2009) – as reported by EIA FRS (2011), with top chart displaying normalized Brent price normalized to 2005 for comparison; (middle axis) displays year, left axis shows proportion of upstream cost and bottom axis indicates the ratio of development costs to total upstream cost
Figure 2.4b  Two distinct cycles in reserves: quantity of proved reserves-to-Brent prices for oil (1955-2015) – (right-axis) indicates regions of each cycle which lead to increasing pressure on development costs and declining pressure on development costs; (top-axis) notes duration of cycle states from trough-to-peak and peak-to-trough
Figure 2.4c  Range of estimates for ratio of proved reserves to oil price – historic trend with 5-year moving average (solid black); a Monte Carlo simulation of 200 runs randomly selects from a base year R-$ value between 1950-2014 with uniform distribution and projects this value at $\rho = 1\%$ p.a. (thin lines); values for 600 Gtoe of oil (>140 years of supply at 2014 levels) are provided for Rogner (1997) and GCAM (2012) and 570 Gtoe for MESSAGE (Riahi et al., 2012)

2.2 Nordhaus (2009) on the perils of a learning model: extended to energy resources

The LBE theory for future hydrocarbon supply is conceptualized by Rogner (1997) with long-run market prices determined by marginal production costs ($P = MC$). Market prices are exogenous in this model, as they are driven by the learning that results from continually extracting the geologic resource base.

Though markets for energy commodities are global in scale, resources are locally produced under myriad conditions dictated by firm structure, international politics, royalty and tax accounting, technology, geology and access to markets. Surmising an aggregate estimate of macro-level productivity improvements to inform an appropriate learning rate is at best a speculative venture because of uncertainties in the data, as demonstrated by the volatile year-to-year productivity rates in Section 2.1.3. Rogner (1997) initially acknowledged this, noting: "Because data are consistently poor and have limited availability, estimating productivity gains over extended periods of time is a risky undertaking. Hence, there could be a wide margin for error around this productivity estimate. The projection of a long-term 1\% per year growth rate may well prove too conservative (or too optimistic)."

The challenging task of specifying robust learning rates for energy technologies is identified throughout the broader literature. McDonald and Schrattenholzer (2001) survey the literature,
producing a guide to learning rate selection for a range of energy technologies. Aguilera (2014) reviews several shapes of such cumulative supply curves, and notes that while technological change is generally expected to improve the economics of unconventional and lower grade oil and gas resources, significant upstream investments will be needed to realize these productivity gains. Aguilera and Ripple (2012), the Global Energy Assessment (Rogner et al., 2012), and Bauer et al. (2016) also note that such cost-quantity curves assume perfect implementation of capital investments needed to achieve them. The original formulation of the Rogner (1997) productivity model acknowledges that upstream investments are needed, but they are taken as a given, and so in essence are provided for ‘free’ when IAMs use these supply curves.

Yeh and Rubin (2012) highlight a number of issues with technology experience curves, namely the difficulty of estimating key parameters and the uncertainty of their eventual shape (i.e. evidence for ‘S-shaped’ curves that show rapid growth initially but plateau). Clarke et. al (2006) review literature on learning-by-doing to emphasize there is no single source of learning that dominates single parameter formulations of productivity gains incurred by technological change, i.e. simple experience curve formulations condense a range of factors. Ferioli et al. (2009) support the hypothesis that a chosen learning rate is a ‘surrogate’ for more complex factors by demonstrating a measured “learning curve” can result as an artifact of multiple underlying and simultaneous component processes. 25 Gillingham et al. (2008) review many representations of technological change used in energy models, noting these face common problems with comprehensive empirical data to calibrate parameters in a convincing way.

As highlighted in this literature, learning models of future energy technologies face common problems with empirical evaluation. Therefore, it is most relevant to view them as primarily theoretical in nature, representing hypotheses of technological change. Nordhaus (2009) develops such a theoretical case in order to argue that learning curves for future energy supply strategies are potentially dangerous when applied in policy models: they are highly sensitive to artificial learning rates that could be indistinguishable from measurement errors and simply represent normative choices.

2.2.1 Nordhaus (2009) generic theoretical case

To explore whether exogenous factors could result in cost declines mistakenly measured as productivity gains created by learning, Nordhaus develops a theoretical case where exogenous technical change is denoted as $h$ and true endogenous learning as $r$. The price function $p_t$ for a generic industry is assumed to equal instantaneous marginal cost $c_t$, where the rate of cost declines equals the decline in price in Equation 2.1, with $g_t$ representing a constant growth rate for industry output.

$$ p_t = c_t = h + r g_t $$  \hspace{1cm} (2.1)

With a constant marginal cost, price is determined exogenously to current demand. Growth in output (i.e. demand) can be expressed as in Equation 2.2 with constant price elasticity ($\epsilon$), an elasticity of

25 Notably, Ferioli et al. (2009) state, “Our primary finding is that, even when the learning curve is evaluated over a wide range (i.e., three orders of magnitude of cumulated production) quite different fits of the same set of data are imaginable and at least equally justifiable. We point out that products can often be described as the sum of a learning component and one for which no cost reductions occur.
per capita demand with respect to total output \((\lambda)\), a growth of aggregate per capita output \((\omega_t)\), and a constant population growth of \(n\).

\[
g_t = \epsilon p_t + \lambda \omega_t + n = \epsilon p_t + z
\]  

(2.2)

Nordhaus summarizes the autonomous, non-price induced growth as \(z_t = \lambda \omega_t + n\). Substituting **Equation 2.1** into **Equation 2.2**, the total price decline \((p)\) results (**Equation 2.3**), and time subscripts are dropped since this is an example of constant growth. Output growth \((g)\) is then determined by **Equation 2.4**.

\[
p = h + rg = h + r(\epsilon p + z) = \frac{h + rz}{1 - r/\epsilon}
\]  

(2.3)

\[
g = \epsilon(h + rg) + z = \frac{\epsilon h + z}{1 - \epsilon r}
\]  

(2.4)

The contribution of learning to declining prices would be calculated as \(\rho\), where the learning curve is the ratio of price to growth, \(\frac{p}{g}\) illustrated in **Equation 2.5**.

\[
\rho = \frac{p}{g} = \frac{h + rz}{\epsilon h + z}
\]  

(2.5)

Nordhaus argues that in **Equation 2.5**, the exact contribution of learning is difficult to determine because so many coefficients are present. It is challenging to know how much of the price decline can be confidently attributed to learning in **Equation 2.5** unless we know the exact values of exogenous technical change, the demand elasticity and the rate of autonomous demand growth. For example, in the case of oil and gas there could be another variable denoting political goals to capture the influence of cartels (or domestic budget targets of oil producers).

Nordhaus uses this formulation to develop a quantitative case that illustrates calculations of learning for the generic manufacturing industry. He assumes plausible values for price elasticity \((\epsilon = 1)\), exogenous demand growth \((z = 0.04)\) and a rate of exogenous technical change \((h = 0.01)\). When true learning is zero \((r = 0)\), substituting these values into **Equation 2.5** results in a calculation of ‘learning’ at 20% \((\rho = 0.20)\) from **Equation 2.6**.

\[
\rho = \frac{0.01 + 0.04}{1 \times 0.01 + 0.04} = \frac{0.01}{0.05} = 0.20
\]  

(2.6)

Nordhaus then considers that if the true learning value were greater than zero \((r = 0.25)\) the learning rate receives an even larger upward bias - calculated as \(\rho = 0.4\). This logic supports his conclusion that the learning curves applied in models of endogenous technical change will tend toward a consistent upward bias because of complications induced by interactions between demand, output growth and exogenous technical change. Therefore, disentangling the explicit effect of learning induced price declines - independent of all other exogenous factors - requires a highly detailed study of specific industry conditions.

In summary, Nordhaus suggests:
(a) there is a fundamental statistical identification problem in separating an endogenous learning effect from exogenous productivity gains;
(b) the subsequent estimated learning coefficient is generally biased upwards;
(c) model parameters intended to represent learning effects are not robust to alternative explanations and specifications;
(d) overestimates of learning coefficients will underestimate the total marginal cost of output for a technology; and
(e) models that rely on learning curves are likely to simply choose technologies which incorrectly or arbitrarily specify a high learning coefficient, e.g. an upwardly biased long-run learning rate for any technology will allow it to ‘rise above the rest’.

Though Nordhaus (2009) agrees that productivity benefits follow as workers in firms gain experience with a production process, he expresses skepticism that embodied learning can be measured reliably for large global systems. The cumulative 'supply' of learning could be embodied in firm, a group of workers, an individual worker, or it could result from international or interindustry spillovers (Clarke et al., 2006 also emphasizes the learning effect of spillovers). Further, a measured learning improvement may not be durable (Yeh and Rubin, 2012 highlight such discontinuities in learning).

2.2.2 Drilling into factors of oil and gas productivity: a framework for components of potential learning?

As highlighted by Ferioli et al. (2009) and Nordhaus (2009), learning rates can be the result of multiple underlying component factors. The case developed by Nordhaus (2009) for exaggerated learning in a generic industry can be extended to examine the LBE theory by considering specific technical features of oil and gas extraction.

Hamilton (2012) analyzes the impact of technology and price on oil production over the last century in the United States (1859-2010) and across the world (1973-2010), extending far beyond the small window covered by EIA FRS data in Section 2.1 of this paper. Hamilton draws on these data to conclude that individual oil producing regions have not demonstrated a pattern of continuously increasing productivity from ongoing technological progress.

In Hamilton’s view, price incentives and technology have reversed declines in output resulting from geological or geographic factors, but only temporarily. Measured productivity gains in oil producing regions initially increase as new fields are developed, followed by productivity declines dominated by the natural depletion rate of wells, and mitigated through enhanced oil recovery techniques. Hamilton suggests the primary historical source of industry productivity gains and increasing global oil production during the 20th-century has been the exploitation of new geographical areas.

While Hamilton is only focused on empirical aspects of the past and does not consider the potential long-run theoretical contribution of learning and unspecified technological breakthroughs to productivity, his analysis serves as a reminder of the engineering factors related to geology and geography which distinguish the oil and gas industry from other forms of manufacturing. 26 The

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26 Further, given the important role of oil in the economy, wholly political decisions have resulted in rapid growth of output and subsequent price declines, outside of what any would consider as free market equilibrium conditions. At
The determination of a true learning rate for oil and gas could be further distorted by such complex industry conditions, adding another element to the issues raised by Nordhaus (2009). For energy resources it is unclear whether the role of learning and upstream technology improvements can always be fully distinguished from productivity gains resulting from specific geographic or geologic factors.

This dilemma mirrors echoes Adelman (1990): that the oil industry is an “endless tug-of-war between diminishing returns and increasing knowledge.” As currently formulated, the LBE model projects future supply costs as determined by a function of increasing knowledge, which pulls Adelman’s tug-of-war in a single direction.

The cycles of cost and reserves reviewed in Section 2.1 suggest that Adelman’s metaphor is apt - the reserve base does get pulled in both directions. Though applications LBE supply curve generally use lowest cost resources first, this weakly captures the effect depletion may have on costs of accessing the full geologic resource stock over the long-run, and misses an opportunity to understand the investments needed to offset declines. 27

The use of compounded learning as the prime determinant of projected future oil and gas supply costs develops Adelman’s industry metaphor in a way that confirms the concern of Nordhaus (2009). Hamilton’s analysis highlights the factors of oil production that counter the increasing returns from knowledge and learning, indicating a path toward integrating the insights of Nordhaus and Adelman. Global oil and gas production in the 21st-century will balance, benefit and suffer from both increasing knowledge and diminishing returns.

2.2.3 Measuring learning-by-extracting alongside geological and geographical factors

Accordingly, the case of Nordhaus (2009) can include additional factors relevant to productivity in the oil and gas industry. The parameter \( o \) is introduced to represent upstream productivity that results from geographic expansion and geological conditions. When the price, cost, output and growth assumptions of Nordhaus (2009) are adopted, the original equation for declines in price \( p \) as a function of productivity gains results as Equation 2.7.

\[
p = h + o + r(\epsilon + z)
\]

In this equation, following the notation from Section 2.2.1 the rate of true endogenous learning is denoted by \( r \), exogenous technical change by \( h \), constant price elasticity by \( \epsilon \), and \( z \) is a function of autonomous, non-price induced growth. With this modification, the industry cost function is assumed to involve factors specific to engineering for oil and gas extraction \( o \), which may also influence productivity independent of learning induced technical change.

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27 Though energy models commonly draw from such cost-quantity curves sequentially, depleting resources left-to-right, today’s oil supply of approximately 68 mbd conventional, 15 mbd natural gas liquids, and 8 mbd unconventional production (IEA, 2016) would draw from multiple points in the availability curve at any one time in order to meet the time constraints of demand (see Chapter 5).
In a case that considers production from an oil well in Texas, \( r \) would capture endogenous learning that leads to productivity improvements for on-site extraction (e.g. the local crew gets better at operating the well). The specific location and geologic nature of the oil well would impose productivity considerations captured by \( o \), such as favorable drilling conditions resulting from the initial pressure at the wellhead or the natural profile of production increases and declines indicative of a maturing oil well.

A calculation of the learning coefficient \( \rho \) from Equation 2.7 results in Equation 2.8, where exogenous and true endogenous learning are combined with productivity gains enabled by geology and geography. If we adopt the values of exogenous technical change, used by Nordhaus in Section 2.2.1, with a true learning rate of \( r = 0.25 \) and consider that geology or geography may contribute at a 1% productivity gain (\( o = 0.01 \)) then the learning coefficient would be measured at \( \rho = 0.5 \), twice the true rate of learning (\( r \)).

\[
\rho = \frac{\rho}{\gamma} = \frac{h + or + rz}{2 + rh + eo} = \frac{0.01 + 0.01 + 0.25 \times 0.04}{0.04 + 0.01 + 0.01} = 0.5
\] (2.8)

With these plausible values for exogenous technical change, autonomous growth and demand elasticity, the sensitivity of \( \rho \) to \( o \) and its relationship to \( r \) can be further considered: with \( o \rightarrow 2r \) the marginal contribution of \( o \) to \( \rho \) rapidly declines as the calculated learning curve approaches unity. Following from this case, even if \( o \) were twice the value of \( r \), the calculated effect would remain roughly unchanged from when \( o < 0.8r \). This association is plotted in Figure 2.5a where the measured learning rate (black line) follows an asymptotic trajectory, the true learning rate (blue line) remains static, and the geographic-geologic productivity gain ranges from values of \( 0 < o \leq 2r \).
Figure 2.5a  Relationship of productivity rates in Equation 2.8 – using the values in the Nordhaus (2009) case, the ratio of geographic-geologic productivity gain (o) to true learning (r) (bottom axis) is plotted against the measured productivity gain (% per year) (left axis); the black line represents the measured productivity gain ($\rho$), the yellow line the geographic-geologic productivity gain (o), for a static true productivity gain (r = 0.25)
Figure 2.5b  Possible values for productivity gains from each component for a measured learning rate of 1% per year ($\rho = 1\%$) – possible values for productivity components ($o$ – left axis and $r$ – bottom axis) that could result in a measured learning rate of 1% per year, plotted for a range of values that correspond to the capex productivity measured in Section 2.1.2 with parameter values from Nordhaus (2009) (orange line) and a specification more consistent with historical values for demand elasticity and growth.

If we interpret the H-H-R (1997) assumption of 1% endogenous learning for global oil and gas as $\rho = 0.01$, using the structural form of Equation 2.8, we can solve for plausible values of geographic-geologic and true learning based productivity that could produce such a productivity measurement. Figure 2.5b plots this relationship for a range of $r$ values that corresponds to annual capex productivity measurements from Section 2.1.2, and the slope indicates that $o$ and $r$ are negatively correlated. Two specifications of Equation 2.8 are provided in this figure based on the Nordhaus (2009) parameter values used in this section (orange line), and a case with more historically consistent values for oil (yellow).

Based on the relationship depicted in Figure 2.5b (orange line), in a case where geological conditions result in a negative contribution to productivity such that $o = -1.25\%$, then the equivalent learning rate to maintain a +1.0% productivity gain on average would need to sustain 7% per year. Conversely, a high true learning rate of 25% could be masked by a contribution from $o$ at -2% per year, underestimating the influence of technological change. It follows that with a measured learning rate of +1% that $o$ and $r$ could easily mask their relative contribution, i.e. a sustained high level of true learning is needed to compensate for a slightly negative contribution by $o$, or conversely, a high level of true learning could appear low with an order of magnitude smaller contribution from $o$.

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28 The parameter values for the historically consistent case are exogenous productivity at 1% ($h = 0.01\%$), demand growth at 1.1% ($z = 1.1\%$) and elasticity of demand at 0.1 ($\varepsilon = 0.1$).

29 In a case where true learning is zero, exogenous productivity gains dominate.
In summary, a measurement of learning induced productivity that fails to capture the effect of \( o \) could readily obtain a biased value for an extrapolation of the learning-by doing effect for future oil and gas production. These considerations illustrate that truly disentangling the contribution of endogenous learning from geology, geography or exogenous factors is extremely difficult without explicit studies of producing fields. Establishing the appropriate value of a learning parameter for long-term fossil energy supply is a complex process that needs a further robust modeling effort to remain relevance in future studies on climate and energy policy.

For the FRS data considered in Section 2.1, the mean value for decadal upstream productivity appears to be negative \( (\rho < 0) \), further complicating the picture. Was learning-by-doing negative or did geology, geography or exogenous factors dominate cost increases? Presuming a deterministic level of true learning over a long-time frame needs to overcome measurement issues such as these to become a plausible description of future hydrocarbon economics. When an observable productivity trend is the product of two unknowns, guessing the value of each without an empirically constrained distribution of plausible values is difficult to separate from a normative choice. In the next section we consider the relevance of these considerations for projections of long-run technology costs.

2.3 Implications of chosen learning rates for long-run energy economics and climate change mitigation cost projections

Fossil energy supply curves constructed with the LBE theory generally indicate that the vast quantity of fossil occurrences in the Earth’s crust will readily dominate 21st-century choices for energy supply. Thus, policy goals for reducing carbon emissions to limit future climate change face stringent competition from the low-cost hydrocarbon deposits expected to result from compounded learning. The projected cost of any backstop technology that could readily substitute for these resources can also receive a bias from any selected learning rate. This section considers a simple example, and then applies various estimates of the LBE learning parameter in the GCAM IAM to test its effect.

2.3.1 Influence of learning rates on total 21st-century cost of oil supply and required low-carbon backstop prices

If annual oil production growth continues across the 21st-century at 1.1% p.a. (21st-century trend), 660 Gtoe is withdrawn from the H-H-R Supply Curve. Varied rates of productivity from +1% to -1% applied to the oil cost ranges calculated by Rogner (1997) (Figure 2.6) adjusts the total discounted cost of supply by more than a factor of 7. As this case for oil demonstrates, an upwardly biased learning rate for 21st-century fossil energy supply can easily underestimate the cost of future oil supply by 1.6-to-7.4x per barrel.

Understanding the cost of oil supply will also overstate the investment required to mitigate its GHG emissions with a low carbon alternative. If we equate the cost of future oil supply in the \( \rho = + 1.0\% \) case to a market price of $50/bbl average over the century, a $120/bbl zero carbon backstop oil substitute available today appears as a significant cost: a 60% reduction in the backstop cost is required for substitution with no deadweight loss. Yet, with an oil supply calculated at \( \rho = -1.0\% \), this backstop is already 200% more cost effective than oil over the long-run – optimal energy policy in
this case calculates that short-run substitution should be incentivized because of negligible deadweight losses. 30

This simple case depicts how slight changes to the learning rate applied for an oil, gas and coal dependent policy baseline can frame a consistent series of mitigation steps as either net costs or net benefits - substantiating Nordhaus’ concern that a learning model for developing long-term energy strategies is potentially ‘dangerous’.

Figure 2.6  Cumulative discounted cost of 21st-century oil supply – growth in oil production at 21st-century consistent level (1.1%/year) with H-H-R price bands at learning rates of $\rho = +1\%$, 0.5\%, 0\%, -0.5\% and -1\% for discount rate of 5%; (right bar) multiples of total 21st-century oil supply cost compared to the $\rho = +1\%$ case

Ferioli et al. (2009) provide a similar example from the case of wind turbine learning curves from 1995 applied to estimate multi-decade deployment and investment costs (Neij, 1997). The cost of wind power capacity in 1995 was estimated at $1,333/(1995)/kW with a total installed capacity of 5 GW worldwide and a learning rate of 4\% per year (Neij, 1997). These led to projected installation costs for the year 2004 that were 5-25\% above the actual reported installation, in less than a decade from the initial estimate (Ferioli et al., 2009). Further, cost reductions in wind power capacity were achieved at only one-fifth the cumulative investment estimated by the initial learning curve.

As demonstrated by the case of oil withdrawn from the original H-H-R Supply curve and the projected cost of wind power, uncertainties in learning rates can have a significant impact on the economics of multi-decade energy projections. While the simple examples in previous sections illustrate the basic influence of a chosen learning rate, they do not provide an integrated description of the significance fossil resource productivity gains could have on supply and demand in a long-run scenario. Therefore, we turn to an IAM.

30 Learning calculated at 0\% also considers that the $120 backstop is already more effective than oil.
2.3.2 Fossil productivity in the long-run: the LBE model in the GCAM IAM

The GCAM IAM is widely used to develop long-run energy scenarios, and uses an exact implementation of the LBE theory to structure its oil, gas and coal supply curves. Therefore, we can conduct a sensitivity analysis of learning rates for future fossil energy production in GCAM based on data analyzed in this chapter.

By default, the GCAM IAM applies a 0.75% per year productivity gain to every fossil resource in all 32 regions. However, it allows learning rates to be set per region and time period. Six alternate reference cases were constructed in GCAM with different specific rates of learning for conventional oil production from 2005-2100. Each case uses a conventional oil learning rate consistent with the range in the EIA FRS data set based on $\rho = +1\%, +0.5\%, 0\%, -0.5\%$ and -1% and a value that reflects the 1978-2008 average trend of $\rho = -3.6\%$ (which also approximates the opex time-series average from Section 2.2.2). No other aspects of these six scenarios were modified from the original GCAM reference case (GCAM-ref). Results from the default GCAM-ref scenario are plotted as a dark gray line to provide comparison ($\rho = 0.75\%$).

2.3.2.1 Effect of learning rates on prices and cost-quantity curves

Figure 2.7a shows the varied cost trajectories produced by each reference case. In the $\rho = +1\%$ (red) and GCAM-ref (dark gray) scenarios, the cost of conventional oil remains at a consistently low level, leading to higher demand for this resource. In these two scenarios, total depletion of conventional oil occurs before end of the century, and then the cost curve explodes upward. The thirty-year decadal trend scenario (light blue) highlights the absurdity of using long-run averages to inform the chosen learning rate, as effective prices double their level from GCAM-ref before 2040 to more than $170$ per barrel. The other rates of learning ($\rho = +0.5\%, 0\%, -0.5\%$ and -1%) indicate a range of stable oil price trajectories without severe discontinuities. Table 2.1 summarizes the prices for each alternate scenario at twenty-year intervals, emphasizing that even slight differences between learning rates can lead to dramatic discrepancies after many decades.

The underlying 21st-century cost-quantity curves for each alternate scenario are plotted in Figure 2.7b, framed by two reference points for conventional oil resources from the BGR (2015) assessment – a light grey line for total conventional oil reserves ($7,140$ EJ) and a dark black line for conventional oil reserves and resources ($7,140$ EJ + $6,815$ EJ = $13,960$ EJ). Learning rates greater than zero are consistent with supply curves for 30% more oil than BGR (2015) reserves and resources, while the zero-learning case uses all reserves and resources.

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31 As Chapter 4 is focused on GCAM in greater detail, a more comprehensive description of the model’s core structure and functionality in that section.
Table 2-1 - Alternate GCAM reference cases for conventional oil learning rates – effect on cost of oil (% change from unmodified GCAM-ref)

<table>
<thead>
<tr>
<th>Annual learning rate ($\rho$) (2005-2100)</th>
<th>Change in cost of oil supply (% change from GCAM-ref)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020</td>
</tr>
<tr>
<td>+1.0%</td>
<td>-0.8%</td>
</tr>
<tr>
<td>+0.5%</td>
<td>+0.9%</td>
</tr>
<tr>
<td>0%</td>
<td>+3.0%</td>
</tr>
<tr>
<td>-0.5%</td>
<td>+5.6%</td>
</tr>
<tr>
<td>-1%</td>
<td>+8.8%</td>
</tr>
<tr>
<td>-3.6%</td>
<td>+38.4%</td>
</tr>
</tbody>
</table>

Figure 2.7a 21st-century oil cost trajectories from GCAM alternate learning reference cases – (left axis) oil cost in $2014 USD per GJ, and per boe (right axis)
2.3.2.2 Effect of learning rates on production profiles and resource substitution

Twenty-first century conventional oil production profiles for the GCAM learning rate scenarios are plotted in Figure 2.8a with a reference line to mark the year-2014 rate. In 2014 conventional crude oil was produced at 67.2 mbd, natural gas liquids (NGLs) at 14.8 mbd, and unconventional oil at 7.6 mbd (IEA, 2016). Conventional oil production in the learning rate scenarios between $\rho = -1\%$ and $\rho = +1\%$ reaches a maximum between 2020 and 2030 around 95-100 mbd - about 20% higher than recent levels. Positive learning rates lead to more gradual production declines after 2030, and a production resurgence after 2060 with learning above $\rho = 0.5\%$ as production experience accumulates, so that conventional oil is more competitive in later decades. Key features of each production profile are detailed in Table 2-2.

Conventional oil declines in GCAM are offset by backstop resources. A backstop resource is a substitute energy source that is expected to come online when cheaper source are exhausted (Hartwick and Olewiler, 1986). The basic idea of a backstop resource is that sufficient incentive will exist to develop an alternative if the prices of today’s energy sources are high enough. However, for simplicity, the NGL and conventional oil production rates are combined in the reference line at 170 EJ (82 mbd), as GCAM does not appear to distinguish NGL production and consumption from conventional oil. NGLs are hydrocarbons like ethane, propane, butane, isobutene, and pentane. Ethane makes up the bulk of NGL production and is used for ethylene as a plastic feedstock. NGLs are commonly used as fuels for space heat or cooking, as a blend for vehicle fuel, as inputs for petrochemical plants, or as a diluent to increase viscosity of unconventional oil through pipelines.
until prices for the conventional technology reach a certain threshold level, the backstop technology does not receive enough investment or attention, so it awaits its introduction into the marketplace.

Building on Hotelling (1931), Nordhaus (1973) defines backstop technologies as a set of processes that are: (i) capable of meeting demand requirements and (ii) have a virtually infinite resource base. Though the backstop technology could be expensive compared to today’s technology in a long-run model, “if it exists, it assures that the planning problem at least has a feasible solution.” Nordhaus states that, “in some sense, the current stage of history is a transitory phase between dependence on cheap but scarce resources, and dependence on more costly but abundant resources.” The ideation of GCAM’s resource use applies this theory. The abundant backstop resources for liquid fuels in GCAM are unconventional oil and coal-based liquids. Chapter 7 revisits the context of coal-based liquids in more detail.

Unconventional oil and coal rise to the occasion of conventional oil depletion in GCAM scenarios. Bearish outlooks for conventional oil lead to increasingly rapid deployment of these backstop resources (Table 2-2). Unconventional oil production outlooks for each alternate learning scenario are plotted in Figure 2.8b. Curiously, although the historic average productivity rate scenario (light blue) is not consistent with oil price trajectories, GCAM provides highly skillful projections for year-2014 unconventional and conventional oil production rates.

Figure 2.8c plots the cumulative 21st-century production outlooks for conventional oil and its backstop resources as a function of learning rates. At $\rho = -1.0\%$ unconventional and conventional oil production converge at a level of 10,000 EJ. Although the production profiles for coal differ slightly among learning rates (Table 2-2) the total amount of coal extracted remains roughly equivalent at learning rates below 0%. The cumulative amount of 21st-century coal is much less sensitive to learning rates than unconventional production profiles, varying only around 10%.

Table 2-2 - Alternate GCAM reference cases for conventional oil learning rates – effect on oil production phase out and backstop deployment

<table>
<thead>
<tr>
<th>Annual learning rate ($\rho$)</th>
<th>Maximum Year</th>
<th>Minimum Year</th>
<th>Annual Decline Rate</th>
<th>Resurgence Year</th>
<th>Year 2050 Mbdoe/yr</th>
<th>Year 2100 Mbdoe/yr</th>
<th>Year 2050 EJ/yr</th>
<th>Year 2100 EJ/yr</th>
<th>Year 2050 EJ/yr</th>
<th>Year 2100 EJ/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1.0%</td>
<td>2030</td>
<td>2050</td>
<td>-0.89%</td>
<td>2080</td>
<td>13</td>
<td>147</td>
<td>370</td>
<td>600</td>
<td>400</td>
<td>910</td>
</tr>
<tr>
<td>+0.75%</td>
<td>2030</td>
<td>2060</td>
<td>-0.86%</td>
<td>2075</td>
<td>14</td>
<td>134</td>
<td>380</td>
<td>600</td>
<td>410</td>
<td>880</td>
</tr>
<tr>
<td>+0.5%</td>
<td>2025</td>
<td>2100</td>
<td>-0.7%</td>
<td>---</td>
<td>16</td>
<td>83</td>
<td>390</td>
<td>620</td>
<td>420</td>
<td>800</td>
</tr>
<tr>
<td>0%</td>
<td>2025</td>
<td>2100</td>
<td>-1.7%</td>
<td>---</td>
<td>21</td>
<td>100</td>
<td>400</td>
<td>650</td>
<td>440</td>
<td>860</td>
</tr>
<tr>
<td>-0.5%</td>
<td>2025</td>
<td>2100</td>
<td>-3.0%</td>
<td>---</td>
<td>27</td>
<td>120</td>
<td>420</td>
<td>660</td>
<td>480</td>
<td>910</td>
</tr>
<tr>
<td>-1%</td>
<td>2020</td>
<td>2100</td>
<td>-4.7%</td>
<td>---</td>
<td>35</td>
<td>130</td>
<td>430</td>
<td>650</td>
<td>500</td>
<td>920</td>
</tr>
<tr>
<td>-3.6%</td>
<td>2010</td>
<td>2060</td>
<td>-11.8%</td>
<td>---</td>
<td>64</td>
<td>140</td>
<td>430</td>
<td>640</td>
<td>560</td>
<td>930</td>
</tr>
</tbody>
</table>

* Year-to-year decline rate from maximum to post-peak minimum
Figure 2.8a  Conventional oil production outlooks for scenarios of alternate 21st-century learning rates – (left axis) annual conventional oil production in exajoules (EJ/yr), and annual average million barrels per day (right axis – mbd/yr) with reference line for year-2014 conventional oil production (dotted gray line)

Figure 2.8b  Unconventional oil production outlooks for scenarios of alternate 21st-century learning rates – (left axis) annual unconventional oil production in exajoules (EJ/yr), and in units of annual average million barrels per day (right axis – mbd/yr) with reference line for year-2014 unconventional oil production (dotted gray line)
The alternate scenarios show a positive correlation between higher levels of backstop deployment and 21st-century cumulative carbon emissions. Intuitively, more combustion of high-carbon backstop resources that substitute for relatively lower-carbon conventional oil leads to increased carbon intensity of the global energy supply (Figure 2.9a). Backstop resources combine to constitute between 60-74% of total 21st-century carbon emissions in each scenario – ranging between 1,160 GtC and 1,510 GtC (the span between the RCP4.5 and RCP6.0 carbon supply curves – see Chapter 5). Coal combustion results in approximately 1,000 GtC of cumulative emissions for each learning rate scenario (975-1080 GtC). Alternate reference cases solved for a 2°C climate policy goal indicates that policy costs and carbon prices show the same relationship as the CO2 outcomes: higher levels of high-carbon backstop deployment lead to higher carbon prices by 10-30% (Figure 2.9b).

This result confirms the relevance of the sketchbook example from Section 2.3.1 and gives pause to consider whether high-carbon backstop resources are inevitable – as the chosen high-carbon backstop could significantly influence the outlook for 21st-century climate economics given that modest variations in conventional oil learning rates lead to considerable changes to GCAM’s carbon prices.

A 2°C climate policy goal in this thesis refers to steps that intend to limit end-of-century warming to 2°C above pre-industrial levels.
Figure 2.9a  Total 21st-century carbon emissions from conventional oil learning rates – (left axis) 21st-century cumulative carbon emissions (GtC) for all sources and backstop resources, with reference line for GCAM-ref learning rate (dotted black line); scenario conventional oil learning rates (bottom axis); proportion of cumulative carbon emissions from backstop resources (top axis)

Figure 2.9b  Year-2100 discounted carbon price across alternate scenarios – (left axis) year-2100 carbon price discounted at 3% ($2014/ton carbon), and % difference from GCAM-ref (right axis) for varied scenario conventional oil learning rates (bottom axis); note y-axis break
This chapter has considered the widely used ideation for long-term resource assessments in climate and energy policy studies – a learning-by-doing theory. Rogner (1997) articulates a theory of future hydrocarbon energy supply driven by annual productivity gains that result from learning, applied to the global oil, gas and coal resource base at a rate of 1% p.a. ($\rho = +1.0\%$). When compounded across a century, this results in an aggregate productivity improvement that reduces the cost of fossil energy extraction by more than 170% ($P = 170\%/\text{boe}$). While this approach is commonly used in integrated assessments of climate change and energy economics, there are no systematic studies available in the literature to calibrate learning rates per resource and industry.

EIA data on the financial metrics of US and worldwide oil and gas production indicate that decadal productivity trends are not stable and may significantly vary (Section 2.1). From 1988-1996 they were broadly consistent with a +1.0% upstream productivity improvement as projected by Rogner (1997); overall, depending on the measure, oil and gas productivity declined by 3.0% (total upstream) to 5.2% (capex) p.a. from 1977-2009.

The volatility of year-to-year productivity changes in these data indicate the relevance of modeling stochastic processes of discovery, innovation and market conditions when calibrating long-term costs: projection of aggregate productivity gains in oil and gas as a stable secular trend over a century is likely to mislead any model of technology adoption patterns. Further, it appears likely that sustained periods of high demand (e.g. bull markets) reduce short-run and medium-run productivity, dominating any gains induced by learning during the same period (Section 2.1.2). Because conditions of sustained rapid fossil energy adoption are often projected in many long-term energy reference cases scenarios, these factors will be of explicit interest to the research community (Bauer et al., 2017; Clarke et al., 2014; Dellink et al., 2016; Riahi et al., 2017). Conversely, productivity estimates drawn from recent industry bear market conditions for cost reductions in US shale and unconventional technologies must be understood in the full context of labor, capital, markets and producer investment decisions. Recent upstream cost declines may not immediately translate to the next bull market.

LBE supply curves have accurately captured features of secular trends in oil and gas production operational expenditures, however these are one-third of the marginal costs reported by producers. A focus on learning driven productivity gains as a primary determinant of long-run energy resource costs has blurred the distinction between the specific processes, technologies and decisions on capital expenditures required to produce fossil energy commodities. Each fuel type, geography and geology is not a single manufacturing process, but requires a portfolio of technologies with their own learning rates and potentials. However, there is reason to expect that operational learning curves can extend well into the future to capture potential effects from automation, machine learning and information technology.

Across a century time-span, the production of fossil energy will require multiple manufacturing processes. The history of oil illustrates a dramatic span of technology between the horizontal and deepwater drilling of today and the original 19th-century wells of Drake, Pennsylvania. The work in this chapter suggests the present generation of fossil supply curves structured by the LBE theory have extended a learning model suitable for a single manufacturing process in a given facility.
beyond its plausible boundaries. Recent expansion in supply has required new technologies with a different pattern of development costs, indicating the confines of this framework.

Though the LBE model poorly captures development costs, these expenditures play a significant role in driving marginal cost throughout cycles of demand on the ‘warehouse stock’ of reserve vintages (Section 2.1.3). EIA FRS data suggests development expenditures constitute more than half of oil and gas production in times of fast growing demand, a dynamic articulated by Adelman. While an equilibrium R-P ratio describes essential features of oil and gas producer behavior for knowledge of energy resources, this framework appears of limited value for determining future costs and availability. Varied costs of developing reserves into production has contributed to distinct cycles in the oil and gas reserve base over the last six decades (Section 2.1.3).

The learning-driven productivity modeled in LBE Supply Curves is explained by Rogner (1997) to result from optimal investment: this is only possible in an environment where prices may increase without a maximum threshold of demand on market price, e.g. where demand faces no constraints. This chapter shows that industry investment in capital expenditures is not optimal but faces boundary conditions at regular intervals. Relaxing the assumption of optimal investment for supply expansion opens an avenue for recalibrating long-term outlooks on fossil energy supply.

Nordhaus (2009) argues a learning model of productivity is dangerous for long-term energy studies: there are too many exogenous factors to isolate the contribution of learning-by-doing for a homogenous global energy technology (Section 2.2). Consequently, the assessed contribution of learning is generally biased upwards. Where Adelman (1990) sees the future of the oil and gas industry determined by a tug-of-war between diminishing returns and increasing knowledge. The argument was developed that the LBE theory of fossil supply curves has only pulled this rope in one direction.

Section 2.3 indicates that Nordhaus' concerns apply to the LBE model of future fossil energy, which has the potential to distort the necessary policy costs for reducing future GHG emissions. The sketchbook example in Section 2.3.1 illustrates how estimates of energy resources based on autonomous learning can readily bias energy system reference cases for energy and climate policy: projected costs of mitigation and backstop technologies can easily be framed as net costs or benefits with slight changes to a chosen learning rate. Therefore, a rigorous justification is necessary for any selected learning rate in studies that apply Rogner's theory.

Section 2.3.2 confirms that slight changes to the learning rate for conventional oil in an IAM reference case (GCAM) has a significant influence on projected oil production profiles, and the deployment of high-carbon backstop resources: unconventional oil and coal. This establishes a positive correlation between scenarios with more bullish outlooks for backstop resources, higher levels of 21st-century carbon emissions, and increased costs for climate policy. This finding suggest that high-carbon backstop resource costs and availability could have a significant influence on the economics of climate change since they constitute as much as two-thirds of the total emissions in an IAM scenario. Though unconventional oil is the primary backstop resource for liquid fuel, coal also plays a major role, producing roughly 1,000 GtC of cumulative emissions regardless of the conventional oil learning rate. Accordingly, the next three chapters examine the concept of this coal supply curve, and the role of a coal backstop in IAM scenarios of global energy supply.
Chapter 3: The 1,000 GtC coal question: Are scenarios of vastly expanded future coal combustion still plausible?

As in the GCAM reference cases from Chapter 2, studies of global energy futures commonly derive scenarios by assuming continued growth in demand for primary energy resources. Long-run compounding in these projections lead 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 (Clarke et al., 2014; Energy Modeling Forum, 1995; Grübner et al., 1998; Häfele, 1981; Nakicenovic et al., 2000; World Energy Council, 1993).

Through much of the 20th-century ratios of reserves-to-production (R-P) for coal were very high, providing a theoretical basis 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 2,000 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.

These options can be characterized as three distinct modeling approaches:

- **Method A** - projecting a trend from any selected baseline window by assuming continued momentum in consumption growth, as common in medium-term outlooks. 34
- **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). Chapter 2 (Section 2.1.3) reviewed the equilibrium R-P concept for oil, and the following chapter analyzes this important energy model ideation in the context of coal.

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

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34 Examples include the International Energy Agency’s World Energy Outlooks and the Energy Information Administration’s Annual Energy Outlooks.
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 illustrate how this method is used to understand total geologic occurrences of coal in comparison to ultimately recoverable resource figures of oil and gas (Table 3.1). 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) draws 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.

<table>
<thead>
<tr>
<th>Total resource</th>
<th>Quantity</th>
<th>Resource-to-production</th>
<th>Quantity</th>
<th>Resource-to-production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exajoules (EJ)</td>
<td>1995 production rate</td>
<td>Exajoules (EJ)</td>
<td>2014 production rate</td>
</tr>
<tr>
<td>Oil (conventional)</td>
<td>14,200</td>
<td>100</td>
<td>13,800</td>
<td>80</td>
</tr>
<tr>
<td>Gas (conventional)</td>
<td>16,340</td>
<td>200</td>
<td>16,000</td>
<td>120</td>
</tr>
<tr>
<td>Coal</td>
<td>300,000</td>
<td>3,190</td>
<td>456,100</td>
<td>2,840</td>
</tr>
</tbody>
</table>

*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

†Includes reserves and resources

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.

This chapter 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.

Coal reserves have continually dwindled through the early 21st-century despite theoretically favorable market conditions. Future 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.

As information on world coal has improved (e.g. learning), 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 (Chapter 1 provides a detailed McKelvey box diagram to clarify these definitions). Through this chapter, we can 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 would empirically constrain the plausible quantities of recoverable coal in multi-decade scenarios.

To inform 21st-century coal reference cases, we can 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 more than 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. 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 remaining recoverable coal in today's long-run scenarios. The figure used in this chapter of 15,300 EJ is consistent with the range provided by recent studies and analyzed in Section 3.3.1 such as 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 2015, 2014).

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 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.

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 examine the appropriate context for coal in scenarios of the global energy future, this chapter is organized as follows: Section 3.1 addresses the trends in coal supply since 1990 suitable for inclusion in 21st-century reference cases and understands whether total coal resources have been a ‘stock’ that replenished the ‘flow’ of reserves as with oil and gas. Section 3.2 explains why modern coal assessments indicate fewer reserves than vintage reports and understands what these concepts mean for future coal availability curves. Section 3.3 provides a case study to illustrate how legacy assessments have influenced widely used future energy scenarios in the climate change research community. Section 3.4 concludes with a summary and recommendations for integrating future coal use in multi-decade energy system reference cases which provides a context for the work in Chapter 4.

3.1 Reference case trends in coal reserves, resources, production, and prices

Calibration of a relevant 21st-century coal reference case must focus on hard coal reserves, which contain approximately 90 percent of the energy in the world’s coal resource base (Mohr et al., 2015; 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). Therefore, this section focuses on trends in hard coal reserves.


Figure 3.1a plots the range of reported constant US dollar (USD) prices from 1989 to 2016 across 10 major coal market indices (BP, 2015; EIA, 2012; World Bank, 2016) shaded as a gray band. 35

35 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; 6,300 kcal/kg (11,340 btu/lb), less than 0.8 percent sulfur, 13 percent ash; previously 6,667 kcal/kg (12,000 btu/lb), less than 1.0 percent sulfur, 14 percent ash, International Coal Report; Coal Week International; Coal Week; Bloomberg; IHS
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 (Figure 3.1b).

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 2012-2016,
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 economic theory would expect that higher sustained commodity prices
(demand) reclassify marginal geologic deposits (supply) as economically recoverable reserves. Yet,
since the doubling of coal prices and production in 2000, reserves declined by roughly 15 percent
(Figure 3.1c). 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 (Figure 3.1d).

Because of uncertainties in the energy content of recoverable coal, normalized values are provided
to understand this decline. 36 WEC reports that the large number of assessed reserves from the late
1980s in Figure 3.1d 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.

**Figure 3.1a** Trends in global coal market benchmark prices (BP, 2015; EIA, 2012; World Bank, 2016) – minimum and maximum values indicated by gray range, while red line follows the average of benchmark prices
Figure 3.1b  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

Figure 3.1c  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
3.1.1 Can we use a learning hypothesis to characterize the coal reserve-resource boundary?

Chapter 2 analyzed the learning-by-doing model for future fossil energy supply in the context of cumulative resource availability curves. A similar ideation is applied to structure coal resources for IAMs. As noted in Section 2.3.2, GCAM scenarios with a learning rate of zero or lower were empirically constrained to all known conventional oil resources.

An original aggregate assessment for global coal resources was established by the 1913 International Congress of Geologists (IGC) in Toronto. Since then, the World Energy Council (WEC), previously the World Power Council (WPC), and the German Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe, BGR) have maintained regular publications on total global coal resources. As vintage editions of these assessments are difficult to procure, we can rely on the 20th-century values of the IGC, WPC, WEC and BGR reported by Fettweis (1976), Rogner (1997), Gregory and Rogner (1998), Höok (2010) and Rutledge (2011).

These data indicate global coal reserve base trends have followed a process of ongoing subtraction. In other words, more of what used to be considered recoverable reserves has been reclassified as resources over time, or simply removed from the records. Recent WEC and BGR data are consistent with these trends. The global reserves-to-resources dynamic for coal is depicted in Figure 3.2a, which plots the Rogner (1997) synthesis of BGR (1989) and WEC (1992) next to recent BGR studies (BGR, 2014; 2010) used by the IEA (2006-2015) and against Rogner (2012).

An empirical learning curve for increasing knowledge about the global coal resource base measures an annual decline rate greater than -4% in reserves from Rogner (1997) to the BGR (2015) assessment. A similar trend is present in the WEC and BGR vintage reserve data reported by Höok (2010) which includes lignite.
Fettweis (1976) argues that the primary changes in total world coal resources reported to the IGC (1913) and subsequent assessments through 1970s were: (i) changes in reporting definitions on the depth limit of resources (up to 1,200m, 1,800m, or no limit) (ii) the addition or subtraction of hypothetical ‘prognostic resources’ and (iii) the correction of errors. These factors still appear to contribute to the notorious reputation of modern global coal data.

IEA coal database figures on domestic coal supply do not consistently match reserve or resource numbers in annual Coal Information reports (IEA, 2015). Despite growing production, China’s reported coal reserves remained relatively static since 1992 - confusion has resulted from definitions of economically viable reserves and coal classified as basic reserves which denoted coal-in-place (Wang et al., 2013).

Heterogeneous national definitions of reserves and resources further muddle varied assessment techniques that blur the line between whether a nation’s coal reserves have been quantified with a focus on economic or geologic factors (Fettweis, 1979; Wang et al., 2013) or whether a recovery rate has been applied in determining ‘recoverability’ (BGR 2015). In recent years, WEC has omitted reporting on global coal resources, focusing only on reserves.

The assessed size of the total global hard coal resource base (Figure 3.2b) has only recently surpassed values from the early 20th-century (Dale, 2012). Much of the known geologic coal resource base (~70%) is in the hypothetical prognostic resources of Alaska (28%), Siberia (20%) and China (22%) (BGR, 2014; Flores et al., 2004). Quantities of assessed prognostic resources are based on a favorable geological environment assumed from projections and assumptions of the probable dimensions of a potential deposit (Henley, 2004). Applying a learning induced productivity gain to quantities of energy from prognostic resources does not constitute a plausible context for learning-by-doing.

The following section reviews key literature to understand the factors underlying this ongoing decline in assessed coal reserves, and why they indicate the larger vintage figures from historical studies will not be readopted without significant deviation from reference case trends of technological change.
Figure 3.2a  Coal reserves as a fraction of recent coal resource assessments (BGR, 2014; 2010; Rogner et al., 2012; Rogner, 1997)

Figure 3.2b  Salient assessments of the total coal resource base – key points noted from references (BGR, 2014; 2010; Fettweis, 1976)
3.2 Interpreting the information dynamics of global coal reserves: why are modern reserve assessments smaller than legacy outlooks?

Cumulative production reported by IEA since 2001 accounts for up to 80 percent 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 percent 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. 37

Doubling of annual hard coal production since 2000 (see Figure 3.1b 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 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

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37 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 percent 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.
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 percent would be economically recoverable.

Figure 3.3a demonstrates results from the USGS NCRA assessment which led to an average recovery factor across major US basins of 53%. On average 12% was economically recoverable. After economic factors were applied to recoverable coal in the recent USGS Coal Resource Assessment, economically recoverable resources ranged from 4% (San Juan Basin, New Mexico) to 22% (Piceance Basin, Colorado) of the original resources. Of the original 170 Gt of physical coal studied, 71% was deemed recoverable and 15% as economically recoverable (Luppens et al., 2009).

Data from the USGS NCRA are plotted in Figure 3.3a, where the gray portion of each bar represents coal that was removed through previous mining of the basin. The coal left in each basin is termed remaining and shaded with an orange bar. Various technological and land-use restrictions apply to this remaining coal, meaning that a smaller portion is available for mining. These restrictions removed 20% of the original coal in-place from each deposit on average in the USGS (2009) study. Of this available coal, a smaller portion is recoverable due to the specific techniques required for mining. This recoverable portion is shaded with a green bar in Figure 3.3a, and the total recoverable coal per basin is marked with a black bar. Of this recoverable coal, a smaller amount is economically recoverable (shaded with a pink bar).

The USGS study demonstrates how an initially high R-P ratio encourages less careful assessment of coal deposits: more accuracy is required as the ratio declines. Standard in situ reserve figures generally do not account for feasible recovery rates constrained by factors such as overburden, so the amount of total recoverable coal is often much smaller than initial assessments indicate. The USGS flowchart methodology for determining reserves is depicted in Figure 3.3b, and reinforces the understanding of this process as one of continual reductions as information improves. 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). 38

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38 Initial availability figures for several nations come from assessments in the late 19th-century, such as the initial figure for China of 1,000 Gt provided by German geographer von Richthofen during his surveys from 1877-1911 (Fettweis 1976). Recent data available from the UK indicate that coal supply figures are consistent with those from the 1870s (Department of Energy and Climate Change, 2015). Rutledge (2011) writes that in the UK, the 1871 Royal Commission provided the reserve estimate until 1968, after which the updated quantities of reserves fell rapidly.
Figure 3.3a USGS (2009) coal recoverability study detail by basin – total amount of original in-place (gray), remaining after mining (orange), remaining after land-use and technology restrictions (blue), remaining after projected mining and washing losses (green) and economically recoverable (pink); black bar above each marks recovery factor.

Figure 3.3b Process for calculating economically recoverable coal adapted from USGS (2009)
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 1P, 2P, and 3P reserves, as in oil and gas) \(^{39}\); (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 generally 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.

Through 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 contributed to a 90 percent reduction in Germany’s assessed reserves, alongside modified subsidy regimes.

3.2.1 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

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\(^{39}\) The Society for Petroleum Engineers notes that 1P \textit{proved reserves} indicate at least a 90 percent probability that recovered quantities will equal or exceed the low estimate. 2P reserves include proven + probable reserves, indicating a 50 percent probability that the recovered quantities will equal or exceed the best estimate. 3P reserves include proven, probable, and possible reserves, indicating a 10 percent probability that recovered quantities will equal or exceed the high estimate.
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 centigrade. These conditions convert the in-ground coal to producer gas (a mixture of CO₂, CO, CH₄ and H₂), 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 percent 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 meters highlighted the importance of avoiding aquifer systems because of the potential for explosions. In this case, geological subsidence shifted the underground structure, leading to collapse and a subsequent explosion (Walker, 2007). UCG pilots in many locations have caused severe groundwater contamination that persists for years after gasification ceased, with high concentrations of phenols and PAHs readily detected in aquifers extending dozens of kilometers from the gasification site (Campbell et al., 1979; Friedmann et al., 2009; Klimenko, 2009; Liu et al., 2007). Given the documented public response to large-scale coal synfuel and syngas projects (Yanarella and Green 1987), it 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 percent recovery of the primary energy content of in situ coal. Net energy efficiencies from these experiments were less than 40 percent because of energy input to the gasification process. These older UCG sites had to be located near end uses, since the low-energy gas was less economical to transport than solid coal (Grenon, 1979).

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.

3.3 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 (>150–1,200) 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 Figure 3.1d), the response of markets and industry to a low R-P ratio for coal is unknown. Therefore, the heuristic of an equilibrium R-P for coal is not verified

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40 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 3.4.
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 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 indicates that we can 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 can 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 further serve to indicate a relative ceiling on plausible growth rates in coal
production. For example, Thielemann et al. (2007) consider that realizing 1 percent annual growth in
global coal production is consistent over the long run with 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”.

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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 served as the key hypothesis for generations of widely used energy system reference cases which we analyze in Section 3.4.
3.3.1 How much coal should we assume for long-run scenarios?

Mohr et al. (2015) provide a detailed study of historical coal production by nation and rank to estimate future production potentials based on a detailed model of individual mines, regions and deposits. Table 3.2 lists these cumulative production figures by rank with remaining estimated URR.

Analysis of the methodology for this study indicates that no explicit recovery factor was applied, so it the high level can be interpreted as a hypothetical case of 100% recovery. Thus, assuming perfect information, the lower estimates represent approximately 60% and 30% recovery factors respectively.

Table 3-2 - Mohr et al. (2015) estimate of cumulative production by rank and remaining ultimately recoverable resource (URR) – in exajoules (EJ)

<table>
<thead>
<tr>
<th>Coal Rank</th>
<th>Cumulative Production (through 2012)</th>
<th>Remaining Resource</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Best Guess</td>
</tr>
<tr>
<td>Hard Coals (&gt;16.5MJ/kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anthracite</td>
<td>310</td>
<td>120</td>
</tr>
<tr>
<td>Bituminous</td>
<td>5,200</td>
<td>5,700</td>
</tr>
<tr>
<td>Black</td>
<td>770</td>
<td>800</td>
</tr>
<tr>
<td>Sub-Bituminous</td>
<td>330</td>
<td>230</td>
</tr>
<tr>
<td>Soft Coals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brown</td>
<td>40</td>
<td>70</td>
</tr>
<tr>
<td>Lignite</td>
<td>500</td>
<td>340</td>
</tr>
<tr>
<td>Through 2012</td>
<td>7,140</td>
<td>7,330</td>
</tr>
<tr>
<td>Through 2000</td>
<td>5,400</td>
<td>9,100</td>
</tr>
<tr>
<td>Through 2005</td>
<td>6,000</td>
<td>8,500</td>
</tr>
<tr>
<td>Through 2016</td>
<td>7,700</td>
<td>6,800</td>
</tr>
<tr>
<td>Implied Recovery Factor</td>
<td>30%</td>
<td>63%</td>
</tr>
</tbody>
</table>

Note: Columns do not add because of rounding

Zimmerman (1983) studies the US coal industry and suggests that 50 percent is a reasonable estimate for reserves recoverable from any deposit on a larger scale. Common recovery factors are 80 percent for strip mining and 30-60 percent for underground reserves (Luppens et al., 2009). Reserve recovery in some regions such as India can be as low as 20% (Bauer et al. 2016). As noted in Section 3.2, the mean recovery factor across major US coal basins was 52%. Therefore, a
recovery factor of 50-60% provides a reasonable median estimate and an 80% recovery factor indicates an upper bound for an optimal scenario.

The best guess estimate provided by Mohr et al. (2015) is consistent with the figures provided by BGR (2015). Total remaining hard coal reserves amount to 7,000 EJ, 12,600 EJ and 19,140 EJ respectively for the low, best guess and high estimates. At the plausible upper bound of an 80% recovery factor this indicates 15,300 EJ of recoverable hard coal post-2012. In summary, for a 21st-century supply curve, this analysis indicates that a value on the order of 15,000 to 17,000 EJ is very likely the upper bound coal combustion estimate, assuming the best possible economic and mining conditions.

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.

3.3.2 Revisiting the total carbon supply curve in the context of updated coal estimates

This estimate for long-run coal combustion can be used to inform long-run carbon supply curves for studies of potential greenhouse gas emissions and their eventual climate impacts.

Applying an equilibrium R-P to the total geologic occurrences of coal has allowed 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 3.1 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 3,000 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 (Figure 3.4) 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.
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 4,000 GtC is removed from the supply curve in Figure 3.4a by accepting the implication of modern coal assessments, namely that improving information on reserves has more clearly defined the plausible recoverable portion of the Earth’s geologic coal occurrences. However, many widely used energy scenarios have assumed this level of global coal combustion is the conservative lower bound. The next section examines these scenarios to understand their future coal use profiles.

Figure 3.4  Geologic carbon supply curve for Earth’s fossil occurrences (Rogner 1997) mapped to coal reported at that time; with reserves (Grade A,B,C) in blue, black and red respectively and resources (Grade D,E) in purple and green; assessment for BGR (2015) coal marked in blue dotted line

3.4  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

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41 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.

42 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 MtCO2/EJ. However, our conversion of mass to energy units is a simplification of the carbon content in hard coal, which ranges from 50-86%. 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.
Scope and cost of mitigation efforts and determining climate impacts. 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 (Chapter 5). 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 fromcombustion of 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).

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 1,184 Working Group III (WGIII) scenarios.

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43 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.”

44 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 1,800 GtC with total carbon supply of 6,000 GtC (Nordhaus and Sztorc, 2013). FUND uses the EMF14 standardized scenario (Energy Modeling Forum, 2017) detailed in Table 3.1 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 1,300 GtC from fossil fuels from 2000 to 2100.

45 This chapter 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) have lagged their application in IAMs. For GCMs of the physical climate, the IPCC First and Second assessment reports used equilibrium climate scenarios, the Third uses the IS92 scenarios, the Fourth uses SRES and IS92, and the
3.4.1 Coal in GHG reference case scenarios, 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 1,000 gigatons carbon (GtC) from 2000 to 2100. Figure 3.5 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 32,000 EJ difference between reserves reported in Rogner (1997) and the value of 15,300 EJ calculated 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/m² of year 2100 radiative forcing (IPCC, 1990a). In this scenario, coal accounts for more than two-thirds of the 1,700 EJ primary energy supply at the end of the century, as detailed by WGIII. With global annual coal use at 160 EJ in 2015, this projection would constitute a further 600 percent expansion over the next eight decades (BP, 2015). 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 (Leggett et al., 1992). In the most commonly modeled pathways IS92a and IS92b (Strengers et al., 2004), total primary energy supply (TPES) reaches 4.8 times base-year levels (1,460 EJ) by 2100, with half supplied by coal. Coal-based synfuels provide nearly one-fifth of global primary energy in the IS92a scenario. for context, total global primary energy supply in 2015 used 550 EJ/year.

TAR and AR4 applied 40 baseline scenarios from the IPCC SRES (SRES 2000). 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.

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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.
3.4.2 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 1,184 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 RCP reference cases provide detail on fossil fuel use consistent with scenario archetypes 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 3.4.1 (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). 46

Figure 3.6a 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

46 Each RCP is labeled after a value for future radiative forcing; for example, RCP8.5 leads to 8.5 W/m². 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. These scenarios are described in more detail in Chapter 5.
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 percent from coal.

These marker scenarios for each RCP indicate a “return to coal” (Figure 3.6b) best illustrated by the graphic approach developed by Marchetti (1977) to show the evolution of primary energy shares over time. This return to coal is analyzed in more detail in Chapter 5. 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.

Figure 3.6a  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 (GtCO2)
Figure 3.6b  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

Figure 3.6c  21st-century cumulative CO2 emissions from fossil fuels in final RCP scenarios – 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)

Cumulative 21st-century emissions from fossil fuels and industry (FF&I) for the RCP marker cases are shown in Figure 3.6c (IIASA, 2009). The RCP8.5 scenario for a BAU world expects a total of 7,200 GtCO2 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 3,800 GtCO2. Use of oil and gas release 2,000 and 1,400 GtCO2 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 2,550 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 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 150 million barrels per day (mbd) after midcentury, constituting a smaller portion of total cumulative emissions (2,000 GtCO$_2$) while gas combustion steadily grows, resulting in 1,350 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 1,184 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, 2014). These scenarios are analyzed in detail for their fossil fuel use profiles in Chapter 5. Eleven scenario baseline families project internally consistent sets of characteristics for future society through the year 2100. 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.

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47 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, EMFZ2 Reference (2 variants), RCP Baselines (4 variants) (MESSAGE, AIM, GCAM, IMAGE), GEA Counterfactual, REMIND baseline (3 variants) (Blanford et al., 2014; IPCC WGIII, 2014; Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011a).
Figure 3.7 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 1x (green), 2x (yellow), 3x (red) and greater than 3x (purple).

Figure 3.7 illustrates 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 percent of runs exceed the very likely reserve estimate from Section 3.3.1, 60 percent exceed twice that level, and 12 percent 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 3.1 and Chapter 2). The wisdom of such a modeling paradigm for addressing long-term uncertainty in recoverable coal reserves can be readily questioned, and in Chapter 4 an alternative is proposed that can inform revised 21st-century...
reference case scenarios of coal use. This concept is tested for its influence on IAM energy system scenarios.

3.5 Summary - 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 3.1) 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 3.4. 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 this chapter’s analysis of historical reports and reserve definitions, we can 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.

Section 3.1.1 acknowledges 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, 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 today’s reserves are fully recoverable and that remaining resources have the best possible recovery conditions with an 80% recovery factor (Section 3.3). Adopting modern reserve figures as the empirically constrained supply curve for coal serves to harmonize definitions with those used to identify recoverable portions of oil and gas occurrences.

Models of energy future scenarios 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 can 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 3.4, models of projected energy future scenarios 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 observational constraints 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. Therefore, on the next chapter, we analyze the effect of empirically constrained coal supply curves on IAM scenarios of energy futures.
Chapter 4: An integrated climate change assessment with empirically constrained coal supply and transportation demand

Integrated assessments of climate change use reference case scenarios of the global energy system to illustrate plausible accounts of how greenhouse gas (GHG) emission drivers may unfold in the future. These reference case projections serve as policy baselines because they depict ways the world could develop before any explicit actions are undertaken to reduce GHGs (Clarke et al., 2014). Resulting baseline scenarios provide a landscape for understanding the scope, scale, and composition of future economic development, energy systems, and land-use patterns that help decision makers frame their thinking about the long-term.

Characteristics of reference cases establish core dimensions for assessments of climate policy, low carbon technologies and the economics of mitigation by setting a context that provides confidence for short-term decisions on appropriate costs and tools. Studies of climate impacts, adaptation and vulnerabilities also apply common sets of baseline scenarios to represent outcomes from no explicit policy action on climate change (IPCC, 2013).

The research community uses integrated assessment models (IAMs) to develop GHG reference case scenarios and resulting mitigation cases. As reviewed in Chapter 1 IAMs combine economic, energy system, land use and climate models to provide a framework for ideation, classification and codification of global change drivers. Chapter 3.4 demonstrated how many of the long-run energy system scenarios generated by IAMs have projected the recovery of significantly more coal than indicated by today’s upper bound estimates. This chapter builds on the concepts developed in Chapter 3 to understand how an IAM reference case scenario could be influenced by the ideation of a coal backstop energy supply, and whether an empirically constrained coal supply curve is of consequence to the final results.

For this analysis, we can employ the reference energy system of the Global Change Assessment Model (GCAM) IAM. The GCAM reference case projects ongoing growth in liquid fuel consumption, so that by year-2100, refined fuels per-capita triple from today’s levels, reversing the historical trend of stagnation since 1970. Compounding growth in liquid fuel demand exceeds oil supply after mid-century, leading to the large-scale deployment of a backstop transportation fuel supply from synthetic fuels (synfuels). Liquid fuels from coal illustrate the ‘idealized’ backstop resource following from economic theory (Nordhaus, 1973).

This chapter proceeds by systematically investigating the influence of an empirically constrained coal supply curve and transportation demand on the GCAM reference case. First, in Section 4.1 we develop a prototype reference case based on the concepts in Chapter 3. Then, in Section 4.2 we introduce the GCAM model and describe the characteristics of its reference case energy system. Section 4.3 develops several alternate reference cases based on applying empirical constraints to a single key feature of the scenario’s supply or demand. In Section 4.4 these alternate reference case scenarios are applied to develop climate policy outlooks for RCP4.5 consistent scenarios, and in Section 4.5 for 1.5˚ consistent scenarios.
4.1 Empirically constrained coal: a prototype IAM reference case

In Chapter 3 we analyzed the major factors that distinguish modern coal reserve assessments from legacy reports. These concepts can be used to inform an outlook for an empirically constrained coal supply curve in IAMs. Figure 4.1a plots the long-term coal supply curves reported for two leading IAMs: MESSAGE (green) and GCAM (purple) alongside data from Rogner (1997) (orange) (Joint Global Change Research Institute, 2016; 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 Chapter 3.1). Using detailed mine-level US data, he calculated that doubling of coal production capacity would lead to price increases of 1.65 to 2.94-times the average cost of coal. Zimmerman’s detailed modeling work 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.

21st-century energy scenarios can take these factors into account by reassessing their use of coal resource data. As covered in Chapter 3, 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.

Therefore, empirically constrained coal supply curves should stop within a moving average range of modern reserve figures, such as the BGR (2015) line of Figure 4.1a. Otherwise the nearly 440,000 EJ of total geologic coal resources suggested by BGR (2015) appear as eventual reserves.

Figure 4.1c provides a prototype scenario to illustrate this concept. It adopts two features of the Chapter 3.4 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 continued capital investments at each point in time. 48 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 Figure 4.1c 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 (Figure 4.1b) 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. Therefore, 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 (Figure 4.1c).

In Figure 4.1c 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 Chapter 3.4.

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 percent. In terms of final energy use, gas is far more efficient, so this value is a considerable overestimate of the GHG emissions that would result from substituting gas for coal. Substitution with renewables would lead to a 30 percent reduction. 49 If energy efficiency measures are used to address the 27,000 EJ shortfall, total CO₂ 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, the integrated modeling in the remainder of this chapter is necessary to 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. 50

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48 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.

49 This estimate of substituting renewables for the 27 ZJ residual applies the median life-cycle 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.

50 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 presented in the remainder of this chapter. It merely
Figure 4.1a  Supply curves for coal adopted by IAMs – 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)

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.
Figure 4.1b  Original RCP8.5 total primary energy supply – the RCP8.5 TPES was designed to illustrate 21st-century primary energy production consistent with the extent of theoretically extractable occurrences from the literature (Riahi et al. 2011)
Figure 4.1c 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 7,200 GtCO2 (gray), while direct substitution with gas leads to 6,100 GtCO2 (blue), renewables to 4,950 GtCO2 (orange) and efficiency to 4,600 GICO2 (red). The efficiency case is equivalent to the amount of 2000-2100 cumulative FF&I CO2 emissions illustrated by mitigation efforts in the RCP6.0 marker scenario.

4.2 The GCAM reference energy system (GCAM-ref) and its high-carbon backstop

The prototype long-run energy system scenario of Figure 4.1c does not provide an integrated picture of the potential influence empirically constrained coal supply curves could have on projections of future supply and demand. Therefore, we can employ the GCAM IAM to test the influence of the coal backstop on a long-run energy system reference case in the remainder of this chapter.

GCAM has been a key IAM used in IPCC assessments and climate policy research over the last two decades, providing a world model that traces interactions between the macro-economy, energy system, land system, water supplies and the physical Earth. The energy sector of GCAM is based on the Edmonds-Reilly energy model (Edmonds and Reilly, 1983a; 1983b; 1983c). The Edmonds-Reilly model was renamed MiniCAM in the mid-1990s, and then renamed to GCAM in the mid-2000s (JGCRI, 2016a). GCAM is primarily maintained and developed by the Joint Global Change Research Institute (JGCRI) at Pacific Northwest National Labs (PNNL). The lineage of models that preceded GCAM were originally designed to answer research questions related to the total amount of mid 21st-century fossil fuels that would be available and combusted, as in the original papers on the Edmonds-Reilly model (Edmonds and Reilly, 1983c; 1983b; 1983a).
As a Representative Concentration Pathway (RCP)-class model, GCAM generates internally consistent sets of the full suite of GHG emissions which are components of the anthropogenic contribution to changes in radiative forcing (RF). Accordingly, simulation outputs from GCAM readily compare with scenarios, policies, and emission targets used by the IPCC and the broader research community. GCAM has produced global fossil fuel emission scenarios from the very first IPCC assessment through the latest suite of SSP scenarios.

Among leading IAMs, GCAM is commendable as the only one openly available in open-source, with a common system of XML files that allow for information sharing among researchers. Because the model is deterministic, parallel runs with the same input files will produce the same output results, allowing GCAM to serve as a useful tool for comparing scenarios throughout the research community. To ensure that GCAM’s results are interpreted and understood in the appropriate context, we can initially draw from the GCAM overview to describe the key features of this model (JGCRI, 2016a).

4.2.1 GCAM core features: description of ideation, macroeconomics and energy system

GCAM’s core operating principle (ideation) is based on establishing market equilibrium through interactions between representative agents. Resources are allocated by representative agents in GCAM as they draw from information based on prices to make decisions. Representative agents exist in various regions and sectors of the model, and make decisions to shape features such as land allocation, technology choice, energy demand, and electricity. These agents interact through transferring goods and services to the market.

The GCAM solver seeks market equilibrium by establishing a set of prices that create a balance between supply and demand in all markets in all regions. As a recursive and dynamic partial equilibrium model, GCAM solves for prices in 32 distinct regions during each scenario run. These prices are established in each period based on the current period, rather than through an optimization over the entire scenario. For each time step GCAM looks for a price vector that clears all markets through mapping input prices ($\hat{p}$) to output disequilibria ($\hat{y}$) with: $\hat{y} = F(\hat{p})$. The GCAM solver seeks the root of the equation where $0 = F(\hat{p})$.

Though GCAM supports several different solvers, the Broyden Solver is the most stable because it converges on a solution through backtracking iteratively to ensure that each set of prices leads to an improved approximation of $0 = F(\hat{p})$ (JGCRI, 2016b). However, this backtracking procedure leads to critical instabilities when one or more prices has no impact on excess demand in solved markets – this occurs at high and low price extremes. GCAM’s input supply and demand functions saturate in these price regimes, creating zero derivatives of the iteration steps which is an intractable condition for the solver.

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51 This study applies GCAM v4.2 to provide comparability of results with broader series of IAM model outputs projected in the SSP-RCp scenario framework and the IPCC WGIII Database. As of late 2016 there is a revised version of GCAM v4.3. The main feature of this new version replaces the MAGICC model of climate change with the ‘hector’ model. For this work, GCAM 4.2 is applied because the newer version is unstable in its link between the GCAM solver and the hector climate model for relatively modest policy targets, e.g. solving for RCP4.5 led to many discontinuities with the unmodified reference energy system.

52 Each five-year period of the model is solved independently, but information passes from one to the next.
GCAM’s macroeconomic system provides a one-way transfer of information to the other model components, and sets the scale of the human enterprise. The other GCAM systems (energy, Earth, water, land) do not influence GDP. GDP in each of the 32 regions is calculated using a simple formulation based on population and GDP growth rates with Equation 4.1 where GDP is the size of the economy, P is population, and r is the GDP per capita growth rate.

\[ GDP = P \left( \frac{dP}{P} \right) (1 + r) \]  

(4.1)

The energy sector in GCAM is classified based on three stages: (i) primary energy - energy resources, (ii) secondary energy - energy transformation and (iii) final energy - final energy demand. Energy resources include oil (conventional and unconventional), natural gas, coal, uranium, wind, solar, geothermal, hydropower, biomass and traditional biomass. Energy transformation describes all processes between energy resources and sectors of final demand. The energy transformation sectors are: electricity, refining, natural gas processing, hydrogen production and district services. Final energy consumption sectors include buildings, industry and transportation.

Each transformation subsector has a ‘nest’ of possible technology choices to model competition between different fuels and feedstocks in meeting final demand. This competition is determined by a logit function which shapes the share of each technology and its momentum. Where multiple factors influence a choice, representative agents choose between a series of preferences ordered by prices. Each factor involved in a technology decision is converted into a set of prices, and less desirable options are assigned a cost penalty which is added to the basic prices. This allows decision elements to be condensed into a single indicator quantified by price.

An example from Chapter 7 demonstrates how this set of choices is operationally implemented: agents prefer faster transportation modes, so all slower modes are assigned a cost penalty. An example from the refining sector is relevant to this chapter: technologies for refining in GCAM can choose between oil, biomass liquids, coal-to-liquids and gas-to-liquids. Though the majority of the world’s coal-to-liquids (CTL) production is in South Africa today, this technology is available to all regions in GCAM starting in the first future time period. The GCAM energy system documentation notes that CTL is substantially more CO2 intensive than other refining technologies – where crude oil emits approximately 5.5 kg CO2 per GJ of fuel, CTL emits over 130 kg CO2 per GJ.

Since GDP is a one-way input into the energy system and this chapter is focused on examining the influence of empirically constrained coal on energy system reference cases and associated outlooks for mitigation, we can leave further detail on GCAM’s socioeconomics and demand factors to Chapter 7.

4.2.2 GCAM-ref: total primary energy supply and refinery inputs

The GCAM reference energy system (GCAM-ref) serves as the baseline for this study. The primary energy supply of GCAM-ref is plotted in Figure 4.2a. TPES grows rapidly throughout the century to reach 1,480 EJ/year by 2100 - 2.7-times today’s level of 550 EJ/year (BP, 2016). The composition of TPES in GCAM-ref features a modest 2030 peak and decline for oil supply offset by expansion of unconventional resources, gradual growth for natural gas, nuclear, and renewables, and rapid
expansion after mid-century for coal and biomass. Because the largest proportion of final energy from 2015-2100 is liquid fuels (40-45%), we focus on inputs to refineries throughout this section.

Expanded primary energy supplied from coal and biomass after 2030 comes from a burgeoning synfuel industry which relies on CTL, with GTL, cellulosic ethanol and BTL (FT Biofuels) playing a minor role (Figure 4.2b). Essentially unconstrained low-cost coal, high liquid transportation demand and ambitious technological progress in CTL produce the conditions for a ‘return-to-coal’ in GCAM-ref. CTL becomes a major transportation fuel after 2030, reaching 30% of year-2100 refinery inputs at 98 million barrels per day oil equivalent (mbd) (Figure 4.2b). Compared to today, total liquids in 2015 averaged 94 mbd with refined fuels at 82 mbd on average (International Energy Agency, 2016). Thus, while GCAM-ref reports refinery inputs for CTL larger than today’s total liquids production, a diverse portfolio of liquid fuel options ensures that CTL only composes 30% of total refinery inputs at century’s end. Other major synfuel technologies at this time include GTL (9.8% year-2100 supply) and BTL (5.8%). Total fuel from FT processes totals 130 mbd.

Figure 4.2c examines GCAM-ref refinery inputs per-capita levels alongside historical trends. In the GCAM reference case per-capita liquids demand (green circles) grows from 1990-2100 at a rate of 1.3% per year (compound annual growth — CAGR), breaking with the -0.3% p.a. decline since 1971 (black line).

Despite the rapid scale-up of coal, production costs remain relatively stable, with costs that peak later in the century around 20% higher than today’s level (Figure 4.2d). Coal costs increase faster than those for oil and biomass. However, costs for natural gas increase at roughly twice the rate of coal.
Figure 4.2a  GCAM-ref energy system (1990-2100) – total primary energy supply in EJ per year: oil (blue), natural gas (red), coal (green), biomass (yellow) and nuclear, hydro, solar, wind and other (gray)

Figure 4.2b  GCAM-ref refinery inputs by technology (1990-2100) – oil refining (blue), coal-to-liquids (red), gas-to-liquids (green), Fischer-Tropsch biofuels (yellow), cellulosic ethanol (light blue), and biodiesel, sugar cane and corn ethanol (gray)
Figure 4.2c  GCAM-ref refinery inputs per-capita (1971-2100) – GCAM-ref (green) and IEA historical data (black)

Figure 4.2d  GCAM-ref primary energy resource costs (1990-2100) – normalized to 2015; oil (blue), natural gas (red), coal (green), biomass (yellow)
4.2.3 Coal-based synfuels represent a theoretical high-carbon backstop resource in the GCAM-ref energy system

The rapid scale-up of synfuel technologies to meet vastly expanded demand with virtually no resource cost increase in GCAM-ref illustrates the economic concept of an idealized backstop. Backstop resources have a robustly articulated theoretical basis in economics, and have accordingly played a major role in policy models (e.g. since Nordhaus, 1973). The liquid fuel backstop in GCAM is applied to depict which technologies could enable continuously compounding demand growth. This ‘upside’ backstop allows perfect substitution for today’s refined fuels in final energy demand if the scale of transportation services outstrips the supply available from our current use of oil.

Synfuels provide a common candidate in long-run outlooks for a transportation fuel backstop because total potential resource availability of coal, biomass and gas methane hydrates are more extensive than oil resources and the technology exists to convert these to liquids. Resources with high ratios of resources-to-production tend to shape the outlook for which liquids backstop is chosen in a long-run policy model since the total quantity can be readily included in an LBE supply curve and it ‘never runs out’, allowing demand to grow without constraint.

Though today’s reserve-to-production ratios and synthetic fuel production costs may not justify immediate substitution of synthetic refinery inputs for the liquid transportation fuels that supply passenger vehicles, freight, aviation or shipping, it is considered that the total inventory of geological resources will eventually be reclassified as economically recoverable reserves within an equilibrium range (Rogner, 1997; Wellmer, 2008; Wellmer and Berner, 1997). Thus, long-run policy models have tended to favor high R-P resources as the backstop (GEA, 2012; Häfele et al., 1981; Nakicenovic et al., 2000; Riahi et al., 2011).

Commercial prospects for expanded production of synfuels use the well-known Fischer-Tropsch (FT) process to convert coal (CTL), biomass (BTL) and gas (GTL) into liquid fuels (commonly abbreviated X-to-L). FT synthesis applies a series of chemical reactions to develop liquid hydrocarbons from feedstocks such as coal, natural gas or biomass.

Coal-based liquids have achieved remarkable resource efficiencies of 3 tons coal and 4 tons water per ton of oil equivalent, allowing CTL technologies to readily scale-up in regions that combine geologically favorable conditions for vast coal formation, extensive freshwater supplies and support from local populations (Couch, 2008; Höök and Aleklett, 2010; Höök et al., 2014). Though modern synfuels supply as much as 0.3% of today’s total global liquids production, they have been applied extensively during vigorous periods of economic transformation during the 20th-century, such as in South Africa after the 1950s and Germany during the 1930-1940s.

Deployment of CTL in GCAM-ref is equivalent to 80mbd from 2050-2100, yet as shown in Figure 4.2d the cost of coal supply remains virtually static. These are highly idealized demand and supply conditions that emulate theoretical expectations for a ‘high-carbon’ backstop for the global energy supply.

Weyant (1993) considered the role of backstop resources for his review of climate policy costs in the early energy policy models upon which GCAM is based:

[T]he degree to which “backstop” technology assumptions – advanced technologies with high cost and unlimited supply – are employed has a large impact on the cost of control
estimates… in lieu of backstops, some analysts use resource supply curves with large flat segments at higher prices… Most long-run projections of the costs of controlling carbon emissions foresee a major role for coal in the future baseline energy mix, and since coal is abundant on a global basis, this assumption limits future energy prices increases… Manne and Richels (1990) who include both a carbon-base backstop (like synthetic oil from coal) in their analysis, and a carbon-free energy backstop (like synthetic oil from biomass) in their analysis, have observed that the long-run carbon tax in such a set-up can be calculated on the back of an envelope, as the difference between the costs of the carbon-free and carbon-based backstops, divided by the carbon emissions rate of the carbon-backstop… In the long run, the assumptions made about the cost of substitutes for conventional oil and gas determine the cost of controlling carbon emissions. It is generally assumed that the long-run carbon-based fuel alternatives (for example coal generated electricity and coal based liquid synthetic fuels) will be less expensive than non-carbon alternatives (like solar-generated electricity and liquid fuels made from biomass). If this were not the case, there would be no projected long-run costs of controlling carbon emissions.

Though simulations of technology and policy since 1993 have become more sophisticated than the simple backstop example described by Weyant, his review included the original Edmonds-Reilly model at the root of GCAM, and distinctly noted that while some models include explicit backstops, others employ a backstop through a roughly flat resource supply curve that levels off at a certain point as covered in Chapter 3 and Section 4.1.

Weyant’s example of the backstop price can be more formally represented as in Figure 4.3 which depicts a conventional supply-demand plot with quantity of fossil carbon (Q) on the horizontal axis and price (P) of energy on the vertical axis. In the reference case plot (Figure 4.3a) the geologically present fossil supply curve (S1) intersects with the low-carbon supply curve (S2) after a considerable quantity of carbon emissions. In Figure 4.3b the empirically constrained carbon supply curve cost accelerates more rapidly, and intersects the low carbon backstop price after only 2,500 GtC of carbon emissions. In each plot point C represents the intersection between demand and carbon supply. As the area of the triangle formed by points A-B-C in the empirically constrained fossil case is smaller than in the geologically present case, the gap between the cost of the carbon and low-carbon supply is smaller, leading to a lower policy cost to reduce carbon emissions. 53

53 The price and quantity values used in Figure 4.3 are applied to characterize this case and have not been calibrated to stand-alone, they are merely illustrative.
Figure 4.3a  Case A: reference case of carbon supply curves with geologically present carbon supply – geologically present fossil supply curve (S1) and low carbon supply (S2) with demand curve (D1)

Figure 4.3b  Case B: carbon and low-carbon supply curves with empirically constrained carbon supply – empirically constrained fossil supply curve (S1*) and low carbon supply (S2) with demand curve (D1)
4.2.4 GCAM-ref climate outcomes

Rapid expansion of carbon intensive coal-based liquids in GCAM-ref leads to ongoing growth in CO₂ emissions from transportation after other major sectors begin stagnating in 2070 once global population reaches a maximum (Figure 4.4a). In GCAM-ref CO₂ emissions from coal-based liquids are exceeded only by those from coal in electricity use by year 2100. Total emissions from coal are 53% of the 21st-century cumulative carbon released to the atmosphere by this reference case scenario. Major components of radiative forcing (RF) from GCAM-ref are plotted in Figure 4.4b using the MAGICC 6.8.1 climate model. Cumulative 21st-century CO₂ emissions of 6,250 GtCO₂ with 38% from transportation and liquid fuels results in an RF of 6.6 W/m², and a global mean surface temperature increase (ΔGMST) of 3.8°. ⁵⁴

4.2.4.1 Notes on GCAM and MAGICC methodology

These projections of radiative forcing are adjusted from the raw MAGICC outputs to simplify their presentation independent of all RF components such as snow, land use, mineral dust, or clouds. Though the total RF depicted in Figure 4.2b is consistent with the final output from MAGICC (RF_total = 6.6 W/m²), the specific contribution of each gas depicted is around 5% lower to account for earth system interactions and atmospheric forcing components that reduce total RF. The full GHG emission profile of GCAM-ref results in total GHG forcing of 7.05 W/m² with contributions from major GHGs of CO₂ [5.76 W/m²], CH₄ [0.78 W/m²], N₂O [0.22 W/m²] and F-gases [0.22 W/m²]. In Figure 4.2b, these four major GHGs are scaled per-year in the time-series using a ratio between their combined contribution and the final total: for year-2100 the total effect of these four gases is RF_majorGHGs = 6.98 W/m² so the scaling factor is \( \frac{RF_{total}}{RF_{majorGHGs}} = \frac{6.6}{6.98} = 0.95 \).

Climate projections in this work are conducted with MAGICC 6.8.1 using CMIP3 climate change parameters and C4MIP-BERN settings which were used to produce the original RCP results. Because GCAM does not provide per-sector detail on sources of fluorinated gases (F-gases), in non-mitigation cases, emissions from F-gases were harmonized with the RCP8.5 scenario from the IIASA RCP Database. In moderate mitigation cases, F-gases are harmonized with RCP4.5 and mitigation cases that aim for 1.5°C F-gases are harmonized with RCP2.6.

Further note on methods: GCAM uses MAGICC 5.3 for internal climate projections which has been adapted to Coupled Model Intercomparison Project 5 (CMIP5) outputs which generally have higher RF forcings and lower GMST due to sensitivity changes. Throughout this chapter, we report results from MAGICC 6.8.01 with CMIP4 tunings pre-AR5, thus GMST response is higher and RF is lower than CMIP5 climate model tunings.
Figure 4.4a  CO2 Emissions in GCAM-ref by sector – transportation and liquids (blue), electricity (red), industry (green), gas systems (yellow), buildings (light blue)

Figure 4.4b  Radiative forcing in GCAM-ref by GHG component – CO2 (blue), CH4 (brown), N2O (brown), fluorinated gases (light blue); top axis notes the global mean surface temperature increase in each year of the time-series
4.3 Developing alternate GCAM reference cases based on empirically constrained supply and demand factors

As discussed in Section 4.2.3, GCAM deploys a high-carbon backstop in the form of coal to supply high levels of demand for liquid fuels. Since GCAM is a model based on the operational principles of supply-demand equilibrium, a coal-supply empirical constraint can only be fully explored in the context of scenarios that also assess the influence of demand.

Therefore, to test the influence of the demand and supply assumptions that generate GCAM's carbon backstop, this section develops two alternative reference cases, and a synthesis case to examine their combined effect. GCAM-ref serves as the baseline for these reference case modifications and is noted as reference case [I]: I-GCAM-ref.

4.3.1 Alternate reference case [II] - GCAM-Empirically Constrained Coal (ECCo)

Developments in coal markets over the last twenty-five years reflect trends in the global economy, society, and technology that have better distinguished recoverable coal from the total amount that geologically exists (Chapter 3). Integrating the recovery factors observed from major coal mining regions into an analysis of future coal supply potential suggests the plausible long-term projection of fuel available from coal is within the range represented by modern reserve figures (15-17 ZJ) rather than the entirety geologic coal described by total resources (>400 ZJ) (See Section 3.3.1).

Therefore, we can make two changes to the coal supply curve used by GCAM-ref (I-GCAM-ref) to develop an alternate reference case that illustrates empirically constrained coal (II-GCAM-ECCo):

1. **Coal availability**: coal in the GCAM-ref supply curve is reduced from 265 ZJ to 16 ZJ (a value between 15-17 ZJ)

2. **Coal cost and internal consistency**: this coal is distributed across the six cost categories used by GCAM-ref to provide an internally consistent representation of the increasing coal supply costs observed over the last decade – this effectively doubles the rate of cost increases in GCAM-ref under bullish demand conditions

Both modifications are not intended to fully calibrate the coal supply curve in GCAM-ref to observed price trajectories, but to merely test the sensitivity of the GCAM outputs to a supply curve that begins to resemble essential features of empirical trends.

These two changes shift the coal supply curve (**Figure 4.5a**) from the original position of I-GCAM-ref (S1) to the new supply curve for reference case II (S2). Primary energy cost categories in S2 remain the same as in GCAM-ref (left-axis). In both reference cases. Both the original and the modified supply curves are subject to a $\rho = +0.75\%$ p.a. learning effect in the work conducted for this chapter (Chapter 2).

S2 leads to projections of higher primary energy costs for coal in II-GCAM-ECCo compared to I-GCAM-ref (**Figure 4.5b**). The cost of primary energy from coal in II-GCAM-ECCo (dark blue) is plotted in **Figure 4.5b** alongside the cost curve of I-GCAM-ref (brown) for the period through mid-century – both are normalized to the year 1990 (1990 = 100). Coal supply costs in the modified reference case gradually increase until the base year cost doubles around mid-century. After 2060,
coal supply costs in I-GCAM-ref maintain their slope, while in II-GCAM-ECCo the slope increases, and the price trajectory accelerates toward infinity. This is effectively the same as the original RCP8.5 scenario from Section 4.1, since in the year after 2100 (2101), the amount of remaining recoverable coal in that reference case would also zero out.

A range of marker prices from thirty coal indices are plotted alongside the cost curves of both reference cases in Figure 4.5b (Chapter 3.1). Maximum and minimum prices (orange and blue dashed lines) for these data are indexed to the average of this series for year 1990 (yellow sold line). Though the cost of coal projected by II-GCAM-ECCo increases faster than in I-GCAM-ref, the rise is far more gradual than observed market trends. Despite five years of price declines from 2010-2015, the average coal market price in constant dollars has fallen to a level that is still twice the year 2000 price in constant dollars – a level not reached until 2055 in reference case [II] and 2100 in I-GCAM-ref.

GCAM-ECCo phases out coal before 2070 leading to a call on primary energy from oil, natural gas, biomass, nuclear power, wind and solar to meet late-century demand (Figure 4.5c). Primary energy demand formerly met by coal rebounds to other energy resources in reference case II, at a ratio of approximately 1 EJ coal to 2/3 EJ of another resource. By 2100 coal is replaced with 20% more oil, 25% more natural gas, 5% more biomass and nuclear, and 2% more wind and solar than the original I-GCAM-ref. The coal phase-out eliminates the original contribution of 96 million barrels per day oil equivalent (mbdoe) of CTL from I-GCAM-ref with as much as 72 mbd of oil by end of the century (Figure 4.5d). GTL fills most of the gap between oil and demand after 2060.

Reductions in CTL deployment curtails transportation sector CO₂ emissions by up to 10 GtCO₂/year compared to I-GCAM-ref. Larger total GHG declines occur in electricity and industry as natural gas, nuclear, wind and solar provide lower carbon electricity (Figure 4.5e). Cumulative 21st-century emissions in alternate reference case [II] reaches 5,750 GtCO₂ - a 20% overall reduction from GCAM-ref.
Figure 4.5a  Supply curve for coal empirically constrained from I-GCAM-ref to II-GCAM-ECCo – the I-GCAM-ref supply curve ($S_1$) shifts to the left to create the II-GCAM-ECCo-supply curve ($S_2$).
Figure 4.5b  Coal supply costs in I-GCAM-ref and II-GCAM-ECCo – The II-GCAM-ECCo supply curve leads to primary costs (dark blue) that increase faster than in I-GCAM-ref (brown), but both reference runs fall underneath the observed trend in average market prices (yellow solid line) from thirty major coal market prices (Chapter 3.1), summarized by the gray range between maximum (orange dotted line) and minimum prices (blue dotted line)
Figure 4.5c  Change in primary energy by resource: II-GCAM-ECCo from I-GCAM-ref – ΔEJ/year primary energy from oil (blue), natural gas (red), coal (green), biomass (yellow) and other sources (gray)

Figure 4.5d  Change in refined fuels: II-GCAM-ECCo from I-GCAM-ref – ΔEJ/year refinery inputs from oil (blue), GTL (red), CTL (green), BTL (yellow) and cellulosic ethanol (light blue) and other (gray)
4.3.2 Alternate reference case [III] – GCAM-Demand Empirically Constrained to Observed Rates (DECOR)

Climate change assessments generally proceed by assuming that the human population will be better off in the future than it is today. This increase in future wealth is expressed by IAM scenarios with ongoing growth in GDP. However, socioeconomic developments over a century are a speculative venture. There is simply no way of knowing what may happen to expenditures on transportation if global per-capita incomes grow by seven times as in the GCAM-reference case. Though these issues are explored with more depth in Chapter 7, for this section, it is important to note that GCAM formulates energy service demand using an estimate of the income elasticity of transportation demand (the amount that demand increases with respect to changes in income). 55

The unmodified I-GCAM-ref scenario projects a static and unchanged income elasticity value for each transportation service mode in all time periods (Figure 4.6a). Yet, previous versions of GCAM (v3) assumed an ongoing decline in the income elasticity of demand for transportation services through the year 2100. The case for a gradually declining transportation service demand income elasticity follows from several empirical observations:

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55 GCAM uses a price and income elasticity to calibrate transportation demand, however with 7-times higher per-capita GDP and low-cost energy by 2100, income elasticity becomes the primary determinant of transportation demand (see Chapter 7).
(1) as nations have developed, initial income elasticities for transportation demand rapidly increased, and then declined over time (Fouquet, 2012)

(2) nations with slow growing populations have demonstrated the lowest income elasticities for transportation demand, e.g. Japan and Germany, as reflected in the GCAM3 data

(3) upon initial adoption, transportation infrastructures show evidence of rapid growth before plateau and saturation in many nations (Grübler, 1990)

Accordingly, this alternative GCAM reference case III-GCAM-Demand Empirically Constrained to Observed Rates (DECOR) adapts the regional values for aviation, passenger transport and freight reported by GCAM3, but with a slightly higher rate of decline after global population growth reaches a maximum, accounting for post-2005 developments in OECD nation transportation. In many developing regions, this modification leads to higher elasticities in earlier periods than GCAM-ref with lower elasticities across the world in later periods. The income elasticity for freight remains homogenous across regions, as in GCAM-ref, but follows a path of gradual decline.

**Figure 4.6b** depicts the profile of income elasticities for transportation service demand employed by this alternate reference. The range of regional elasticities for passenger and aviation demand are shown by the shaded gray area, while the solid green lines mark the minimum and maximum values throughout the time series. The red solid line shows the average income elasticity across all regions. A dotted blue line illustrates the homogenous value applied for global freight demand income elasticity.

Dashed lines in **Figure 4.6b** display income elasticity trends in three marker regions. South America (red dashed line) starts higher than the global average and stays above it for all periods despite a gradual decline. China (green dashed line) begins the century much above average but decades of rapid industrialization since the 1990s lead to a more rapid decline in transportation expenditures, so the nation’s late century profile more closely corresponds to that of developed regions. The EU-12 (yellow dashed line) starts the century below average, and then declines faster around mid-century, reflecting its demographic transition.

Per-capita transportation expenditure patterns in I-GCAM-ref (**Figure 4.6c**) emphasize rapidly growing demand for aviation and freight with moderate growth for shipping and passenger transport and rapid declines for bus, walking and cycling (this transportation demand profile is addressed with more detail in Chapter 7). Modifying these income elasticities for relative consistency with an empirically observed trend of modest decline results in reference case [III] which projects the global transportation services of **Figure 4.6d**. In this alternate reference case, per-capita aviation demand (yellow triangles) only doubles by 2060 and then levels off later in the century, freight (red circles) increases by a multiple of 2.5, while passenger transport (green triangles) begins a gradual decline after 2030. These simple modifications to income elasticities also lead GCAM to also reduce per-capita walking (purple triangles) and cycling (silver triangles) further below the levels of GCAM-ref.

**Figure 4.6e** compares changes in per-capita transportation services in III-GCAM-DECOR from the I-GCAM-ref baseline in the three major transportation modes for liquid fuel demand. The modified
income elasticities for transportation demand in reference case [III] reduce demand for international aviation by up to 70% (yellow), passenger transport by up to 60% and freight by 40%.

Lower demand for transportation services in alternate reference case [III] leads to an 8 ZJ (8%) reduction from GCAM-ref in cumulative global primary energy over 1990-2100 (Figure 4.6f). Coal resources experience the highest level of curtailment (up to 100 EJ/yr), followed by natural gas (up to 55 EJ/yr) and oil (up 80 EJ/year) versus the original reference case. All technologies for liquid fuel supply are reduced GCAM-ref by as much as 200 EJ by year 2100 - an amount equivalent to 100 mbdoe (Figure 4.6g). Refined liquids in 2100 from oil, CTL and GTL fall 50 mbd, 32 mbd and 10 mbd respectively. Lower use of fossil fuel resources also reduce cumulative CO₂ emissions in [III] from GCAM-ref by 9%, leading to a release of 6,600 GtCO₂ vs. 7,240 GtCO₂ (Figure 4.6h).

Figure 4.6a Transportation service demand income elasticities for the original GCAM reference case – the I-GCAM-ref regional transportation service demand income elasticities for passenger transport and aviation (blue solid line) and freight (dotted blue line)
Figure 4.6b  Transportation service demand income elasticities for the alternate III-GCAM-DECOR reference case – the III-GCAM-DECOR regional transportation service demand income elasticities for passenger transport and aviation adapted from GCAM version 3 with regional decline rates empirically calibrated post-2005: freight (dotted blue line), average income elasticity across all regions (solid red line), minimum and maximum (green), several example countries include China (green dashed line), EU-12 (yellow dashed line), South America (red dashed line)
Figure 4.6c  Global transportation service demand by mode in I-GCAM-ref – transportation demand by mode per capita (based on kilometers per capita), normalized to the year-2015 level; aviation (yellow), freight (red), international shipping (blue), passenger transportation (green), bus and light duty vehicles (blue), walking (purple), cycling (silver)
Figure 4.6d  Global transportation service demand by mode in III-GCAM-DECOR – transportation demand by mode per capita (based on kilometers per capita), normalized to the year-2015 level: aviation (yellow), freight (red), international shipping (blue), passenger transportation (green), bus and light duty vehicles (blue), walking (purple), cycling (silver)
Figure 4.6e  Global transportation service demand change by major modes in III-GCAM-DECOR from I-GCAM-ref – aviation (yellow), freight (red), passenger transportation (green)

Figure 4.6f  Change in primary energy by resource: III-GCAM-DECOR from I-GCAM-ref – ΔEJ/year primary energy from oil (blue), natural gas (red), coal (green), biomass (yellow) and other sources (gray)
Figure 4.6g  Change in refined fuels: III-GCAM-DECOR from I-GCAM-ref – $\Delta E_J$/year refinery inputs from oil (blue), GTL (red), CTL (green), BTL (yellow) and cellulosic ethanol (light blue) and other (gray)

Figure 4.6h  Change in CO2 emissions by sector: III-GCAM-DECOR from I-GCAM-ref – $\Delta GtCO_2$/year emissions from top 5 sectors – transportation and liquids (blue), electricity (red), industry (green), gas systems (yellow), buildings (light blue)
4.3.3 A synthesis reference case: [IV] - GCAM— Supply and Transportation Observationally Constrained (STOiC)

Our fourth reference case [IV] combines the transportation demand and coal supply constraints of cases [II] and [III] to develop a synthesized scenario: GCAM-Supply and Transportation Observationally Constrained (IV-GCAM-STOiC).

Lower demand for transportation services combined with a coal phase-out by 2070 leads the projected IV-GCAM-STOiC primary energy supply to rely on more biomass, oil and natural gas as in [III], but to a smaller degree (Figure 4.7a). Rebound of primary resource supply in year-2100 to oil is just 1%, natural gas at 17% and biomass at 3%.

Though synfuels still play a role in GCAM-STOiC, they are less pronounced – average synfuel deployment from 2050-2100 is less than 60 mbdoe (Figure 4.7b). The CO₂ emission profile for this reference case results in significant late century declines in transportation, electricity and industry, more than either of the reference case modifications achieve in isolation (Figure 4.7c). CO₂ emissions from transportation and electricity fall by more than 50% after 2065 vs. a 26% and 30% decline over this period in reference cases [II] and [III]. The total cumulative emissions in IV reach 5,300 GtCO₂ – a 25% reduction from I-GCAM-ref.

Figure 4.7a Change in primary energy by resource: IV-GCAM-STOiC from I-GCAM-ref – ΔEJ/year primary energy from oil (blue), natural gas (red), coal (green), biomass (yellow) and other sources (gray)
**Figure 4.7b** Change in refined fuels: IV-GCAM-STOiC from I-GCAM-ref – $\Delta EJ$/year refinery inputs from oil (blue), GTL (red), CTL (green), BTL (yellow) and cellulosic ethanol (light blue) and other (gray)

**Figure 4.7c** Change in CO2 emissions by sector: IV-GCAM-STOiC from I-GCAM-ref – $\Delta GtCO_2$/year emissions from top 5 sectors – transportation and liquids (blue), electricity (red), industry (green), gas systems (yellow), buildings (light blue)
4.3.4 Summary of alternative reference cases

With these four alternate GCAM reference cases articulated, we can summarize their climate outcomes, and energy system outlooks.

4.3.4.1 Climate outcomes of alt-ref cases [II], [III] and [IV]

The GHG profiles of each reference case applied to MAGICC result in the climate change outcomes depicted by Figures 4.8a-c. The demand constrained case [III] leads to a 0.4 W/m² reduction from original reference case GHG forcing of 6.6 W/m² by year-2100 (Figure 4.8b). RF from GHGs fall further from the baseline with reference case [II], reaching a maximum of 5.6 W/m² in year 2100 (Figure 4.8a). In the synthesis reference case [IV] RF reaches 5.2 W/m² – a 1.4 W/m² reduction from I-GCAM-ref (Figure 4.8c). The modified reference cases produce probabilistic 21st century changes in global mean surface temperatures (ΔGMST) outcomes with medians of 3.1° (IV) to 3.6° (II) by varying historical parameters through 600 iterations (Figures 4.8d-f).

Figure 4.8a  Change in radiative forcing by component: II-GCAM-ECCo from I-GCAM-ref – CO₂ (blue), CH₄ (brown), N₂O (brown)
Figure 4.8b  Change in radiative forcing by component: III-GCAM-DECOR from I-GCAM-ref – CO2 (blue), CH4 (brown), N2O (brown)

Figure 4.8c  Change in radiative forcing by component: IV-GCAM-STOiC from I-GCAM-ref – CO2 (blue), CH4 (brown), N2O (brown)
Figure 4.8d  **Change in global mean surface temperature: II-GCAM-ECCo** – median (dashed line), 75th/25th percentile range (red), 20th/80th percentile (gray)

Figure 4.8e  **Change in global mean surface temperature: III-GCAM-DECOR** – median (dashed line), 75th/25th percentile range (red), 20th/80th percentile (gray)
4.3.5 Table of reference case properties

Table 4.1 summarizes the basic energy system properties of the scenarios developed in this section to provide a clean test of the influence that supply-demand empirical constraints have on the GCAM IAM’s reference case. The synthesis case [IV] reduces the average amount of refined fuels in the second half of the century by 25% from I-GCAM-ref, leading to a 60% reduction in synfuel backstop deployment.

Now that each of these four reference cases have been fully articulated, they can be used to provide a clean comparison of how their underlying assumptions influence outlooks for climate policy. In the following two sections, these baselines are applied to understand their solutions for (i) a moderate climate policy target - total 21st-century radiative forcing stabilizes at 4.5 W/m², and (ii) a strong climate policy target - year 2100 global mean surface temperatures are limited to only 1.5°C above pre-industrial levels.
Table 4-1 - Summary of four alternate GCAM reference case properties: climate, primary energy, coal emissions, and liquid fuels

<table>
<thead>
<tr>
<th>#</th>
<th>Ref. Scenario (Empirical Constraint)</th>
<th>Year 2100 MAGICC</th>
<th>Total 21st-century</th>
<th>2050-2100 Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ΔGMST Median °C</td>
<td>Total RF W/m²</td>
<td>CO₂ GtCO₂ Oil ZJ Coal ZJ Coal CO₂ GtCO₂</td>
</tr>
<tr>
<td>[I]</td>
<td>GCAM-ref (---)†</td>
<td>3.7°</td>
<td>6.6</td>
<td>6,800 24 38 3,600</td>
</tr>
<tr>
<td>[II]</td>
<td>ECCo (Supply)†</td>
<td>3.2°</td>
<td>5.5</td>
<td>5,330 28 16 1,400</td>
</tr>
<tr>
<td>[III]</td>
<td>DECOR (Demand)‡</td>
<td>3.6°</td>
<td>6.2</td>
<td>6,200 21 35 3,300</td>
</tr>
<tr>
<td>[IV]</td>
<td>STOIC (Supply+Demand)§</td>
<td>3.1°</td>
<td>5.2</td>
<td>4,870 25 16 1,400</td>
</tr>
</tbody>
</table>

* Unmodified GCAM v4.2 Reference Scenario
† Replaced GCAM4 values for static income elasticity of transportation spending with GCAM3 feature of gradually declining 21st-century income elasticity
‡ Adapted GCAM reference coal supply curve so that costs gradually increase and recovery is constrained to BGR (2015) reserves
§ Combined the features of runs II and III
‖ For top 5 sectors – these comprise the majority of CO₂ emissions in each scenario

4.4 Climate policy case I - solving for a moderate mitigation target: RCP4.5

This section develops projections for a moderate mitigation target by applying the four alternate GCAM reference cases [I-IV] to create policy scenarios for stabilizing atmospheric radiative forcing at 4.5 W/m² by the year 2100. These are identified as [alternate baseline #]-RCP4.5 throughout the text.56

4.4.1 GCAM alternate reference case scenarios for RCP4.5: total primary energy supply

The RCP4.5 mitigation case developed by GCAM-ref (I-ref-RCP4.5) projects efficiency savings that lead to a 15% reduction in global primary energy use by 2100 from the original reference case (Figure 4.9a). Accordingly, the TPES in I-ref-RCP4.5 only reaches a multiple of 2.2-times year 2015 levels at the end of the century.

I-GCAM-ref produces an RCP4.5 consistent scenario by significantly curtailing the use of coal after mid-century, so that annual coal use is effectively reduced 90% in year-2100 (Figure 4.9b). Coal use in the reference case baseline is replaced with increased biomass production (+80%) that also substitutes for oil (-30%). Expanded contributions from nuclear (+160%), wind (+95%) and solar (+190%), also substitute for coal in electricity generation.

56 Note: As GCAM was the IAM chosen to develop the original RCP4.5 marker scenario, this model provides a useful point for comparison (Thomson et al., 2011). However, GCAM-ref is not the baseline for the RCP4.5 marker scenario. GCAM-ref leads to a higher 21st-century RF than the CCSP2.1 scenario used by GCAM to develop the RCP4.5 marker case. The results of GCAM-ref are not directly comparable with the results for policy taxes and technology composition reported by Thomson et. al (2011).
4.4.1.1 II-ECCo-RCP4.5: total primary energy supply

The empirically constrained coal reference case produces an outlook for RCP4.5 which closely tracks the I-ref-RCP4.5 solution until 2080 (Figure 4.9c) – the point at which 16 ZJ of coal are used in the original reference mitigation case with an unconstrained coal supply curve. From 2080-2100, the primary energy trajectory of this mitigation case diverges to use 10% more biomass and 10% more energy from other sources to offset 20% less oil, 6% less gas and 25% less coal. The net reduction in primary energy from these substitutions amounts to a reduction in TPES by 30 EJ/year or about 2%. This reduction in TPES indicates that elimination of the cheapest backstop resource leads to a negligible 2% ‘efficiency’ effect in primary resource use under the GCAM mitigation scenario compared to the unmodified baseline.

4.4.1.2 III-DECOR-RCP4.5: total primary energy supply

The empirically constrained demand reference case for RCP4.5 deploys 20% more coal than the original I-ref-RCP4.5 scenario. Reduced transportation demand eases pressure on the RCP4.5 carbon budget of ~4,000 GtCO$_2$, allowing for this slightly increased allowance of high carbon energy supply. Oil, gas, biomass and other resources that supply transportation fuels are curtailed by up to 180 EJ/year in this scenario (Figure 4.9d).

4.4.1.3 IV-STOiC-RCP4.5: total primary energy supply

The IV-STOiC-RCP4.5 scenario combines the profiles of [II]-RCP4.5 and [III]-RCP4.5 to project a net reduction in year-2100 TPES of more than 15% (Figure 4.9e). The [IV]-RCP4.5 scenario phases out coal after 2090.
Figure 4.9a  I-GCAM-ref-RCP4.5 energy system (1990-2100) – total primary energy supply in EJ per year: oil (blue), natural gas (red), coal (green), biomass (yellow) and nuclear, hydro, solar, wind and other (gray)

Figure 4.9b  Change in primary energy by resource: I-GCAM-ref-RCP4.5 from I-GCAM-ref – ΔEJ/year primary energy from oil (blue), natural gas (red), coal (green), biomass (yellow) and other sources (gray)
Figure 4.9c  Change in primary energy by resource: II-ECCo-RCP4.5 from I-ref-RCP4.5 – $\Delta$EJ/year primary energy from oil (blue), natural gas (red), coal (green), biomass (yellow) and other sources (gray)

Figure 4.9d  Change in primary energy by resource: III-DECOR-RCP4.5 from I-ref-RCP4.5 – $\Delta$EJ/year primary energy from oil (blue), natural gas (red), coal (green), biomass (yellow) and other sources (gray)
4.4.2 GCAM alternate reference case scenarios for RCP4.5: liquid fuels

Mitigation policy in I-ref-RCP4.5 (Figure 4.10a) induces deployment of FT biofuels and cellulosic ethanol to substitute for oil and higher carbon synfuels in the baseline (CTL and GTL). This climate policy trajectory leads to total refined fuel deployment of only 250 mbdoe by year-2100 – reducing total end of century liquids by 25% from the original reference case.

In GCAM mitigation scenarios, each liquid fuel uses varying degrees of carbon capture sequestration (CCS). BTL is applied in conjunction with CCS in a process commonly known as biomass energy carbon capture sequestration (BECCS). [I]-RCP4.5 achieves its mitigation target by expanding late-century BTL by more than 50 mbdoe, while curtailling CTL, oil and GTL fall by up to 150 mbdoe (Figure 4.10b). This reduces oil and GTL by -30%, CTL by -93% and increases BTL by +290% from the original baseline year-2100 liquid supply.

4.4.2.1 II-ECCo-RCP4.5: liquid fuels

The [II]-RCP4.5 scenario (Figure 4.10c) follows a similar ‘fan’ profile as displayed in the solution for TPES: after 16 ZJ of cumulative coal combustion by 2080, BTL and cellulosic ethanol substitute for CTL. This mitigation solution for RCP4.5 clarifies how GCAM directly substitutes BTL for CTL in mitigation cases.

4.4.2.2 III-DECOR-RCP4.5: liquid fuels

Empirically constrained demand for transportation fuels in [III]-RCP4.5 reduces late-century liquids production by nearly 60 mbdoe (Figure 4.10d). This altered demand profile deploys less of all
refinery inputs except for cellulosic ethanol from 2080-2100. Accordingly, BTL use falls 30%, oil by 23%, gas by 25% and CTL by 30%.

4.4.2.3 IV-STOiC-RCP4.5: liquid fuels

Perhaps counterintuitively, the synthesis [IV]-RCP4.5 scenario results in a smaller overall reduction for liquid fuel demand than in case [II] – up to 5% more total liquids are used in the later periods (Figure 4.10e). Because CTL is more expensive in [IV] than [II], liquid fuels from unconventional oil substitute for coal in early years, making unconventional sources cheaper in later periods through ongoing technological change. This leads to as much as 20% more oil use in 2100 than in case [II]-RCP4.5. This dynamic illustrates how GCAM applies technological change to supply strategies selected in any one period, so their emergence in earlier periods makes them cheaper later in the century. Such projections serve to reduce the effect price elasticities could have on constraining demand in later periods.

Figure 4.10a I-GCAM-ref-RCP4.5 refinery inputs by technology (1990-2100) – oil refining (blue), coal-to-liquids (red), gas-to-liquids (green), Fischer-Tropsch biofuels (yellow), cellulosic ethanol (light blue), and biodiesel, sugar cane and corn ethanol (gray)
Figure 4.10b Change in refined fuels: I-GCAM-ref-RCP4.5 from I-GCAM-ref – ΔEJ/year refinery inputs from oil (blue), GTL (red), CTL (green), BTL (yellow) and cellulosic ethanol (light blue) and other (gray)

Figure 4.10c Change in refined fuels: II-ECCo-RCP4.5 from I-ref-RCP4.5 – ΔEJ/year refinery inputs from oil (blue), GTL (red), CTL (green), BTL (yellow) and cellulosic ethanol (light blue) and other (gray)
Figure 4.10d Change in refined fuels: III-DECOR-RCP4.5 from I-ref-RC4.5 — $\Delta$EJ/year refinery inputs from oil (blue), GTL (red), CTL (green), BTL (yellow) and cellulosic ethanol (light blue) and other (gray)
4.4.3 GCAM alternate reference case scenarios for RCP4.5: CO₂ emissions by sector

The CO₂ emission profile for major sectors in [I]-RCP4.5 peaks in mid-century at 50 GtCO₂ after growing 35% from the 2015 level (Figure 4.11a). After this point, carbon emissions from electricity generation, industry, gas systems and buildings all decline and eventually stabilize around 2070, which is the year of maximum global population. However, despite climate policy, CO₂ emissions from transportation continue to grow until they are 180% larger in year-2100 than in 2015.

Because we have applied GCAM to solve for an end-of-century RF target as the objective for these successive model runs, changes to baseline emissions in one sector allow for more GHGs in another sector within a mitigation case. The total 21st-century carbon budget remains around 4,000 GtCO₂ to reach RCP4.5 regardless of the underlying assumptions. Any interpretation of GCAM’s results across varied reference cases must realize the model will deploy technologies to maintain internal consistency with this end-of-century target.

4.4.3.1 II-ECCo-RCP4.5: CO2 emissions by sector

In [II]-RCP4.5 carbon emissions are virtually unchanged from the original reference case mitigation solution until 2080, further illustrating the maintenance of an internally consistent carbon budget for each mitigation target (Figure 4.11b). Total CO₂ emissions in year-2100 fall by as much as 4
GtCO2/yr - as these sectors are not using coal so they are increasingly using energy which is less carbon intensive.

4.4.3.2 III-DECOR-RCP4.5: CO2 emissions by sector

The [III]-RCP4.5 scenario projects a -10 GtCO2 decline in transportation emissions from the original reference [I]-RCP4.5 scenario (Figure 4.11b). This leads to a nearly equivalent CO2 rebound into other sectors.

4.4.3.3 IV-STOiC-RCP4.5: CO2 emissions by sector

GCAM struggles to produce enough CO2 emissions to achieve the carbon budget consistent with RCP4.5 in case [IV]-STOiC-RCP4.5 (Figure 4.11d). This leads CO2 emissions to follow a bouncy-bouncy pathway after the model target finder tries to allocate its available CO2 budget to sectors that do not deploy coal (Dowlatabadi 2016 – Private Communication).

![Figure 4.11a CO2 Emissions in I-GCAM-ref-RCP4.5 by sector](image)

Figure 4.11a CO2 Emissions in I-GCAM-ref-RCP4.5 by sector – transportation and liquids (blue), electricity (red), industry (green), gas systems (yellow), buildings (light blue)
Figure 4.11b Change in CO2 emissions by sector: II-ECCo-RCP4.5 from I-ref-RCP4.5 – $\Delta$GtCO2/year emissions from top 5 sectors – transportation and liquids (blue), electricity (red), industry (green), gas systems (yellow), buildings (light blue)

Figure 4.11c Change in CO2 emissions by sector: III-DECOR-RCP4.5 from I-ref-RCP4.5 – $\Delta$GtCO2/year emissions from top 5 sectors – transportation and liquids (blue), electricity (red), industry (green), gas systems (yellow), buildings (light blue)
4.4.4 GCAM alternate reference case scenarios for RCP4.5: climate outcomes

Carbon capture and sequestration (CCS) commonly plays a major role in stabilizing atmospheric CO₂ concentrations within IAM generated mitigation scenarios. Figure 4.12a compares total cumulative primary energy with CCS deployed by [I]-ref-RCP4.5 (top x-axis table) and the three alternate projects as lines that show the reduction from the original GCAM reference scenario. This figure indicates that demand constraints have a larger influence on CCS deployment than supply constraints. The [II]-ECCo-RCP4.5 (green line) shows a slight reduction in CCS deployed (-2.5%) from the default GCAM reference case. However, the alternate reference cases [III] and [IV] sequester 20-30% less carbon to meet the 21st century target. Total primary energy with CCS in these demand constrained scenarios are equivalent to 20-30 years of TPES in 2015.

The GHG profile of GCAM’s RCP4.5 scenarios are consistent with a mean global surface temperature increase of 2.4°C (median) by 2100 over pre-industrial levels (Figure 4.12b). GHG forcing is stabilized at 3.9 W/m² with the sum of total forcing maintained at 4.2 W/m² (Figure 4.12c).
Figure 4.12a  Change in total cumulative primary energy with carbon capture and sequestration: [II], [III] and [IV] from I-ref-RCP4.5 – changes to total cumulative primary energy with CCS (∑ EJ) deployed in alternate reference case solutions for RCP4.5 with I-ref-RCP4p5 CCS total in the top x-axis table and reduction from this baseline: II-ECCo-RCP4.5 (green), III-DECOR-RCP4.5 (red) and IV-STOiC-RCP4.5 (yellow)

Figure 4.12b  Change in global mean surface temperature: GCAM RCP4.5 scenarios – median (dashed line), 75th/25th percentile range (red), 20th/80th percentile (gray)
The underlying characteristics of each alternate reference case lead to varied cost profiles for achieving the RCP4.5 scenario in GCAM. Cumulative climate policy costs compared in constant dollar terms show that baselines [II] and [III] reduce total costs of 30% and 40% respectively from the original GCAM reference case (Figures 4.13a,b). The [IV]-STOiC baseline can reach RCP4.5 with cumulative costs that are 70% less than [I]-GCAM-ref, effectively summing the cost reductions from the other scenarios. 57

GCAM produces RCP4.5 scenarios by implementing a global carbon price starting in the year 2020. The undiscounted and discounted carbon price profiles are plotted for each reference case in Figures 4.13c and 4.13d respectively. Undiscounted carbon prices in each reference case gradually increase until peak population year. After this point, undiscounted values for [I]-RCP4.5 continue grow to reach $250/tCO2. The carbon shadow price for scenario [II]-RCP4.5 accelerates from 2070-2100 to reach $360/tCO2, reflecting the higher costs of capturing carbon from the larger quantities of unconventional oil and biomass which substitutes for CTL. In [III]-RCP4.5 the carbon shadow price stabilizes and gradually declines to reach $150/tCO2 in year-2100, and in [IV]-RCP4.5 the carbon shadow price declines to a level consistent with 2070 at less than $100 per ton.

The peak-and-decline profile for undiscounted carbon prices in [IV]-RCP4.5 follows intuition: since much of the challenge in lowering future carbon emissions stems from long-term technology and infrastructure choices, once the cost is high enough to catalyze the adoption of the alternative low carbon technology, the cost of climate policy would reasonably decline. In essence, once the low carbon ‘switch’ is made, the cost of carbon can generally decelerate, and eventually hit zero. In

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Note on discount rate: these results discount costs with plausible rate that captures the opportunity cost of money: the 52-week average of 3 year US treasury yields. This discount rate is maintained throughout the analysis of costs in subsequent plots.

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Figure 4.12c Radiative forcing in I-GCAM-ref-RCP4.5 by GHG component – CO2 (blue), CH4 (brown), N2O (brown), fluorinated gases (light blue); note reference tick on left-axis for original forcing of GCAM-ref
Case [IV], this switch comes through a coal-phase out and stabilization of transportation demand. This suggests that some combinations of demand and supply constraints may indicate a temporal nature for climate policy: if the problem could be solved by a certain decade, initial policy actions could be phased out in later time periods.

Figure 4.13a Cumulative undiscounted climate policy (2020-2100) costs to achieve RCP4.5 for four alternate GCAM reference cases [I-IV] – I-ref-RCP4.5 (blue squares), II-ECCo-RCP4.5 (green triangles), III-DECOR-RCP4.5 (red circles), IV-STOiC-RCP4.5 (yellow triangles); (right axis) reduction in cost from I-ref-RCP4.5 baseline
Figure 4.13b Cumulative discounted climate policy costs to achieve RCP4.5 for four alternate GCAM reference cases (2020-2100) – I-ref-RCP4.5 (blue squares), II-ECCo-RCP4.5 (green triangles), III-DECOR-RCP4.5 (red circles), IV-STOiC-RCP4.5 (yellow triangles); (right axis) reduction in cost from I-ref-RCP4.5 baseline
Figure 4.13c Undiscounted carbon prices to achieve RCP4.5 for four alternate GCAM reference cases (2020-2100) – I-ref-RCP4.5 (blue squares), II-ECCo-RCP4.5 (green triangles), III-DECOR-RCP4.5 (red circles), IV-SToIC-RCP4.5 (yellow triangles)
Properties of the RCP4.5 mitigation case solutions developed by GCAM from each alternate baseline are summarized in Table 4.2. Though reference case [II] reduces the overall climate policy cost, it does so through higher carbon shadow prices: more biomass and unconventional oil substitutes for coal, increasing overall costs of meeting energy demand with CCS. The synthesis case [IV] reduces discounted policy costs to $30 trillion USD, with average discounted carbon prices of $45/tCO₂, or roughly $12.30/tC. In summary, this section has shown that empirically constrained supply and demand projections can lead to significant reductions in the estimated costs for achieving scenarios of climate policy.

Figure 4.12b indicates that an RCP4.5 scenario is consistent with a range of global mean surface temperatures that increase by 1.8 to 3.0˚C from pre-industrial levels. Therefore, an RCP4.5 scenario has a very low probability of meeting the Paris Agreement goals that aim for 2˚ or less, and effectively serves as a ‘well below 3˚C scenario’. Therefore, we can extend this analysis by comparing the outlooks produced by [I]-GCAM-ref and [IV]-GCAM-STOiC for well below 2˚ scenarios.
Table 4-2 - Summary of four alternate GCAM reference case mitigation economics for a RCP4.5 consistent scenario

<table>
<thead>
<tr>
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<th></th>
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<tbody>
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<td>GCAM-ref (---)</td>
<td>$110</td>
<td>---</td>
<td>$110</td>
<td>$70</td>
<td>---</td>
</tr>
<tr>
<td>II</td>
<td>ECCo (Supply)</td>
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<td>-30%</td>
<td>$160</td>
<td>$70</td>
<td>---</td>
</tr>
<tr>
<td>III</td>
<td>DECOR (Demand)</td>
<td>$70</td>
<td>-40%</td>
<td>$70</td>
<td>$50</td>
<td>-30%</td>
</tr>
<tr>
<td>IV</td>
<td>STOiC (Supply+Demand)</td>
<td>$30</td>
<td>-70%</td>
<td>$40</td>
<td>$45</td>
<td>-40%</td>
</tr>
</tbody>
</table>

* Discounted at 52-week average 3-year US Treasury yield

4.5 Climate policy case II – solving for a strong mitigation target of well below 2˚

The December 2015 Paris Agreement has motivated analysis and development of climate policy scenarios consistent with limiting future warming to ‘well below 2˚’, directing focus toward a 1.5˚C policy goal (IPCC, 2016; Peters, 2016; Rogelj et al., 2016; Tschakert, 2015). Decision I/CP.21 of the Conference of Parties to the United Nations Framework Convention on Climate Change (UNFCCC) invited the IPCC to develop a special report on 1.5˚C. This report is under development and expected for publication in 2018.

Therefore, this section compares and tests the [I]-GCAM-ref solutions for warming well below 2˚ against the alternate reference case [IV]-GCAM-STOiC across two policy targets: (i) a future emission scenario that achieves warming of 1.5˚ without overshoot (RCP3.1) and (ii) an overshoot (OS) scenario, which exceeds 1.5˚ earlier in the century, but peaks and declines to stabilize global temperatures at 1.5˚C. 58

The GCAM RCP3.1 scenario stabilizes atmospheric forcing at 3.1 W/m² which leads to a median global surface temperature increase of 1.5˚ above pre-industrial levels in 2040, and Δ1.56˚ in 2100 (Figure 4.14a). In the overshoot scenarios, the median global surface temperature increase reaches a peak of Δ1.8˚ in 2070 which is reversed to Δ1.5˚ by 2100 through heavy use of negative emission technologies that drive total annual CO₂ emissions negative after 2070 (Figure 4.14b). In the GCAM RCP3.1 scenarios, CO₂ forcing is stabilized before 2040 at 2.1 W/m² (Figure 4.14c). The GCAM overshoot scenarios reduce CO₂ forcing below 2.0 W/m² before end of the century (Figure 4.14d).

Discounted cumulative policy costs for RCP3.1 with alternate reference cases are compared to a 2.0˚ scenario created with [I]-ref in Figure 4.15a. The total cost of achieving RCP3.1 with [IV]-STOiC is at least 20% lower than a 2˚ policy target with the original [I]-ref baseline. Achieving 1.5˚ by overshoot in [IV]-STOiC is equivalent to the cost of RCP3.1 with [I]-ref (Figure 4.15b). In summary, a

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58 Note: Each of the GCAM generated mitigation scenarios are harmonized with the fluorinated gases of the RCP2.6 scenario.
more aggressive policy target with the empirically constrained supply and demand [IV] baseline is equivalent to the cost of less stringent goals modeled with GCAM-ref.

Discounted carbon prices for the [IV]-STOiC-RCP3.1 scenario remain below the post-2050 average for a 2° scenario from [I]-GCAM-ref (Figure 4.15c). These results provide further confidence that much lower levels of 21st-century warming could result from a carbon price profile pursued to achieve a 2° scenario than previously expected when unconstrained supply and demand profiles are applied.

Properties of the 1.5° scenarios developed from baselines [I] and [IV] are summarized in Table 4.3. Notably, the discounted average carbon price from [IV]-STOiC-RCP3.1 is only 4% more than the I-ref-2°C case.

Figure 4.14a Change in global mean surface temperature: GCAM RCP3.1 scenarios — median (dashed line), 75th/25th percentile range (red), 20th/80th percentile (gray)
Figure 4.14b Change in global mean surface temperature: GCAM 1.5° - overshoot (OS) scenarios – median (dashed line), 75th/25th percentile range (red), 20th/80th percentile (gray)

Figure 4.14c Radiative forcing in GCAM RCP3.1 by GHG component – CO2 (blue), CH4 (brown), N2O (brown), fluorinated gases (light blue)
Figure 4.14d Radiative forcing in GCAM 1.5° overshoot (OS) by GHG component – CO2 (blue), CH4 (brown), N2O (brown), fluorinated gases (light blue)
Figure 4.15a Discounted cumulative climate policy costs to achieve 1.5°C of warming without overshoot: RCP3.1 scenarios for baselines [I] and [IV] – I-ref-RCP3.1 (light blue), I-ref-2.0°C (dark blue), IV-STOiC-RCP3.1 (yellow), I-ref-RCP4.5 (gray) – reference line for I-ref-2°C (black); (right axis) reduction in cost from I-ref-2°C baseline
Figure 4.15b Discounted cumulative climate policy costs to achieve 1.5°C of warming with overshoot: scenarios for baselines [I] and [IV] – l-ref-1.5°C-OS (light blue), IV-STOIC-1.5°C-OS (yellow), l-ref-RCP4.5 (gray) – reference line for l-ref-2°C (black); (right axis) reduction in cost from l-ref-2°C baseline
Figure 4.15c Discounted carbon prices to achieve 1.5°C of warming without overshoot: RCP3.1 scenarios for baselines [I] and [IV] – I-ref-RCP3.1 (light blue), IV-STOIC-RCP3.1 (yellow), reference line for I-ref-2°C average post 2050 (black dashed line)
Figure 4.15d Discounted carbon prices to achieve 1.5°C of warming with overshoot: scenarios for baselines [I] and [IV] – I-ref-1.5°C-OS (light blue), IV-STOIC-1.5°C-OS (yellow), reference line for I-ref-2°C average post 2050 (black dashed line)

Table 4-3 - Summary of four alternate GCAM reference case mitigation economics 1.5°C consistent scenarios

<table>
<thead>
<tr>
<th>#</th>
<th>Ref. Scenario (Mitigation Case)</th>
<th>Cumulative Policy Cost* $2015 tril.</th>
<th>%Δ I-ref-2°C</th>
<th>Mean Carbon Tax (2020-2100)* $2015/CO2</th>
<th>%Δ I-ref-2°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCP3.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[I]</td>
<td>GCAM-ref</td>
<td>$250</td>
<td>+30%</td>
<td>$140</td>
<td>+33%</td>
</tr>
<tr>
<td>[IV]</td>
<td>TACO</td>
<td>$150</td>
<td>-20%</td>
<td>$110</td>
<td>+4%</td>
</tr>
<tr>
<td>1.5°C-Overshoot</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[I]</td>
<td>GCAM-ref</td>
<td>$440</td>
<td>+130%</td>
<td>$260</td>
<td>+150%</td>
</tr>
<tr>
<td>[IV]</td>
<td>TACO</td>
<td>$250</td>
<td>+30%</td>
<td>$200</td>
<td>+90%</td>
</tr>
</tbody>
</table>

*Discounted at 52-wk average 3-year US Treasury yield
4.6 Summary

This chapter has analyzed the economics of high-carbon backstop resources in IAM reference cases and outlined a framework for empirically constrained scenarios of coal supply. Because GCAM is built on the operational principle of supply-demand equilibrium, a demand constrained reference case is also developed. In summary:

- **Section 4.1** builds on Chapter 3 to argue that long-term studies of the global energy system should adopt empirically constrained coal supply curves because it is very unlikely that 21st-century coal production will exceed today's reserves.

- **Section 4.2** details the GCAM IAM's energy system reference case: this scenario reaches high levels of 21st-century RF (>6.0 W/m²) through vastly expanded demand for transportation services that rely on a stable supply of low-cost high-carbon fuels (**Section 4.2.2**). This leads to 80 million barrels per day of coal-based liquid synfuels on average from 2050-2100, illustrating the idealized concept of a high-carbon backstop (**Section 4.2.3**). These underlying assumptions produce climate change scenarios that lead to 4°C warming above pre-industrial levels (**Section 4.2.4**).

- **Section 4.3** develops three alternate GCAM reference case scenarios based on an empirically constrained coal supply curve [II], an empirically constrained formulation of transportation demand [III], and a synthesis case built on combining these assumptions [IV]. These alternate reference case scenarios reduce deployment of the backstop resource in GCAM by up to 60%.

- These alternate scenarios allow for a clean comparison of the influence of underlying assumptions on climate policy developed by the GCAM IAM in **Section 4.4** - for a 'well below 3°C scenario' (RCP4.5) the empirically constrained scenarios reduce costs by more than 70% from the unmodified GCAM reference case.

- **Section 4.5** compares the 1.5°C climate policy outlooks produced by the original GCAM reference case and the [IV] synthesis reference case. The 1.5°C climate policy scenario based on empirically constrained supply and demand (Scenario [IV]) costs less than the 2°C scenarios created by the unmodified GCAM reference case.

These alternate reference case scenarios have employed a deeply simplified calibration of coal costs. As noted in **Section 4.3**, the cost of coal in the [III]-ECCo reference case only doubles through 2050. This gradual increase is much less than the rise in average coal costs observed under 21st-century socioeconomic conditions consistent with the GCAM-ref scenario outlook. Additional efforts to empirically match the long-term pathway of coal prices in GCAM to those observed in the early 21st-century may only enable further reductions in the projected costs of climate policy.

The work in this chapter was not conducted to unduly scrutinize any aspect of GCAM. GCAM provides the only robust open-source RCP-class IAM, and is an impressive model that provides considerable detail on global change drivers and outcomes. Anyone who spends some time with the model can readily respect its high-resolution scenarios.
However, any model like GCAM can only reproduce logically coherent outcomes from the initial input assumptions that structure its reference scenarios. The future is inherently uncertain – but deterministic models like GCAM can be easily used and interpreted in ways that depict some outcomes as highly certain.

In the context of transportation demand, competitive costs are emerging for electric vehicles, energy storage and lower energy intensity grid power, which all appear more plausible before 2050 than in the 1990s when the general framework for technological change in GCAM was envisioned. The ability to meet transportation service demands with more dematerialized and distributed patterns of ownership because of matching problems solved by information technology are also difficult to ignore as a feature in a plausible baseline energy system.

Perhaps the future will be dominated by coal-intensive synfuels, but development on such a large scale will be deeply sensitive to prevailing political conditions. Because IAMs are ‘a-political’, synfuels can look like a sure bet – despite the steep uphill battle required to achieve regulatory and popular support for siting and scaling these production facilities over the many decades needed to achieve growth of several orders magnitude. In the early 20th century, it is challenging to see whether synfuel development as depicted by GCAM maintains any semblance of realism.

In recent years, Western China developed vast support infrastructure in anticipation of a modern CTL renaissance but Beijing’s policy reversal after lackluster pilot performance left many of these projects unrealized. Associated projects are largely considered as contributions to the ‘ghost town’ phenomena where overbuilt housing and facilities built on a large scale are unoccupied (Rong and Victor, 2011). Therefore, recent favorable economic conditions and an extended period of policy support for rapid deployment of liquid fuels from coal have resulted in little empirical support for such future projections such as those from GCAM-ref.

The results of Sections 4.4 and 4.5 suggest mitigation scenarios that depict the ‘removal’ of such high levels of CTL could easily be considered a ‘smoke and mirrors’ mitigation strategy. These cases vastly reduce GHGs but only through excising what appears an initially implausible outcome. Any criticism of the viability of BECCS, CCS or the difficulty of achieving climate policy targets must realize these critical baseline uncertainties.

In the following chapters, we can extend this analysis of coal in reference case energy system scenarios to a wider range of IAMs, for a consideration of why they project such high levels of future coal combustion and whether these outlooks maintain internal consistency.
Chapter 5: Why do climate change scenarios return to coal?

Chapter 4 detailed the influence of empirically constrained coal supply curves in the GCAM IAM providing a foundation to expand the analysis to a consideration of the backstop resource in a broader range of IAMs in this chapter.

Since 1870, more than 70% of anthropogenic greenhouse gas (GHG) emissions have resulted from the combustion of fossil fuels (Le Quéré et al., 2016). 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 IAMs as a landscape for exploring the socioeconomic and energy system developments that lead to various levels of GHG emissions (Nakicenovic et al., 2000; Riahi et al., 2017; van Vuuren et al., 2012). 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 (IPCC, 2006; Kriegler et al., 2012; Moss et al., 2008; O'Neill et al., 2015; 2013; Riahi et al., 2017; van Vuuren and Carter, 2014; van Vuuren et al., 2011a). Each final scenario is defined using independent projections of future radiative forcing (representative concentration pathways – RCPs) and socioeconomic storylines (shared socioeconomic pathways – SSPs) (O'Neill et al., 2013; van Vuuren et al., 2011a).

Radiative forcing (RF) measures the change in Earth’s energy balance with units of watts per square meter (W/m²) (Myhre et al., 2013). 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/m², with an uncertainty span ranging from 1.1 to 3.3 W/m² (IPCC, 2013). 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 at 3.0 W/m² where carbon dioxide contributes 2.0 W/m² (Butler and Montzka, 2017). A common climate model experiment is a doubling of atmospheric CO2 concentration, and we are approximately half way to that level in terms of RF (Myhre et al., 2017).

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 (Figure 5.1). The initial RCP publications include underlying reference case scenarios of primary energy supply consistent with the internal logic of each level of forcing (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011b). 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 (IIASA, 2009; IPCC, 2014; van Vuuren et al., 2011a).
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 Clark et al., 2016; Golledge et al., 2015; Hsiang et al., 2017; Mengel et al., 2016; Nazarenko et al., 2015; Tokarska et al., 2016). 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 are simply pathways of RF designed for use in climate models which can be linked to plausible socioeconomic scenarios described by SSPs (Moss et al., 2010; van Vuuren et al., 2011a).

Figure 5.1   The four representative concentration pathways (RCPs) – RCPs correspond to a specific value for total radiative forcing in 2100 (left) and CO₂-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 (IIASA, 2009; van Vuuren et al., 2011a)

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 (Clarke et al., 2014). These WGIII reference case scenarios reach an average of 7.1 W/m² in year 2100, between RCP6.0 and RCP8.5. As of late 2016, a series of five SSPs are available for continued research (Riahi et al., 2017). 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 (Ebi et al., 2013).
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 (Dreborg, 1996; O’Neill et al., 2015; Robinson, 2003; 1990; 1982; Rozenberg et al., 2014; Vergragt and Quist, 2011). This backwards technique enables the end state of key variables for each pathway to be in mind while they are developed (O’Neill et al., 2015; Rozenberg et al., 2014). Table 5.1 provides descriptions of the end-points IAM scenarios should achieve to illustrate an RCP or SSP, alongside key references for associated scenarios.

**Table 5.1 - IAM marker models and scenarios for climate change pathways: Representative Concentration Pathways (van Vuuren et al., 2011a) and Shared Socioeconomic Pathways (Riahi et al., 2017)**

<table>
<thead>
<tr>
<th>Scenario / Pathway</th>
<th>Marker IAM (Relevant Precursor Scenario)</th>
<th>Underlying Model and Scenario Documentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCP8.5 – Rising radiative forcing pathway (~1370ppm CO2eq) – no intervention, i.e. ‘business as usual’</td>
<td>MESSAGE (A2r)</td>
<td>(Messner and Schrattenholzer, 2000; Messner and Strubegger, 1995; Riahi et al., 2011; 2007)</td>
</tr>
<tr>
<td>RCP6.0 – Stabilization without overshoot (~850 ppm CO2eq) – intervention for stabilization (high)</td>
<td>AIM (SRES B2)</td>
<td>(Kainuma et al., 2003; Masui et al., 2011)</td>
</tr>
<tr>
<td>RCP4.5 – Stabilization without overshoot (~650ppm CO2eq) – intervention for stabilization (medium)</td>
<td>GCAM (CCSP 2.1)</td>
<td>(Clarke et al., 2007; Thomson et al., 2011)</td>
</tr>
<tr>
<td>RCP2.6 – Peak in radiative forcing before 2100 and then decline (peak at 490ppm CO2eq) – intervention for stabilization (low)</td>
<td>IMAGE</td>
<td>(Bouwman and Kram, 2006; van Vuuren et al., 2011b; van Vuuren, 2007)</td>
</tr>
<tr>
<td>SSP5 – Fossil-fueled development – ‘taking the highway’</td>
<td>REMIND</td>
<td>(Kriegler et al., 2017)</td>
</tr>
<tr>
<td>SSP4 – Inequality – ‘a road divided’</td>
<td>GCAM</td>
<td>(Calvin et al., 2017; Joint Global Change Research Institute, 2012)</td>
</tr>
<tr>
<td>SSP3 – Regional rivalry – ‘a rocky road’</td>
<td>AIM</td>
<td>(Fujimori et al., 2017; 2014; 2012)</td>
</tr>
<tr>
<td>SSP2 – Middle of the road – ‘dynamics as usual’</td>
<td>MESSAGE</td>
<td>(Fricko et al., 2017)</td>
</tr>
<tr>
<td>SSP1 – Sustainability – ‘taking the green road’</td>
<td>IMAGE</td>
<td>(van Vuuren et al., 2017)</td>
</tr>
</tbody>
</table>

This chapter examines the energy system scenarios that map to the RCPs by first conducting a meta-analysis, and then understanding the key ideation behind energy models which produce them. This analysis supports the argument developed in Section 5.4 that SSP5-RCP8.5 is an exceptionally unlikely end-point of future CO2 forcing because it is biased by the IAMs which
understand possibilities for the future global energy system with a return to coal hypothesis. This return to coal hypothesis: (i) represents a significant discontinuity in historical primary energy development trends (**Section 5.1**), (ii) is assessed for plausibility with an untested and empirically unverified model of technological change in resource extraction technology (**Section 5.2**), (iii) results from a temporal information asymmetry between fossil resource assessments (**Section 5.3**) and (iv) repeats the pattern and rationale of historical projections that dramatically overestimated future coal use (**Section 5.3.2**).

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 (**Chapter 3**), 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 (Nakicenovic et al., 2000; Riahi et al., 2011; 2007; van Vuuren et al., 2011a): an implausible outlook for a vast coal backstop (Mohr et al., 2015; Ritchie and Dowlatabadi, 2017a). However, SSP5-RCP8.5 continues to remain an important focus in the climate change research community because it produces a high signal-to-noise ratio which overwhelms uncertainty in GCMs and ESMs (**Section 5.5**).

To develop this case, **Section 5.1** 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. 59

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 (1997) (Rogner, 1997). 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) which was initially explored in **Chapter 2**.

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 5.2** argues this formulation of technical change for ‘timeless’ 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

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59 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 CO₂ 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.
basis for future energy system scenarios that return to coal (Section 5.3). Section 5.4 summarizes the lines of evidence that indicate RCP8.5 should not be a priority for future scientific research and Section 5.5 details why despite this analysis, it is poised to remain a key focus in the climate change research community because of its strong carbon signal.

5.1 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 Figures 5.2a-d. These are framed by corresponding end-point ranges from the RCP and SSP marker scenarios (IPCC WGIII, 2014; Masui et al., 2011; Riahi et al., 2011; Riahi and van Vuuren, 2016; Thomson et al., 2011; van Vuuren et al., 2011b). Primary energy describes the energy embodied in natural resources before any conversion that enables end-use (Newell and Iler, 2017). An annual measure of TPES accounts for the sum of primary energy consumed from all resources during a given year.

Figures 5.2a-d 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). 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/m² and thus define an uncertainty range for energy system reference cases spanning RCP6.0 to RCP8.5 (Clarke et al., 2014; IPCC WGIII, 2014).

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 are denoted with ‘base’ (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011b). 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. (2017).

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60 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.

61 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 (Newell and Iler, 2017). 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.

62 All conversion factors in this article apply values from the Global Energy Assessment Table 1.B.1 (Grubler, 2012).

63 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 analysis.
5.1.1 AR5 outlooks for primary energy resource use

Figure 5.2a displays the TPES outlooks in IPCC AR5. These projections of primary energy use cluster at century’s end between a median level of 1,260 EJ/yr (30,200 Mtoe/yr) and a high level of 1,420 EJ/yr (34,000 Mtoe/yr) with the 20th-percentile (low) level at 900 EJ/yr (21,400 Mtoe/yr). Global TPES was estimated at 560 EJ/yr (13,280 Mtoe) in 2016, and so these scenarios envision a global energy system 1.6 to 2.5 times larger than today (BP, 2017).

Figure 5.2 IAM uncertainty ranges for 21st-century fossil resource production outlooks from IPCC AR5 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.

**Note:** throughout the text, high levels correspond to 80th-percentile trajectories, medium to 50th-percentile trajectories, and low to 20th-percentile trajectories.
Figure 5.2b  Annual oil production scenarios (right axis includes units of Mtoe/year and mbd/year)

Figure 5.2c  Annual gas production scenarios (right axis includes units of Mtoe/year and Bcm/year)
5.1.1.1 Outlooks for oil production

Oil production trajectories in AR5 (Figure 5.2b) 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 (Riahi et al., 2011), 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 (BP, 2017; International Energy Agency, 2016).

5.1.1.2 Outlooks for gas production

Scenarios of gas production in AR5 (Figure 5.2c) reach a median level of 230 EJ/yr (5,600 Mtoe/yr) with high and low levels at 300 EJ/yr (7,000 Mtoe/yr) and 120 EJ/yr (3,000 Mtoe/yr) respectively. In 2016 global gas output was estimated at 134 EJ/yr (3,200 Mtoe) (BP, 2017).
5.1.1.3 Outlooks for coal production

AR5 projections for year-2100 coal production (Figure 5.2d) 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.

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

A comparison with historical development trends in energy use per-capita can assist with interpreting the uncertainty ranges provided by the AR5 and SSP resource production outlooks (BP, 2017). Figures 5.3a-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 (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 (Figure 5.3a). 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 provides 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 (Figure 5.3b). 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 (Figure 5.3c). 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 (Figure 5.3d). 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 further explored in Chapter 6 (Grübler, 2008). Over the last decade China’s unprecedented
expansion in coal production drove an increase to 21 GJ/ global person. A further rise in world 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 (EIA, 2016; International Energy Agency, 2016; Korsbakken et al., 2016; Qi et al., 2016). 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 (Grübler et al., 1998; Ritchie and Dowlatabadi, 2017a). 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.

High levels of coal use throughout the economy are characterized by scenarios that consider slow progress in non-coal energy technologies such as in the RCP8.5 marker scenario. The original RCP8.5 scenario inherits the narrative of the predecessor A2r scenario where coal increasingly dominates global energy supply as slower rates of economic growth limits technological progress in other energy technologies (Riahi et al., 2011; 2007). 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.

5.1.3 Summary of how IAM primary energy profiles describe the future with a 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/m² 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-

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65 China’s coal production recently peaked in 2013 at a level 2.8-times higher than in the year 1999 (BP 2017)
66 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.
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. This theory of future global energy system development is a 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 next section provides 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.
Figure 5.3b  Oil use per-capita
Figure 5.3c  Natural gas use per-capita
5.2 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. 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 (Rogner, 1997). In Chapter 2 we examined how this ideation shapes resource outlooks for oil and gas, and whether its basic tenets can be supported with recent data.

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.

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Bauer et al. (2016) describe equivalent LBE supply curves as Cumulative Extraction Cost Curves (CECC) (Bauer et al., 2016).
The IAMs providing marker scenarios for RCPs and SSPs use resource supply curves uniformly derived from this LBE methodology. 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 (McCollum et al., 2014).

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 (Bauer et al., 2016). Costs of energy supply in various IAMs can span a broad range due to assumptions about the cost of transportation, subsidies, rent, and taxes (Joint Global Change Research Institute, 2012; McCollum et al., 2014).

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 (Aguilera, 2014; Rogner et al., 2012). Several papers have argued the original Rogner (1997) fossil availability curve is overly optimistic on its assumptions for oil, gas and coal recoverability (Brecha, 2008; Höök et al., 2010), but these perspectives place limited emphasis on the economic determinants of reserve assessments and resource recovery. Bauer et al. (2016) 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 (Bauer et al., 2016). 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 (Chapter 2).

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.

### 5.2.1 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 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 (McGlade, 2012). The oil, gas, and coal classified as resources represent the totality of their geologic deposits in the Earth’s crust (Hartwick and Olewiler, 1986; Tilton and Skinner, 1987).  

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 (Rogner, 1997). 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 to 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. Adelman, 1995; 1993; Adelman and Watkins, 2008; Watkins, 2006; Wellmer, 2008; Wellmer and Berner, 1997), 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. 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.

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70 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.

71 Though Rogner (1997) 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.
5.2.2 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 Figure 5.4a.

The method developed by Rogner (1997) 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 (Bauer et al., 2016).

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 (van Vuuren, 2007). 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 (McCollum et al., 2014).

**Figure 5.4** 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

**Figure 5.4a** The original LBE supply curve reproduced from Rogner (1997)

**Figure 5.4b** The LBE fossil fuel supply curve reported for MESSAGE adapted from (Riahi et al., 2012) for base year dollars (RCP8.5, SSP2)

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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).
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. (2016) note, this learning parameter is widely used despite no empirical tests or calibrations available in the literature for any energy resource. To re-iterate, the evaluation of the LBE model in Chapters 2 and 3 for oil, gas and coal resource economics finds 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 describe empirical developments in coal resources.

Figures 5.4b and 5.4c plot the LBE supply curves reported for MESSAGE and GCAM, which provide marker scenarios for RCP8.5/SSP2 and RCP4.5/SSP4 respectively (Joint Global Change Research Institute, 2016; Riahi et al., 2012). For example, GCAM reports a 0.75% per year cost decline to represent technological improvements that reduce the costs of resource extraction (Joint Global Change Research Institute, 2016). This compounded technological progress explains GCAM’s consideration that 167.5 ZJ (4,000 Gtoe) of unconventional oil is available at less than $45/boe (constant dollars), equivalent to 900 years of oil use at 2016 levels.

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73 The SI of Bauer et al. (2016) provides a valuable review of productivity in coal extraction for various regions, finding increases in some areas and declines in others.
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 (van Vuuren et al., 2011a). The next section considers whether this assumption continues to provide a plausible basis for the return to coal hypothesis that supports use of the high coal scenarios which provide the core ideation behind energy system scenarios consistent with SSP5-RCP8.5.

5.3 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, this thesis interprets them 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 (Grübler and Nakićenović, 2001; Riahi et al., 2017; Schneider, 2002; 2001); and, b) that hindsight, consistency and epistemological rigor in methodology suggests the different hypotheses do not have the same probabilities of being realized (Capellán-Pérez et al., 2016; Sokolov et al., 2009; Webster et al., 2012). 74

Capellán-Pérez et al. (2016) provide an important and timely study of issue (b) by conducting a probabilistic assessment of the RCPs (Capellán-Pérez et al., 2016). These authors find uncertainties in coal production dominate the likelihood of realizing RF levels exceeding RCP6.0. 75 Scenarios that reach RCP8.5, RCP7.0 and RCP6.0 in GCAM are assigned probabilities of 12%, 25%, and 44% respectively by Capellán-Pérez et al. 2016. However, these probabilities are based interpreting ultimately recoverable coal (URR) outlooks published from 1913-2008 as equally likely. 76 Recent studies suggest coal resource estimates published during and after the early 21st-century coal bull

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74 Though a full discussion of uncertainty in the context of emission scenario storylines exceeds the scope of this paper, van Vuuren et al. (2008) provide an excellent dialogue on this topic in their development of conditional probabilistic projections for the Special Report on Emission Scenario (SRES) narratives (Nakicenovic et al., 2000; van Vuuren et al., 2008).

75 Notably, Webster et al. (2008) reach a similar conclusion about the role of coal in dominating reference case uncertainties for RF and cumulative CO2 emissions.

76 More than 30% of the database of coal estimates applied to determine these probabilities in Capellán-Pérez et al. (2016) exceed the upper bound for today’s recoverable coal (Dale, 2012). Contemporary assessments place estimates of remaining recoverable coal on a spectrum of 8,000 to 25,500 EJ (Mohr et al., 2015), well below the mean of 35,000 ± 45,000 EJ applied to estimate a 12% likelihood of RCP8.5.
market are more accurate, and so pre-1990 assessments of unlimited cheap coal should not be
given equal weight (Mohr et al., 2015; Chapter 3; Rogner et al., 2012). Eliminating outdated legacy
assessments from the methodology of Capellán-Pérez et al. (2016) would constrain uncertainties for
clean coal recoverability to a degree that implies an upper bound for 21st-century RF between RCP6.0-
RCP7.0, and that the probability of RCP8.5 is virtually zero.

However, outside of Capellán-Pérez et al. (2016) there are no other studies that apply formal
techniques for uncertainty analysis toward assessing the relative 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 (McCollum et al., 2016; McJeon et al., 2014; van Ruijven and van Vuuren, 2009;
vvan Vuuren et al., 2008) – an outcome ensured by the supply curve structure of IAMs. Edmonds et
al. (1997) explored the reemergence of coal after 2050, and questioned its plausibility as a key
uncertainty in earlier sets of emission scenarios. 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 – a dynamic
particularly relevant to the case of coal.

5.3.1 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 (Figure 5.5a - black line) (BP, 2017). 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 (Watkins, 2006; Wellmer, 2008). Global R-P ratios for coal (Figure 5.5a - red line) are
regularly 100-900 years, many decades and centuries beyond that of oil & gas resources (Flawn,
1966; Ritchie and Dowlatabadi, 2017a). 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 (Grubert, 2012; Ritchie and Dowlatabadi, 2017a; Rutledge,
2011).

As examined in Section 5.2, IAMs develop scenarios of growing primary energy demand for the full
21st-century (Figure 5.5b - green line), which pass several decades beyond the horizon of
available information on most hydrocarbon and other resources (Figure 5.5b - black line). By adopting the basic assumptions of Rogner (1997) 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 (Figure 5.5b - red box). Illustrations of long-run TPES growth may readily project an artificial reliance on a coal backstop when passing through this domain (Figure 5.5b - 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. 77

To examine this dynamic Figure 5.5c 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 occur (Figure 5.5c): $\frac{E_{J\text{ coal}}}{E_{J\text{ coal}} + E_{J\text{ oil}}}$, i.e. the primary energy from coal (EJ coal) as a proportion of primary energy from oil and coal (EJ coal + EJ oil).

In Figure 5.5c 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 classifies 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.

77 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 (Rogner et al., 2012; Rogner, 1997).
Figure 5.5a  Reserves-to-production (R-P) ratio for oil (black line) and coal (red-line) from 1965-2015 (BP, 2017; Ritchie and Dowlatabadi, 2017a) and Chapter 3
Figure 5.5b  Horizon of information for 21st-century energy demand projections (green line) compared with data vintages of coal (red line) and oil (black line)
5.3.2 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, as in the case study of Chapter 3 that focused on post-1990 scenarios dominated by coal. This section revisits several studies before that period which 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 which applied total geologic assessments that were a precursor to the LBE model (Häfele, 1981). MESSAGE developed two scenarios of global primary energy use: *IIASA-High* and *IIASA-Low* (Häfele, 1980). 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.

**Figure 5.6a** 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 (Figure 5.6a - 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 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. Figure 5.6b-e provides a retrospective on these outlooks for US TPES from a series of integrated models, reports, and agencies (BP, 2017; Ford Foundation, 1974; Greenberger, 1983; Morgan and Keith, 2008; Reuyl et al., 1977; Smil, 2003).

The Solar Energy in America's Future (SEAF) (Reuyl et al., 1977) and Ford Foundation Energy Policy Project (1974) (Ford Foundation, 1974) produced uncertainty ranges for future energy use outlined by several scenarios based on depicting (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 Figure 5.6b these energy system trajectories (dotted lines) frame estimates for primary energy use at the end of the 20th-century from other reports (Greenberger, 1983; Morgan and Keith, 2008; Smil, 2003). Each study overestimated annual primary energy for the United States over the duration of each projected period, and only the low demand/zero energy growth scenarios came close to providing accurate guidance. 78

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 (Figures 5.6c-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

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78 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’ (Greenberger, 1983). The same philosophy applies to the Section 5.2 reference energy scenarios developed by IAMs.
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.

**Figure 5.6** Multi-decade projections of primary energy from IIASA Energy in a Finite World and a range of US energy policy studies

![Graph showing multi-decade projections of primary energy](image)

**Figure 5.6a** 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)
**Figure 5.6b** Annual US TPES (EJ/yr) from a range of studies through the year 2000 (Ford Foundation, 1974; Greenberger, 1983; Morgan and Keith, 2008; Reuyl et al., 1977; Smil, 2003)
Figure 5.6c  Scenarios of US primary energy per-capita developed for SEAF and Ford Foundation studies
Figure 5.6d  Scenarios of US primary energy from oil per-capita developed for SEAF and Ford Foundation studies

Figure 5.6e  Scenarios of US primary energy from coal per-capita developed for SEAF and Ford Foundation studies
5.4 The return to coal hypothesis and SSP5-RCP8.5

This thesis chapter has described how IAMs produce upwardly biased scenarios of future RF with a return to coal hypothesis which is 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/m² was selected based on the high forcing scenarios available in the literature which relied on a return to coal (Fisher et al., 2007; IPCC WGIII, 2000; Nakicenovic et al., 2000; Riahi et al., 2011; 2007; van Vuuren et al., 2011a). 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 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 (McGlade et al., 2013; McGlade, 2012; Mohr et al., 2015; Mohr and Evans, 2011). 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 the previous sections:

1. IAMs depict future energy scenarios with a return to coal that is a significant discontinuity in historical primary energy development trends (Section 5.1). This return to coal hypothesis dominates the scenarios of CO₂ 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 5.2).

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 5.3.1).

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 5.3.2). 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. Rogelj et al., 2016).

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 (Capellán-Pérez et al., 2016; Mohr et al., 2015; Wang et al., 2017). The RCP8.5-Ext scenario which uses simple rules to extend its forcing components through the year 2300 is equally improbable (Meinshausen et al., 2011). The Extended Concentration Pathway 8.5 (ECP8.5) scenario projects total future emissions of 5,000 gigatons of carbon, equating to the full extent of the original Rogner (1997) carbon supply curve – a resource outlook dominated by prognostic and hypothetical coal resources in extreme locations for which the discussion in Chapter 3 applies.

Perhaps 8.5 W/m² 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 (van Vuuren et al., 2011a). Since the RCP scenarios play an important role in constituting the scientific evidence base for future climate change (O’Neill et al., 2016), 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 CO₂ and other GHGs can be based on well-articulated evidence for trajectories of future social and technological change, labelled 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?

5.5 Why climate change scenarios return to coal: a strong carbon signal to overwhelm uncertainty in climate models

The initial energy models developed after the 1970s oil crisis produced long-run projections of the global energy system dominated by a coal backstop. These coal backstop scenarios began to play an important role in the climate change research community as the energy-economy models were adapted to produce emission scenarios (Häfele, 1981; Williams, 1978). Chapter 1 detailed how many of these energy-economy models, such as the IIASA MESSAGE IAM and the Edmonds-Reilly model were augmented to calculate projections of future GHG emissions by adding emissions factors to their outlooks for fossil fuel combustion.

One anonymous reviewer of the Chapter 3 version published in Energy Economics noted that, “initial climate modeling and baseline scenarios date back to the early 1980s and consequently incorporated coal resources (in addition to reserves) as the logical backstop. In addition, early unrefined GCMs required a strong carbon signal that only could be only provided by large coal use throughout the 21st century.” This robust carbon signal from coal was required to provide a high
signal-to-noise (S/N) ratio given the complex nature of the climate over the long-run, to clearly identify an anthropogenic influence that stood out in the approach taken by GCMs to simulate the Earth’s climate.

The science of global climate modeling began to make major leaps in the late-1970s (e.g. Manabe and Wetherald, 1975), and since that time it was generally recognized that identifying the human impact on the climate is foremost a problem of separating signal from noise (Allen et al., 1994; Easterling and Wehner, 2009; Santer et al., 2011; 1995; Wigley and Jones, 1981; Wigley and Raper, 1990). The warming signal that results from human-caused changes in the concentration of atmospheric greenhouse gases is situated against the background noise of the Earth’s natural climate variability. A robust analysis of signal and noise in climate change scenarios is important for interpreting results of any impact assessment, since future scenarios contain components of anthropogenic signal and internal climate noise. This is generally addressed in climate change assessments through two methods: (i) maximizing the signal and minimizing the noise, or (ii) producing scenarios with both signal and noise, alongside control scenarios with only noise (Mearns and Hulme, 2001).

Because this year-to-year noise is significant, climate models can show decadal periods with little to no warming despite significant anthropogenic forcing (Easterling and Wehner, 2009). This is because global temperatures have displayed considerable variability on all timescales. This variability is generally segmented into (i) high-frequency variability (for periods less than ten years) and (ii) low-frequency variability (for periods greater than ten years) (Wigley and Raper, 1990).

Santer et al. (2011) conduct timescale simulations of signal and noise in the lower troposphere (TLT) with GCMs, finding that interannual noise has such a significant effect, the S/N ratio is less than 1 on 10-year timescales. However, this improves significantly for 32-year trends, reaching up to 3.9. Therefore, these authors conclude temperature records of at least 17 years are required to identify the magnitude of human effects.

Dowlatabadi (2000) emphasizes how long-term climate oscillations have led to regional climate changes in excess of 1˚C and that natural anomalies and oscillations have been observed to produce rates of temperature change between 0.1˚C and 0.2˚C per decade across 30-70 years. Ecosystem responses to this natural warming play out with various lags and path dependencies. These factors complicate any impact assessment that starts by assuming today’s state represents an equilibrium or optimal baseline.

Tebaldì and Friedlingstein (2013) assess the S/N of mitigation by comparing RCP2.6 against RCP4.5 and RCP8.5 scenarios using a suite of Earth System Models (ESMs). In RCP2.6, global emissions peak in 2020 and rapidly decline below zero after mid-century. Yet, the long atmospheric lifetime of CO₂ coupled with climate system inertia means that warming rates will not immediately decline, even if GHG emissions fall rapidly as modeled under an RCP2.6 scenario. These authors find that a median mitigation signal difference between RCP2.6 and RCP4.5 is detectable by 2045 across the ESMs, with a 95th percentile year of 2077. When comparing RCP2.6 and RCP8.5 the median signal difference is detectable eight years earlier in 2037. The median ranges of this study
indicate that the difference between trajectories is likely detectable 17-25 years after the peak year of emissions, which is coherent with the time lag identified by Santer et al. (2011).

GCMs are based on mathematical equations that describe the physical evolution of energy in the planetary system and how it influences winds, ocean currents, temperature and other features of the Earth’s climate. GCMs divide the world into a grid, and solve for the climate in each projected period by resolving the physical properties of each grid cell. The computational intensity of any GCM will depend on the size of its grid cells, which can be on the range of 100km. Smaller scale-processes, such as cloud formation, are parameterized to reduce the complexity of equations representing each grid box. Many of these parameterized processes are involved in the feedback mechanisms which determine the climate response to GHGs. Since these parameterizations are reduced form estimates of the real world, they introduce significant uncertainties into this modeling approach. 

Uncertainties in the response of the climate to anthropogenic forcing can be addressed by producing ensembles, where different models use relevant sets of parameterizations, or similar initial conditions to produce a range of outcomes that could result from a single forcing scenario in a model. During the development stage, each global climate model has their properties adjusted in a process of tuning to best match our best scientific knowledge of today’s Earth system state (Mauritsen et al., 2012). This tuning process commonly takes place by adjusting cloud-based parameters, the ocean surface albedo, or the natural aerosol climatology (Hourdin et al., 2012; 2016; Voldoire et al., 2012).

While GCMs generally reproduce the observed 20th-century warming of approximately 0.7°C, the absolute temperatures of each GCM scenario can vary widely, by a span of several degrees between the hottest and coldest model. In CMIP3 this range was roughly three degrees (>3 K), with the majority of models biased cold. Therefore, the span between the hottest and coldest absolute Earth temperatures simulated by GCMs was more than four times the magnitude of 20th-century warming to that point. Thus, high forcing scenarios such as RCP8.5 provide the added benefit of dominating the span of baseline historical temperatures simulated by GCMs.

This high contrast signal is shown in Figure 5.7a by plotting the Coupled Model Intercomparison Project 5 (CMIP5) climate model results for monthly global average temperature (tas) in kelvin for historical simulated (gray) and future RCP scenarios against the observational trend (black). Each individual line represents a GCM simulation, and the lines are transparent so that a higher degree of overlap is marked by darker shading. The RCP scenario results are shown for RCP8.5 (red), RCP6.0 (orange), RCP4.5 (light blue) and RCP2.6 (dark blue).

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79 This paragraph draws from the very helpful descriptions of GCMs in Bader et al. (2008) and Collins et al. (2010).

80 Mauritsen et al. (2012) note that parameterized processes which are non-linearly dependent on absolute temperature need to be exposed to realistic temperatures to provide realistic simulations in GCMs, such as phase transitions of water that involve evaporation, precipitation, snow coverage, sea-ice, tundra, and glacial melt. Where GCMs were criticized for underestimating Arctic sea-ice melt since the IPCC’s Third and Fourth Assessment reports, Mauritsen et al. (2012) suggests that since sea ice melt occurs at specific absolute temperatures, this model behavior is not very surprising given that the historical Earth temperature baselines were biased cold.

81 Data on tas are from the KNMI Climate Explorer which helpfully summarizes GCM and ESM scenarios for statistical analysis, rather than requiring the download of bulk GCM scenarios from an Earth Grid System Federation repository.
The CMIP5 historical simulations span a range of 7 K from 283-290 K, and the RCP scenarios produce a 9 K range from 285-294 K. Figure 5.7b plots each RCP range of results to contrast their specific response signals. While both the RCP8.5 and RCP6.0 scenarios show clear bands that emerge regardless of starting temperature, the RCP4.5 and RCP2.6 scenario responses demonstrate the strongest convergence in models that start with a cold bias. The RCP8.5 scenario is consistent with rates of warming of 0.6°C per decade, while RCP6 and RCP4.5 correspond with 0.4°C and 0.2°C per decade respectively.

Figure 5.7c shows the contrast between the high and low scenarios, and a parallel comparison of the intermediate scenarios: RCP8.5 and RCP2.6 provide the most pronounced difference, while juxtaposing RCP6.0 and RCP4.5 shows considerable overlap (Figure 5.7c). Thus, we can conclude that the strong carbon signal from coal has played an important role in the history of climate science (Chapter 3), and is positioned to remain an important contributor because it provides an elegant method of overwhelming uncertainty in the long-term projections of global climate models. Accordingly, the SSP5-RCP8.5 coal backstop scenario which originated from the tradition of post-1970s energy-economy modeling remains the most important scenario for climate models in the next round of experiments that will form the scientific evidence base for the IPCC’s Sixth Assessment (O’Neill et al., 2016).
Figure 5.7a  CMIP5 Global Mean Temperature (tas) projections from GCMs and ESMs with historical observation from NASA GISS — historical simulations (gray lines), NASA GISS temperature trend (black), RCP8.5 (red), RCP6.0 (orange), RCP4.5 (light blue), RCP2.6 (dark blue)
Figure 5.7b  CMIP5 Global Mean Temperature (tas) projections from GCMs and ESMs – RCP scenarios –
historical simulations (gray lines): (upper left) RCP8.5 (red), (upper right) RCP6.0 (orange), (lower left) RCP4.5 (light blue), (lower right) RCP2.6 (dark blue)

Figure 5.7c  CMIP5 Global Mean Temperature (tas) projections from GCMs and ESMs with historical observation from NASA GISS – RCP scenario comparisons – historical simulations (gray lines), NASA GISS temperature trend (black); (left) RCP8.5 (red) vs. RCP2.6 (dark blue); (right) RCP6.0 (orange) vs. RCP4.5 (light blue)
5.6 Summary

This chapter has analyzed the fossil energy projections produced by IAMs for use as scenarios of anthropogenic radiative forcing in climate model experiments. In summary:

- **Section 5.1** conducts a meta-analysis of the energy system reference cases used in the IPCC Fifth Assessment Report, finding they reflect IAMs which represent developments in the future global energy system with a return to coal hypothesis.

- **Sections 5.2 and 5.3** understands the structural reason why coal is the dominant resource in scenarios produced by these models, namely that the learning-by-extracting model of long-run energy supply curves is a ‘timeless’ approach to fossil energy resources, so the coal backstop is codified into long-run projections and appears the most reliable choice for future energy supply.

- **Section 5.3.2** details the high-coal projections produced by the energy-economy models of the late 1970s and early 1980s which calibrated the uncertainty range for future outcomes based on continuous growth in energy resource demand dominated by coal, which significantly overestimated today’s levels of coal use.

- **Section 5.4** synthesizes this work, to argue that SSP5-RCP8.5 is no longer relevant for continued emphasis in scientific studies, because it was based on the high-coal scenarios produced by IAMs with a legacy understanding of coal, and

- **Section 5.5** details why SSP5-RCP8.5 scenarios will remain a focus of future climate change studies, since they provide a strong signal-to-noise ratio which overwhelms uncertainties in global climate models.

In the next chapter, we look at how these scenarios future climate change can be developed and presented in a broader way, independent of model structure, for a structure-neutral approach to uncertainty in global change assessments.
Chapter 6: A general approach to energy system uncertainty in global change scenarios – structure neutral phase methods for graphical and analytical solutions

In Chapter 5 we arrived at the synthesis of concepts presented earlier in the thesis, namely that IAMs rooted in concepts of 1970s energy-economy modelling produce long-run scenarios dominated by a coal backstop energy supply. These scenarios were used to provide a strong carbon signal to early global climate models, and consequently played an important role in the development of climate science (Chapter 2-5). Though these mega coal scenarios have since become anachronisms, they are deeply entrenched in climate science because they overwhelm uncertainties in projections of future global change by providing a high signal-to-noise ratio.

The climate science community has, in a sense, moved on from IAMs as the pure conceptual basis of future GHG scenarios by creating a simple framework for experiments based on idealized end-points for radiative forcing, drawn from stylized trajectories. These are the RCP scenarios, which are a key object of study for this thesis (Moss et al., 2010; O’Neill et al., 2013; van Vuuren et al., 2011a; 2013; 2012). A scenario architecture based on end-point specifications opens the possibility to develop a more general approach to uncertainty, by solving these RCP end-point scenarios analytically and graphically, so that the carbon signal components can be assessed independently from the structure of any single model.

As covered in Chapter 5, the RCPs are projections of greenhouse gas (GHG) concentrations that result in radiative forcing (RF) levels of 8.5, 6.0, 4.5 and 2.6 W/m². Initially, RCP modeling teams were assigned these four end-point RF targets and designed scenarios to attain them (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011a; 2011b). The RCPs are now supported by a series of more robust Shared Socioeconomic Pathway (SSP) scenarios (Riahi et al., 2017).

The collection of integrated assessment model (IAM) scenarios based on five SSP narratives provide a conceptual foundation for conditions in global society that could lead to each level of RCP forcing (Calvin et al., 2017; Fricko et al., 2017; Fujimori et al., 2017; Kriegler et al., 2017; van Vuuren et al., 2017). These IAM scenarios use the SSP storylines to structure their internal assumptions about technological change, resource availability, economic and demographic trends to the year 2100 (Bauer et al., 2017; KC and Lutz, 2014; Leimbach et al., 2017; Riahi et al., 2017). When taken together, the full suite of SSP-RCP scenarios provide a common infrastructure for the climate model experiments and studies of global change that will inform the next IPCC assessment (O’Neill et al., 2016). In effect, they provide a common language the scientific community can use to develop a discourse about climate change.

However, possible trajectories for carbon dioxide (CO₂) emissions from fossil fuel combustion may be broader than the span covered by detailed IAM scenarios. Therefore, this chapter proposes a method for analyzing RCP components independently from the structure of IAMs, as a way to assess uncertainties for model-based studies of global change.

The cumulative amount of fossil CO₂ emissions internally consistent with each RCP can be reached using a constrained set of developments in the global energy system. This constraint involves a
trade-off between the total amount of energy used and its average carbon content. In other words, a lower energy demand trajectory paired with a higher average carbon intensity of energy supply will arrive at the same level of cumulative CO₂ emissions in the year 2100 (and vice-versa).

Because the SSP-RCP scenario architecture is based on year-2100 end-points, the 21st-century fossil fuel and industry (FF&I) carbon budgets consistent with each RCP can be calculated based on possible combinations of two principal factors over this period: (i) total energy resource use and (ii) its average carbon intensity. Framing RCPs in terms of these two dimensions allows a phase space of global energy use to describe them.

The phase space of a dynamic system represents its key parameters as axes to present the full range of its physically possible states, where each coordinate describes a unique feasible scenario. In this chapter, a future energy system phase space is developed to describe RCPs based on analytical solutions from a decomposition analysis of cumulative emissions (Kaya, 1989). This allows for display of the fossil energy system states that correspond with RCPs across a broad range, independent of any single IAM scenario.

It is important to note that IAM scenarios of future total RF are not entirely based on GHG emissions from the energy system – and can include significant contributions from land use change. Since the RCPs are full sets of RF components, we denote the FF&I carbon budget aspect of each as RCP* for the rest of this paper. Similar phase space approaches could readily be developed for other GHGs and tailored to specific studies of global change.

Using RCPs as benchmark pathways of GHG concentrations provides distinct benefits to the research community by decoupling climate model runs from the extensive development process needed for fully integrated scenarios of their underlying drivers. Though the SSPs now present a highly-detailed foundation for RCP scenarios, a phase space approach contributes additional conceptual support for their use in scientific studies since the RCPs are independent of any single IAM scenario or model structure. Further, this method can be applied to complement IAM scenarios, ensuring they provide sufficient coverage of future energy system uncertainties within the RCP framework.

To demonstrate the RCP phase space method, we can focus on fossil fuel emissions from energy system ‘no policy’ reference cases. Reference cases intend to understand plausible hypotheses for future developments in global energy use which could precede climate policy. Subsequently, these reference cases are applied as ‘baseline scenarios’ for climate impact assessments and policy analysis (Bauer et al., 2017; Clarke et al., 2014).

The original RCP scenarios presented RCP8.5 as the sole pathway of the world without any climate policy, while the other RCPs depicted some form of policy intervention aimed at mitigation (IIASA, 2009; van Vuuren et al., 2011a). However, the range from RCP4.5 to RCP8.5 was initially identified as a plausible span for future reference case scenarios (van Vuuren et al. 2011a). This range is further reinforced by the outcome of the SSP development process which produced no policy reference cases that led to levels of RF within this spectrum (Riahi et al., 2017; Riahi and van Vuuren, 2016). Therefore, the phase space in this chapter is based on RCP4.5, 6.0 and RCP8.5,
with RCP2.6 excluded because it illustrates negative emissions technologies from climate policy measures which precludes it from serving as a reference case.

The IAM reference cases preceding mitigation in AR5 WGIII result in total emissions that correspond to the range between RCP6.0 and RCP8.5. When this set of AR5 WGIII and SSP-RCP marker scenarios are presented in total, they illustrate how IAMs collectively orient outlooks for our global energy future as the origin of cost and technology assessments for reducing future GHG emissions, and the challenges any policy goal will face in efforts to limit warming.

The following work describes the method for producing and reading an RCP phase space (Section 6.1). In Section 6.2 the AR5 WGIII reference case scenarios are placed within the phase space. Analyzing large sets of global change scenarios with a phase space approach allows data mining techniques, such as the k-means cluster analysis we apply, to rapidly distill their key characteristics (Section 6.2.3). This is demonstrated by identifying IAM outlooks for fossil resource use consistent with the identified clusters (Section 6.3). Section 6.4 uses the phase space to compare scenarios for SSPs and the International Energy Agency to those produced for IPCC AR5, and provides outlooks for mitigation cost estimates based on the SSP outlooks for reference case carbon intensity trajectory. Section 6.5 summarizes this chapter.

6.1 Developing an energy system phase space for climate change scenarios

The total amount of global carbon emissions ($F$) that could result from combustion of fossil fuels over the next century can be depicted by a two-dimensional phase space diagram (Figure 6.1a). This phase space expresses the average carbon intensity of energy supply ($F/E$) with the horizontal axis, and total primary energy resource use ($E$) with the vertical axis. The $(x,y)$ coordinates at each point in the phase space summarize a single fossil fuel carbon emission scenario for the years 2016 through 2100. These coordinates are ($F/E$, $E$), and so when multiplied they equal a specific amount of cumulative CO$_2$ emissions across these 84 years.

While global energy scenarios are usually depicted as time-series lines rather than points, this phase space supresses the time dimension in order to provide a clean display and analysis of many scenarios at once. A more traditional presentation of the IPCC AR5 scenarios as time-series is provided in Section 6.2. For a ready comparison to today, the right axis of Figure 6.1a shows the average level of primary energy used across the next 84 years (2016-2100). 83

Producing a phase space of energy system coordinates allows the CO2 emission scenario configurations consistent with RCPs to be presented as lines based on analytical solutions.

6.1.1 Solving RCP scenarios analytically

Based on the Kaya identity (1989), the cumulative amount of 21st-century greenhouse gas emissions ($F$) can be decomposed as a function of average emissions intensity ($F_{intensity} = \frac{F}{E_{primary}}$)

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82 Primary energy is the energy contained in natural resources before conversion or transformation for end-use (Newell and Iler, 2017).

83 This right-axis of the phase space is simply: $\frac{E}{84}$
over the remainder of the century and the total amount of primary energy supply \((E_{\text{primary}} = \text{TPES})\). This identity for each RCP*, or any emission scenario, can then be represented as in Equation 6.1.

\[
F_{\text{intensity}} = \frac{F_{RCP*}}{E_{\text{primary}}} \quad \text{or} \quad F_{RCP*} = F_{\text{intensity}} \times E_{\text{primary}} \quad (6.1)
\]

The total amount of FF&I emissions consistent with RCP8.5, 6.0 and 4.5 are readily calculated from the IIASA RCP Database (IIASA, 2009). Corresponding total 21st-century CO2 emissions for each RCP are approximately, \(F_{RCP8.5} = 7,160 \text{ GtCO2} \), \(F_{RCP6.0} = 4,600 \text{ GtCO2} \) and \(F_{RCP4.5} = 3,010 \text{ GtCO2} \).

We calculate a value for base year range (2000-2015) emissions as \(F_{\text{base}} = 480 \text{ GtCO2} \). Then, the 21st-century carbon budgets for emissions remaining from 2016 through 2100 are equal to \(F_{\text{budget}} = F_{RCP*} - F_{\text{base}} \).

Since we are focused on characterizing the degree of transition projected (decarbonization or re-carbonization) by sets of emission scenarios, we can plot the range of possible solutions for each RCP* with Equation 6.2.

\[
E_{\text{primary}} = \frac{(F_{RCP*} - F_{\text{base}})}{F_{\text{intensity}}} \quad \text{or} \quad E_{\text{primary}} = \frac{F_{\text{budget}}}{F_{\text{intensity}}} \quad (6.2)
\]

We use emission factors for each primary energy source from the IPCC Emission Inventory database where emissions from oil are calculated with \(\epsilon_o = 73.3 \text{ MtCO2/EJ} \), emissions from gas as \(\epsilon_g = 56.1 \text{ MtCO2/EJ} \), and emissions from coal with \(\epsilon_k = 94.6 \text{ MtCO2/EJ} \) (IPCC, 2006).

We can denote oil as \(O\), gas as \(G\) and coal as \(C\), where the proportion of each fossil fuel in the primary energy mix \((E_{\text{primary}})\) is given by \([\Omega, \gamma, \kappa]\) in Equation 6.3:

\[
\frac{O}{E_{\text{primary}}} = \Omega \quad , \quad \frac{G}{E_{\text{primary}}} = \gamma \quad , \quad \frac{C}{E_{\text{primary}}} = \kappa \quad (6.3)
\]

With these emission factors and notation established, the series of solutions consistent with each RCP* can be further decomposed into specific values for total fossil energy from each source with Equations 6.4 and 6.5.

\[
E_{\text{primary}} = \frac{F_{RCP*}}{F_{\text{intensity}}} = \frac{F_{RCP*}}{\epsilon_o \Omega + \epsilon_g \gamma + \epsilon_k \kappa} \quad (6.4)
\]

\[
F_{RCP*} = E_{\text{primary}} (\epsilon_o \Omega + \epsilon_g \gamma + \epsilon_k \kappa) = \epsilon_o O + \epsilon_g G + \epsilon_k C \quad (6.5)
\]

As noted in the introduction, the RCP scenarios are end-points for future RF that could result from different combinations of energy use and its carbon intensity. Therefore, cumulative carbon emissions consistent with RCP*8.5 (red), RCP*6.0 (blue) and RCP*4.5 (green) can be depicted as lines that cross multiple points based on Equation 6.5. Possible fossil CO2 emission scenarios that lead to the RCP* scenarios are plotted as isoclines in Figure 6.1a using this method.
This section proceeds by adding consecutive layers of detail in the RCP phase space to describe its capabilities as a tool for model-based studies of global change, and how to read it.

6.1.2 Placing reference points in the phase space

In Figure 6.1b we can add points of reference that can orient the reader, and assist with interpreting the meaning of each scenario in the phase space. The open blue circle, labeled stasis, represents repetition of today's energy use pattern for the rest of the century. This stasis point is a purely hypothetical condition – it does not account for underlying trends of growth in total energy use and gradual decline of carbon intensity experienced over the late 20th-century. The stasis point does not express a plausible scenario, but merely provides a starting point for understanding future scenarios of global change in relation to today's world.

The purple star, labeled 50-year baseline, reflects the continuation of today’s energy system trends to 2100. This 50-year baseline signal is calculated using all available data from the 2016 BP Statistical Review to project an historically consistent trend to the end of the century (BP, 2016).

These 2015 stasis and 50-year baseline points are depicted as outlines because they are not internally consistent projections of socioeconomics, supply and demand generated by an IAM. Because the phase space values correspond to the energy scenarios produced for the years 2016-2100, a dynamic animated phase space would show the RCP isoclines approaching the present year static point as more emissions are released (e.g. as more of the remaining cumulative carbon budget represented by each RCP* line is used up). In Section 6.2 the stasis and baseline signals are plotted as time-series. Phase space reference lines a

Each point in Figures 6.1a-c describes coordinates which represent a scenario of the carbon intensity that results from a corresponding mix of fuels (horizontal axis). The carbon intensity of each point primarily reflects various combinations of oil, gas and coal.

Based on the notation established above in Section 6.1.1, the three vertical gray lines in Figure 6.1b depict values for the carbon intensity equivalent to an energy system of 100% gas \( y = 100\% \) (gray short-dash line), 100% oil \( \Omega = 100\% \) (gray long-dash line), and 100% coal \( \kappa = 100\% \) (gray solid line).

While these lines are useful for analysis, they should not be misunderstood as the only way to reach each corresponding level of carbon intensity, since multiple combinations of renewable energy, nuclear, carbon capture sequestration or other technologies could lead to the same coordinates. The lines are merely proxy levels of energy system carbon intensity for reference.

6.1.3 IAM scenarios in the phase space

An IAM scenario of future carbon emissions \( F \) from fossil fuels can be represented as a single point in the phase space by:

- summing its projected total primary energy use for the remainder of this century – giving it a coordinate on the vertical axis \( E \)
• summing its projected annual emissions from oil, gas and coal for the remainder of this century and dividing by $E$ – giving it a coordinate on the horizontal axis ($F/E$)

Several individual IAM scenarios of the global energy system are added to Figure 6.1c. The five SSP marker scenarios are designated as squares: SSP5 (purple square), SSP4 (orange square), SSP3 (red square), SSP2 (blue square) and SSP1 (green square) (Riahi et al., 2017; Riahi and van Vuuren, 2016). The red diamond (labeled Year 2100 RCP8.5 Marker) is the original RCP8.5 marker scenario developed by the MESSAGE IAM, which was the only no policy reference case originally provided to illustrate the RCPs (van Vuuren et al 2011, Riahi et al 2011).

Figure 6.1a RCP phase space diagram – future global energy scenarios consistent with RCP*8.5 (red), RCP*6.0 (blue) and RCP*4.5 (green) plotted by cumulative total primary energy (TPES) (vertical left axis) and mean emissions intensity (horizontal axis) with average primary energy resource use over all 84 years (right axis)
Figure 6.1b  Points of reference within the phase space – two points provide reference within this phase space for a hypothetical scenario of stasis from the year 2015 with no additional change in rate of energy use or carbon intensity (blue open circle), and a projection of the historical baseline trend signal through to the year 2100 (purple star), three vertical grey lines represent the carbon intensity values for total primary energy supply consistent with a 100% gas (short dashes), 100% oil (dashes) and 100% coal (solid line) energy system.
6.1.4 Mapping energy system transition in the phase space

This formulation allows for mapping the energy system developments consistent with future levels of climate change based on relative movements to 2015 along the x and y-axes by increased or declining shares of carbon-intensive energy sources. In Figure 6.1c, if the scenario trajectory is upwards, there will be more energy use. If it moves to the right – more carbon intensive, and if to the left, less carbon intensive. The legend on the right of Figure 6.1c provides a guide to this movement in the phase space diagram. In general, a scenario with a greater proportion of coal ($\kappa^+$) or oil ($\Omega^+$) leads to a higher carbon intensity, while a scenario with a greater proportion of gas ($\gamma^+$) leads to a lower carbon intensity.

**Decarbonization** describes a transition toward futures **left of the blue open circle** – these scenarios result in a primary energy supply fuel mix with lower fossil share, and/or a fossil composition with declining share of coal and rising share of gas. **Re-carbonization** describes a transition toward the **right of the blue open circle** - illustrating higher shares of oil or coal in the primary energy mix. **Steady-state** scenarios describe futures **immediately above or below the open blue circle**, where average carbon intensity of energy supply stays the same, evolution of fossil contribution to TPES remains static, or coal replaces declining shares of oil and gas.

Any degree of energy system decarbonization or re-carbonization also depends on the role of non-fossil energy sources. The 50-year baseline signal captures the gradually expanding share of non-fossil energy sources, a slowly declining proportion of coal, and a moderately increasing fraction of
natural gas in decarbonizing the global primary energy (Section 6.2). However, non-fossil energy has tended to play a subsidiary role in IAM GHG emission no policy reference cases, so we focus on fossil energy in the remainder of this paper.

With this general framework and notation established for analyzing and communicating fossil emission scenarios, the energy system phase space can be populated by each IAM no policy reference case from AR5 WGIII.

6.2 IPCC AR5 energy system reference cases: a k-means cluster analysis of IAM no policy scenarios

To understand how AR5 ‘no policy’ reference cases orient projections for fossil carbon emissions, we collect necessary inputs to the equations in Section 6.1.1 from scenarios in the AR5 Database (IPCC WGIII, 2014). 84

6.2.1 AR5 Scenarios: underlying time-series for each phase space point

These IPCC AR5 WGIII reference case scenarios intend to depict possible ‘baseline’ future developments in the global energy supply assuming no explicit climate policies. Figures 6.2a-d plot these data as time-series alongside three alternative trend-lines:

(i) the historical baseline signal between 1965-2015 extrapolated to 2100 (purple line)
(ii) simple replication of the year-2015 energy supply pattern for every year to 2100 (blue line), and
(iii) the data for the RCP8.5 MESSAGE scenario (red line)

These plots complement the pure annual production scenario analysis conducted in Chapter 5.

6.2.1.1 Cumulative Primary Energy [E] – Figure 6.2a

Annual rates of 21st-century primary energy for AR5 reference cases span 460 EJ/year to 1,980 EJ/year by century’s end. As most reference cases project ongoing growth in primary energy, fuel sources with static TPES shares continue to grow. Ninety-nine percent of scenarios project ongoing growth in TPES leading to a mean year-2100 value for all runs that is over twice today’s levels.

6.2.1.2 Oil [Ω] and Gas [γ] – Figure 6.2b and Figure 6.2c

AR5 reference cases project either a static or declining share for oil in global primary energy supply. At the end of the century, oil comprises between 1% and 38% of primary energy, with the mean value across scenarios at 14%. This average is less than half of the year-2015 share of oil at 33% (BP, 2016). Scenarios for gas are similar to those for oil, but comprise smaller declines by the year 2100. In 2015, natural gas had a 24% share and the average value for γ at the end of the century is 18%.

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84 Full 21st-century scenarios in the AR5 database are generated by a series of 16 IAMs (n-221). We draw on the IAM runs from EMF27, LIMITS, AME, AMPERE2, AMPERE3, and ROSE model intercomparison exercises, alongside results from GEA and REMIND.
6.2.1.3 Coal $\kappa$ - Figure 6.2d

The AR5 no policy scenarios project a wider range of possible values for coal’s future share of TPES with no sustained declines across the next century: the lowest value of any scenario is slightly before mid-century at $\kappa = 18\%$, but this specific run reverts toward the scenario database mean after 2060. Some AR5 reference cases model a vast expansion in the use of coal over the next 85 years, alongside a decline in all other energy sources so that by 2100 $\kappa = 94\%$. The mean end-of-century value for all runs is $\kappa = 47\%$ which is consistent with the pathway of RCP8.5 MESSAGE. Coal’s share of total primary energy in 2015 is 29% (BP, 2016).

Figure 6.2a  AR5 reference cases plotted as time-series – [E]: cumulative primary energy use from 2016-2100 [E] with overlays of RCP8.5 MESSAGE marker scenario (red), static 2015 case (blue) and 1965-2015 baseline signal trend (purple) and AR5 baseline runs (gray lines) where darker shading denotes a higher concentration of overlap among AR5 scenarios
Figure 6.2b  AR5 reference cases plotted as time-series – [Ω]: percentage of primary energy supplied by oil from 2016-2100 [Ω] with overlays of RCP8.5 MESSAGE marker scenario (red), static 2015 case (blue) and 1965-2015 baseline signal trend (purple) and AR5 baseline runs (gray lines) where darker shading denotes a higher concentration of overlap among AR5 scenarios.

Figure 6.2c  AR5 reference cases plotted as time-series – [γ]: percentage of primary energy supplied by gas from 2016-2100 [γ] with overlays of RCP8.5 MESSAGE marker scenario (red), static 2015 case (blue) and 1965-2015 baseline signal trend (purple) and AR5 baseline runs (gray lines) where darker shading denotes a higher concentration of overlap among AR5 scenarios.
6.2.2 Populating the RCP phase space with AR5 scenarios

With the inputs to Equation 6.5 collected, each IAM reference case scenario from AR5 is represented as a gray diamond in Figure 6.3, with darker points indicating overlapping scenario end-points. In Figure 6.3, box plots of cumulative energy use and carbon intensity for the full series of IAM reference cases correspond with each axis. The AR5 database reference case mean scenario falls within the range of feasible solutions for CO₂ forcing between RCP*6.0 and RCP*8.5 with a carbon intensity of 67 MtCO₂/EJ and cumulative energy use of 80,000 EJ, indicating a trend of moderate re-carbonization across the entire dataset.

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Some scenarios fall between RCP*4.5 and 6.0 but when the other RF components are included, these scenarios are within a range with total RF of at least 6.0.
Figure 6.3  RCP phase space populated with IPCC AR5 WGIII scenarios from IAMs – each AR5 reference case (gray diamond) is plotted based on mean emission intensity across 2016-2100 (horizontal axis) and cumulative energy use (vertical axis) with transparent overlay of SSP marker scenarios; box plots on the top and right note AR5 scenario mean, median and range

6.2.3  k-means cluster analysis of AR5 scenarios

Describing each IAM scenario as a set of energy system coordinates in this RCP phase space allows for ready application of data mining techniques that can summarize the main characteristics of the full dataset. Accordingly, we can conduct a k-means cluster analysis.

K-means cluster analysis uses an unsupervised learning algorithm to group individual scenario data points into unique clusters with shared characteristics. This identifies groups in large data sets organically, rather than through the application of pre-specified labels or narratives. Results of any k-means cluster analysis depends on a priori assumptions by the analyst about the number of clusters (k). Though the k-means algorithm partitions a data set into k number of clusters, it does not ensure that each cluster is a valid or useful descriptor. With no prior assumptions about the WGIII modelling outputs, they are analyzed using a range of k-values to ensure clustering patterns are not an artifact of an arbitrary k-value.

k-means cluster analyses for $2 \leq k \leq 12$ were conducted on the AR5 WGIII reference case dataset. The position of cluster centers for $k = 12$ is plotted in Figure 6.4a, numbered sequentially by their order of discovery. From these data, changes in the average within-cluster distance between observations and centroid were analyzed for each k value, and the elbow plot of Figure 6.4b was
produced. This elbow plot identified an optimal range between $2 \leq k \leq 7$, narrowing the scope for further investigation.

With $k > 7$ the average distance between observations and cluster centers started to saturate. Cluster centers from $4 \leq k \leq 7$ led to significant horizontal axis overlap and merely repeated the AR5 database reference case mean (orange dot – clusters #4 and #5), the scenarios in the upper right quadrant of the phase space (red dot - #6) or the outlier scenarios to the right of the stasis point (blue dot - #7). Therefore, $k = 3$ was selected for subsequent analysis because it produced the greatest number of salient clusters that effectively summarized the unique scenario typologies in the data set. This resulted in cluster centers located at the three colored dots in Figure 6.4b (red, orange and blue).

Figure 6.4a  k-means cluster analysis of AR5 WGIII database reference cases for $k = 12$ – phase space plot for $k = 12$ – clusters numbered by order of discovery, final clusters for $k = 3$ marked by colored circles in red, orange and blue
6.2.4 Energy system scenarios identified by k-means cluster analysis of AR5 scenarios

Our k-means cluster analysis identifies three distinct types of energy system scenarios in the AR5 WGIII database – further labeled as Groups A, B and C. The cluster centers plotted in Figure 6.5 summarize hundreds of IAM reference case scenarios. Each of these points does not intend to constitute a single specific scenario but are representative of the wider range of AR5 reference cases.

Group A represents the RCP8.5 consistent scenarios of steady-state and re-carbonization coupled with faster energy system expansion (F $\geq$ RCP*8.5). Group B corresponds to the solutions approximating the AR5 database mean which includes reference cases of decarbonization, steady-state, and re-carbonization with intermediate growth in primary energy supply (RCP*6.0 < F < RCP*8.5). Group C describes scenarios with lower growth in energy supply that follow gradual re-carbonization (F = RCP*6.0). In Figure 6.5 dotted lines between the Year 2015 static case and each of the scenario clusters represent the transition pathways followed by each group of scenarios. The dotted line that tracks the 50-year baseline signal indicates a trend of gradual decarbonization while each of the AR5 clusters depict a transition toward re-carbonization.

Identifying distinct clusters of scenarios provides a structure of classification that can allow for novel insights regarding the detailed characteristics of each group. This is demonstrated in the following section through mapping the cumulative oil, gas and coal supply scenarios of each cluster.
Figure 6.5  RCP phase space populated with cluster centers IPCC AR5 WGIII scenarios - Cluster analysis identifies three groupings of A (F ≥ RCP*8.5), B (RCP*6.0 < F < RCP*8.5), C (F ≈ RCP*6.0) AR5 scenarios; the final cluster centers for each group of AR5 scenarios are plotted as solid dots – A (red), B (orange), C (blue); dashed lines represent the degree of decarbonization or re-carbonization transition from the static base year point to the cluster scenario for the 21st-century energy system.

6.3  AR5 reference case clusters: described as characteristics of oil, gas, and coal combustion

To further define these three AR5 reference case groups Figures 6.6a-c plot each IAM scenario of future oil, gas or coal combustion as a dot, shaded by the cluster membership identified in Section 6.2.4. Carbon budgets consistent with RCPs are overlaid on each figure as horizontal lines. These outlooks for each fuel source are indexed to today’s knowledge of their conventional reserves and resources with vertical black lines (BGR, 2015). 86

Scenarios in Group C tend to cluster around combustion of all conventional oil reserves and resources (Figure 6.6a). 87 Group B scenarios equate to combustion of all conventional oil with some or most unconventional reserves and resources. Group A scenarios are less optimistic about future oil supply than Group B - many of the Group A oil scenarios draw clear lines at 8,000 EJ (corresponding to all conventional oil reserves) and 16,000 EJ (corresponding to all conventional oil reserves and resources).

86  BGR identified ‘resources’ denote geologically available quantities of oil, gas and coal that may be recoverable in the future with technological change and sufficient economic conditions, as well as ‘geologically possible’ quantities which have yet to be verified but are likely to exist due to characteristics of known regions.

87  The designation of conventional generally denotes that production is possible with ‘classic technologies’, while extra-heavy oil, bitumen and shale oil are ‘unconventional’ because they require a different set of extraction technologies (see Chapter 1).
Figure 6.6b plots gas supply cases of each scenario group, highlighting that each cluster is less confident about production of future unconventional gas than unconventional oil. On average, Groups A and C use 70% of conventional gas reserves and resources. Group B clusters around the use of all conventional reserves and resources with some unconventional gas. 88 85% of the Group A scenarios present a stringent boundary for natural gas at 14,000 EJ across multiple models, representing a strong consensus on how an IAM can be configured to illustrate end-of-century targets for levels of forcing that meet or exceed RCP*8.5.

AR5 reference cases in Group C use most or all modern hard coal and lignite reserves (Figure 6.6c). These levels of coal combustion roughly correspond to the total coal reserves reported by Rogner et al. (2012). Group B scenarios use at least all hard coal reserves while Group A scenarios are optimistic about future coal supply and demand, projecting the combustion of 33,500 to 79,000 EJ of coal. As we will see in Section 6.4, coal is the dominant fossil resource for each group of AR5 reference case scenarios, regardless of end-point target for radiative forcing.

Figure 6.6a Cumulative oil, gas and coal combustion in AR5 reference cases shaded by cluster grouping (2016-2100) - oil [O] – BGR (2015) resource estimates marked with vertical black lines; Note axis break from 40,000 to 80,000 EJ

88 Note: BGR (2015) reports that unconventional gas reserves are 90% smaller than reserves for unconventional oil.
Figure 6.6b  Cumulative oil, gas and coal combustion in AR5 reference cases shaded by cluster grouping (2016-2100) - gas [G] – BGR (2015) resource estimates marked with vertical black lines; Note axis break from 40,000 to 80,000 EJ
6.3.1 Fossil energy resource couplings exhibited by AR5 scenarios

Each reference case scenario cluster identified in the AR5 database corresponds with tightly coupled combinations of fossil resource combustion. This analysis uses BGR (2015) data on non-renewable energy reserves and resources, with coal reserve figures supplemented by analysis from Mohr et al. (2015) and Chapter 3 - these fossil resource quantities are listed in Table 6.1.
6.3.2 Comparability of oil, gas and coal reserve and resource estimates

Chapter 3 discusses the history of continuous downward revisions in coal reserves, highlighting how ongoing declines reflect many important factors which indicate the total amount of hard coal reserves is the plausible upper bound on future combustion, rather than a lower bound as previously assumed (McCollum et al., 2014; Rogner, 1997). Counter to the trend experienced with oil and gas, coal resources show no evidence of widespread conversion to reserves. Therefore, definitions of ‘reserves’ and ‘resources’ are not equivalent for each hydrocarbon energy resource. While oil and gas reserves indicate a lower bound for combustion, the total amount of coal reserves indicate the likely upper bound. Accordingly, this section compares combustion of all hard coal and lignite reserves with combustion of all known conventional oil and gas (reserves + resources).

Coal reserves and resources are generally assessed using mass-based units. Therefore, a critical uncertainty for the amount of energy that could be recovered from hard coal are regional variations in the energy content of various coal deposits. The estimate of 15,300 EJ of remaining coal is consistent with applying an 80% recovery factor to the theoretical maximum remaining hard coal identified by Mohr et al. (2015) of 19,100 EJ. An 80% recovery factor corresponds to surface mining under favorable conditions.
The right column of Table 6.1 accounts for the total amount of CO₂ emissions that would be released through unabated combustion of these fossil reserves and resources (using IPCC, 2006 emission factors). Total combustion would result in a total of 3,870 GtCO₂ – an amount which exceeds the remaining carbon budget for RCP4.5 by 50%, and constitutes 90% and 60% of the RCP6.0 and RCP8.5 budgets respectively.

<table>
<thead>
<tr>
<th>Exajoules (EJ)</th>
<th>Reserves</th>
<th>Resources</th>
<th>Total</th>
<th>Total CO₂ gigatons CO₂*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>7,140</td>
<td>6,820</td>
<td>13,960</td>
<td>1,020</td>
</tr>
<tr>
<td>Gas</td>
<td>7,260</td>
<td>12,160</td>
<td>19,420</td>
<td>1,100</td>
</tr>
<tr>
<td>Coal</td>
<td>15,300 (hard coal) + 3,270 (lignite)</td>
<td></td>
<td>18,570</td>
<td>1,750</td>
</tr>
</tbody>
</table>
\[\text{Total} \quad 51,950 \text{ EJ} \quad 3,870 \text{ GtCO}_2\]

*Using IPCC (2006) emissions factors

6.3.3 Summary of AR5 energy system reference case characteristics

The fossil energy system characteristics of each scenario cluster are summarized in Table 6.2. Within the phase space, cluster analysis identifies three distinct groups of energy policy reference cases that harmonize with RCP carbon budget ranges.

- **Type A** (F ≥ RCP*8.5) scenarios are consistent with rapid re-carbonization and high growth in energy use where the energy system uses less natural gas and increasing amounts of coal.
- **Type B** (RCP*6.0 ≤ F < RCP*8.5) scenarios generally describe steady-state and modest re-carbonization energy system reference cases with little change in the carbon intensity of energy supply, combustion of 80% more coal than indicated by modern reserves, significant production of unconventional oil and use of all conventional gas.
- **Type C** (F ≈ RCP*6.0) scenarios illustrate a low-growth global energy system that transitions toward gradual re-carbonization with steady expansion of coal combustion, and very limited production of unconventional oil and gas.
Table 6-2 - Summary of fossil energy system reference case characteristics applied by AR5 WGIII scenarios to describe RCP ranges

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>F ≥ RCP*8.5</td>
<td>A</td>
<td>SSP5</td>
<td>High</td>
<td>Re-carbonization</td>
<td>1.0x</td>
<td>0.7x</td>
<td>3.7x</td>
</tr>
<tr>
<td>RCP<em>6.0 &lt; F &lt; RCP</em>8.5</td>
<td>B</td>
<td>SSP2/SSP3/SSP4</td>
<td>Medium</td>
<td>Steady-state/Moderate Re-carbonization</td>
<td>1.4x</td>
<td>1.0x</td>
<td>1.8x</td>
</tr>
<tr>
<td>F ≈ RCP*6.0</td>
<td>C</td>
<td>--</td>
<td>Low</td>
<td>Gradual Re-carbonization</td>
<td>1.0x</td>
<td>0.7x</td>
<td>1.5x</td>
</tr>
</tbody>
</table>

* Cluster mean use of BGR (2015) conventional fossil energy reserves and resources
† These SSP marker scenarios fall into the RCP carbon budget ranges, but may not reproduce the same characteristics of each AR5 cluster, this is analyzed further in Section 6.4

6.4 Comparing IPCC AR5 energy system outlooks to IEA and SSP scenarios in the RCP phase space

The International Energy Agency (IEA) regularly produces several scenarios of the global energy system through the year 2040 as part of its annual World Energy Outlooks (e.g. 2016; 2015; 2014). Of these, the New Policies Scenario (NPS) receives the most focus as a reference case energy system, and ‘broadly serves as the IEA baseline scenario’ for policy modeling and analysis. For example, the IEA Energy Technology Perspectives 2017 (ETP 2017) report extends the NPS through 2060 as the reference case energy system for mapping policies and technologies that could achieve a policy goal which limits 21st-century warming to no more than 2°C above pre-industrial levels, as well as below 2°C scenarios that aim for 1.5°C.

The NPS is designed to reflect:

...the way that governments, individually or collectively, see their energy sectors developing over the coming decades. Its starting point is the policies and measures that are already in place, but it also takes into account, in full or in part, the aims, targets and intentions that have been announced, even if these have yet to be enshrined in legislation or the means for their implementation are still taking shape.... Where considerable uncertainties persist, how far and how fast the policy commitments are met depends upon our assessment of the political, regulatory, market, infrastructure and financing constraints; in such cases, the announced targets may, in our Outlook, be met later than proclaimed or not at all. On the other hand, there are also cases in which energy demand, macroeconomic circumstances and/or cost trends lead countries to go further and faster than their stated ambitions. The projections in the New Policies

89 For a full description of IEA energy scenarios and how they are intended to be used and interpreted see: https://www.iea.org/publications/scenariosandprojections/
Scenario signal to policy-makers and other stakeholders the direction in which today’s policy ambitions are likely to take the energy sector. (IEA 2016, p.33-34)

In other words, the NPS reflects future expectations for the global energy system without additional interventions that are not already announced or planned. This is similar to the context of the IAM SSP-AR5 WGIII scenarios which are used to map outlooks for climate policies in the context of anticipated energy system developments. Therefore, it is useful to compare the IEA NPS to SSP and IPCC AR5 WGIII reference case scenarios.

6.4.1 IEA, SSP and AR5 reference case scenario time-series

Figure 6.8 extends IEA 2016 NPS growth rate trends for oil, gas, coal and primary energy through 2100, 90 allowing for comparison with full century IAM scenarios in the SSP database (Riahi and van Vuuren, 2016). The IEA 2016 NPS projects growth in TPES that closely tracks SSP2 and SSP3 (Figure 6.8 - left). However, the IEA’s reference case outlook is for an energy supply less carbon intensive than all ‘no policy’ SSPs until later this century (Figure 6.8 - right). 91

Figure 6.8   Time-series plots of SSP IAM scenarios and IEA reference case global energy system – SSP1 (green), SSP2 (blue), SSP3 (red), SSP4 (yellow), SSP5 (purple), and IEA reference case (blue dashed line); (left) total primary energy supply; (right) carbon intensity of primary energy supply - note axis break

6.4.2 IEA, SSP and AR5 reference case scenarios: phase space plot and ‘no policy’ equivalence

Notably, the 2015 and 2016 IEA NPS include ‘cautious’ interpretations of how and when Paris Agreement policy commitments will be met. Therefore, a reasonable question arises whether IAM ‘no policy’ reference cases are fully comparable to the IEA NPS. For this purpose, we extend and plot the IEA NPS from years 2014, 2015 and 2016 in the energy system phase space of Figure 6.9a.

The IEA ETP 2017 reference case extends the 2016 NPS through 2060, and produces an even stronger reference case outlook for decarbonization. This provides a parallel confidence check on our method of projecting trends inherent in the NPS, which indicates a simple analysis based on extending the change in growth rate trend post-2040 (acceleration vs. deceleration) provides conservative estimates of the slowing primary energy demand and passive decarbonization in the IEA’s reference case.

The IEA NPS only provides data points for 2014 and 2025 so assessing the decarbonization trend consistent with their projected rate for this period leads to a base year estimate for 2016 that is slightly lower than the other SSPs. The initial variation in base year carbon intensity values can also stem from differences in primary energy accounting.

90 The IEA ETP 2017 reference case extends the 2016 NPS through 2060, and produces an even stronger reference case outlook for decarbonization. This provides a parallel confidence check on our method of projecting trends inherent in the NPS, which indicates a simple analysis based on extending the change in growth rate trend post-2040 (acceleration vs. deceleration) provides conservative estimates of the slowing primary energy demand and passive decarbonization in the IEA’s reference case.

91 The IEA NPS only provides data points for 2014 and 2025 so assessing the decarbonization trend consistent with their projected rate for this period leads to a base year estimate for 2016 that is slightly lower than the other SSPs. The initial variation in base year carbon intensity values can also stem from differences in primary energy accounting.
The year 2014 NPS did not include any Paris Agreement policy commitments, and the 2015 NPS was the first to do so (see Figure 6.9a legend – lower left). When these consecutive annual IEA NPS scenarios are placed in the phase space, the ‘signal’ of the Paris Agreement commitments does not clearly stand out from other social, economic, technological and policy factors. Although the 2015 NPS largely overlaps with the 2014 NPS, in Figure 6.9a it moved slightly in the direction of re-carbonization after accounting for Paris Agreement policies. The 2016 NPS also includes the IEA’s interpretation of Paris Agreement policies and shows a significant shift in the direction of decarbonization.

Given the consecutive motion of 2014-2016 NPS scenarios in the phase space, no conclusive statements can be drawn about the influence of Paris Agreement commitments versus other year-to-year energy system developments. Only a detailed report from the IEA on their interpretation of Paris Agreement contributions alongside documentation of subsequent NPS revisions could answer this question.

It is also important to consider that Paris Agreement commitments may not be effectively implemented - ceteris paribus this is projected by the IEA to be approximately consistent with the phase space point of the 2014 NPS which lies between the SSP1 and SSP4 marker scenarios.

In Figure 6.9b the full range of 24 alternate IAM scenarios based on SSP storyline narratives are plotted alongside the IEA 2016 NPS (further noted as IEA Reference). The bulk of these IAM reference cases end up between the SSP4 and SSP5 marker scenarios. Table 6.3 compares cumulative oil, gas and coal resource use for these scenarios with the dominant resource of each SSP and IPCC AR5 reference case highlighted. The IEA reference case and SSP1 scenarios project a major role for natural gas while the rest of the SSP and IPCC AR5 scenario groups emphasize coal. Of the SSP database reference case scenarios, coal is the majority fossil resource in 66% (n = 16), oil in 21% (n = 5) and gas in 13% (n = 3).

The comparisons developed in this section should not be interpreted as implying that the IEA’s reference case scenario is more (or less) ‘accurate’ than the IAM SSP and AR5 scenarios – only that the IEA’s reference case is carefully designed to reflect expected developments in the global energy system, and as this analysis highlights, these are rather different those projected by the SSP-AR5 scenarios.
Figure 6.9a  Energy system phase space - IEA, SSP and IPCC AR5 scenarios (2016-2100) – IEA New Policies Scenarios (NPS) from years 2014, 2015 and 2016 (blue triangles) compared to SSP marker scenarios (squares) and IPCC AR5 scenario database clusters (circles), legend for movement of consecutive IEA reference scenarios aligned with carbon intensity axis (lower left), Note: the points in this legend are not consistent with the vertical axis.

Figure 6.9b  Energy system phase space for IEA, SSP and IPCC AR5 scenarios (2016-2100) – energy system phase space plot of IEA 2016 NPS compared to full range of IAM scenarios in the SSP database – each shaded dot represents an IAM scenario that expresses one of the SSP storyline narratives.
Table 6-3 - Cumulative oil, gas and coal resource use (2016-2100) - IEA, AR5 and SSP reference case scenarios: mean cumulative combustion of resource per cluster of AR5 scenarios, full range of SSP IAM scenarios (average of marker scenarios plus alternates) alongside the hypothetical stasis and post-1965 baseline signal cases; dominant fossil energy resource shaded gray

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<tr>
<td></td>
<td>multiple of IEA (x)</td>
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<tr>
<td><strong>IEA Reference</strong></td>
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<tr>
<td></td>
<td>16,900</td>
<td>20,500</td>
<td>14,700</td>
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<tr>
<td></td>
<td>(1.0x)</td>
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<tr>
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<tr>
<td>Cluster A</td>
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</tr>
<tr>
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<td>(0.7x)</td>
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<td>(4.6x)</td>
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<td>Cluster B</td>
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<td>(2.3x)</td>
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<tr>
<td>Cluster C</td>
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<td><strong>SSPs</strong></td>
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<tr>
<td>SSP1</td>
<td>15,200</td>
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<td>14,500</td>
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<tr>
<td>Mean (n = 6)</td>
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<td>(0.8x)</td>
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<td>(1.0x)</td>
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<tr>
<td>SSP2</td>
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<td>24,700</td>
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<tr>
<td>Mean (n = 6)</td>
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<td>(0.9x)</td>
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<td>(1.7x)</td>
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<tr>
<td>SSP3</td>
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<td>17,800</td>
<td>33,400</td>
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<tr>
<td>Mean (n = 5)</td>
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<td>(0.9x)</td>
<td></td>
<td>(2.3x)</td>
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<tr>
<td>SSP4</td>
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<td>18,200</td>
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<tr>
<td>Mean (n = 3)</td>
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<td>(1.3x)</td>
<td></td>
<td>(2.6x)</td>
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<tr>
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<tr>
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<td>(0.9x)</td>
<td>(0.5x)</td>
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<tr>
<td><strong>1965-2015 Baseline Signal</strong></td>
<td>17,800</td>
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<tr>
<td></td>
<td>(1.1x)</td>
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6.4.3 Climate policies for 2° in the context of reference case carbon intensity trajectories

In Chapter 4, we found that scenarios consistent with empirically constrained outlooks for future coal are consistent with lower GHG mitigation costs. Such scenarios would follow reference case trends of gradual decarbonization since 1965, rather than the IPCC AR5 scenarios which we find in this chapter have collectively produced an outlook for opposite trajectories of re-carbonization.

To examine this hypothesis further, Figures 6.10a,b analyze the climate policy outlooks produced by IAMs to illustrate each SSP world in the context of their ‘no policy’ reference case trajectories of carbon intensity. These are the carbon prices consistent with outlooks to achieve year-2100 total radiative forcing of 3.4 W/m² – a level broadly consistent with a 2° policy goal. However, results are similar for any radiative forcing target (e.g. 2.6 W/m² which would yield an even higher probability of staying under 2°).

Figure 6.10a plots each climate policy pathway of the five SSP marker scenarios as a line. This line shows carbon prices in the context of momentum established by the scenario’s corresponding underlying baseline carbonization trajectory. The horizontal axis of this figure marks the reference
case ‘no policy’ carbon intensity, and the vertical axis shows the discounted carbon price for a 3.4 W/m² policy goal. Each SSP scenario pathway begins in the year 2020 (marked by a hollow point) and ends at the year 2100 (marked by a circled point). Each point along the path represents the carbon price for a subsequent decade, e.g. the dot after the hollow 2020 origin point represents 2030, and so on. Arrows along each scenario path highlight the evolution of carbon prices in time from 2020-2100.

Plotting climate policy trajectories in this way allows a clear picture of how baseline levels of carbonization influence the effort depicted to achieve a 2°C policy goal. Figure 6.10a shows that ‘no policy’ worlds following the direction of our historical global baseline trajectory toward the left require lower carbon prices to limit warming to 2°C (represented by the IEA Reference Case trend on the top axis). Notably, this is also consistent with the SSP design process which intended for SSP1 and SSP2 to illustrate lower challenges to mitigation than SSP3 and SSP5 (Riahi et al., 2017). Conversely, higher carbon prices result from scenarios that persist around the 2015 stasis line, or move to the right toward re-carbonization.

Projected climate policies and carbon shadow prices can significantly vary between models, so it is unclear whether these cost-carbonization trajectories are independent of each specific IAM used to produce SSP marker scenarios (REMIND, AIM, GCAM, MESSAGE, IMAGE). Therefore, Figure 6.10b plots all of the climate policy cost-carbonization trajectories in the SSP database for these models. In Figure 6.10b each point represents a decade from 2050-2100, with the marker scenarios from Figure 6.10a as an underlying ‘shadow’. This collection of IAM SSP scenarios shows a strong relationship between baseline carbonization trajectories and their climate policy outlooks, independent of model or storyline narrative. The scenarios following the historical direction consistently produce a 2°C policy goal with lower prices than those narrowly aligned around the steady-state carbon intensity level of 2015.
Figure 6.10a Climate policy trajectories for 2° per SSP marker scenario (RCP3.4 - 2020-2100) – climate policy-carbonization pathways for SSP1-5 marker scenarios from 2020-2100 – each dot represents a decadal carbon price-reference case carbon intensity; (lower horizontal axis) reference case carbon intensity and (vertical axis) carbon price discounted at 3% for a scenario that achieves year-2100 radiative forcing of 3.4 W/m² – a level broadly consistent with a 2° policy goal, (top horizontal axis) levels of energy supply carbon intensity correspond to the 2015 stasis and IEA reference case levels with year noted; in each figure the origin year of the scenario path is marked by a hollow circle
Figure 6.10b Climate policy trajectories for 2° - SSP alternate scenarios (RCP3.4 - 2050-2100) – SSP database IAM scenarios for 2050-2100 with hollow points on each alternate scenario marking the year 2050 origin; (lower horizontal axis) reference case carbon intensity and (vertical axis) carbon price discounted at 3% for a scenario that achieves year-2100 radiative forcing of 3.4 W/m² – a level broadly consistent with a 2° policy goal, (top horizontal axis) levels of energy supply carbon intensity correspond to the 2015 stasis and IEA reference case levels with year noted; in each figure the origin year of the scenario path is marked by a hollow circle.

6.5 Summary

This chapter has offered a simple means to compare and display future scenarios of fossil GHG emissions by developing a general approach to energy system uncertainty within the SSP-RCP scenario framework (Section 6.1). The RCPs are end-of-century values for the components of radiative forcing, which can be solved analytically and graphically, independent of an IAM scenario or SSP storyline. Adopting a phase space approach for RCPs can also allow novel insights on how IAMs solve for these end-point targets. Such phase space methods provide a tool for future IPCC assessments and other studies of global change which draw from large data sets of model outputs.

Analysis of the AR5 WGIII reference cases reveal that IAMs largely generate carbon emissions consistent with total forcings above 6 W/m² by departing from the historical baseline trend signal of slowing primary energy demand growth and gradual decarbonisation (Section 6.2). Achieving high re-carbonisation rates of RCP*8.5 or greater leads several IAMs to exhibit near unanimity in limiting recoverable oil and gas while relying on coal production that greatly exceeds current reserve estimates (Section 6.3).

Our cluster analysis indicates that AR5 no policy reference cases are collectively more certain about future coal resources, independent of RCP scenario or model (Sections 6.3 and 6.4). The IPCC
AR5 WGIII database is therefore dominated by scenarios oriented toward re-carbonization rather than the historical baseline trend which leads in the opposite direction. Recent findings on the economics of coal cast doubt on whether this outlook is still valid since recovering more than today’s reserves is very unlikely (Chapter 3).

An RCP phase space also provides a clear picture of whether IAM energy system scenarios provide sufficient coverage of relevant uncertainties for robust climate policy formulation in preparation for future IPCC assessments. A full consideration of uncertain developments must undoubtedly involve scenarios that recognize the possibility of a global energy supply which evolves in steady-state, or toward re-carbonization. However, to remain a useful guide for policy and technology, the future IPCC AR6 and AR7 WGIII scenario database mean will need to shift toward the left in the energy system phase space.

Therefore, we can also propose that future sets of energy policy reference cases for climate research may also aim to encompass additional groupings, where Type D (RCP*4.5 < F < RCP*6.0) could explicitly characterize passive decarbonization that follows the post-1965 trend-lines for primary energy supply growth and gradual substitution of energy carriers with lower carbon intensity. Further, Type E reference cases (F ≤ RCP*4.5) may illustrate futures where low carbon renewable energy sources are more certain than fossil energy, and expanded demand for energy services is met without continuous growth in primary energy supply.

Type D reference cases have recently been illustrated with the fossil energy supply scenarios developed for the Shared Socioeconomic Pathway 1 (SSP1) narrative of ‘green growth’ and sustainable development (Bauer et al., 2017; 2016). These scenarios are plotted in Figure 6.1 (green square) and in Figure 6.9. However, the SSP1 scenarios are also consistent with the IEA’s reference case outlook, which intends to present the expected outcome from today’s ongoing developments in the energy sector rather than an explicit storyline of green growth. Several AR5 WGIII reference cases also correspond to Type D projections, but no distinct clusters form because they are sequestered by the dominant scenario database mean.

Further research is needed to determine if plausible high emission reference cases consistent with RCP*8.5 could be developed with scenarios that do not lead to steady-state or re-carbonization. Though it is unlikely given our current understanding of energy system costs that IAM teams could construct such reference cases since these factors are generally understood to be consistent with lower total levels of future CO2 forcing (van Vuuren et al., 2017).

RCPs, SSPs and similar sets of emission pathways are often described in the literature as equally plausible without any distinct likelihood: they carry no explicit probabilistic elements because any single forcing pathway can result from a diverse range of socioeconomic and technological development possibilities for which distributions are considered unknown (Grübler and Nakićenović, 2001; Nakicenovic et al., 2000; Riahi et al., 2017; van Vuuren et al., 2012; 2011a). Thus, it is interesting that the full collection of WGIII scenarios applied within this framework have illustrated each RCP range with energy policy reference cases using such tightly coupled combinations of fossil energy inputs, regardless of the IAM applied or intercomparison exercise (Section 6.3.2).
Since many scenarios cluster around clear levels of oil, gas and coal combustion, this suggests the IAM community has developed a strong consensus on how to configure model reference cases to meet the end-point constraints of the SSP-RCP framework. In this context, scientific studies that present SSP5-RCP8.5 (Group A) affirm bullish expectations for coal (O'Neill et al. 2016), running counter to recent global energy outlooks (EIA, 2016; International Energy Agency, 2017; 2016; 2015; 2014). For comparison, Section 6.4 placed International Energy Agency (IEA) reference case scenarios in the RCP phase space alongside IPCC AR5 and SSP scenarios, and contrasts their prospects for oil, gas and coal resource use.

As the phase space in this chapter illustrates, the GHG emission reference cases exceeding RCP6.0 in AR5 WGIII are producing only a few of the possible trajectories for a 21st-century energy system that would precede climate policy. The SSP scenarios have improved coverage by presenting a diversified range of plausible themes for future energy resource use. The phase space analysis of SSP no policy scenarios finds IAMs emphasize natural gas when depicting SSP1, in line with the IEA’s reference case (Section 6.4). However, the bulk of the SSP IAM reference case scenarios maintain long-run outlooks dominated by coal regardless of underlying narrative.

Based on the results presented in this chapter, we can suggest that the IAM generated energy policy reference cases used in AR5 were overly and needlessly constrained. WGIII mitigation policy and technology outlooks are also shaped by this condition. For example, IAM reference cases directed toward the historical baseline signal demonstrate significantly lower carbon prices for a 2˚ policy goal than steady-state or re-carbonization pathways (Section 6.4.3).

Since IPCC AR5 global energy system reference cases are collectively oriented toward re-carbonization, they create the impression that any end-of-century mitigation target is unnecessarily difficult to achieve. This could influence undue antagonism toward international climate policy when the four RCPs and corresponding mitigation cases are communicated as in AR5 (Clarke et al., 2014; Rogelj et al., 2016; UNFCCC, 2015). Confirmation that steady-state and re-carbonization scenarios are unlikely indicates ambitious policy goals will be less challenging than previously considered. This analysis demonstrates how the generalized approach to uncertainty in global change scenarios provided by a phase space method can yield novel insights, and contributes a conceptual support for model-based science.
Chapter 7: Maintaining Malthus (1798): a global change scenario archetype continues

So far, this thesis has focused on the use and development of future energy scenarios to address uncertainties relevant to global change research. However, much of this inquiry has focused on supply-side elements (outside of Chapter 4). Therefore, in this chapter we can direct our attention toward demand by addressing the future economic and population growth outlooks used to provide the socioeconomics for these scenarios.

As reviewed in previous chapters, global scenarios of GHG emissions are produced by IAMs based on the logically consistent outcomes of their initial input assumptions and structural model configurations. These scenarios are generally formulated by assuming that we will be better off in the future than we are today as a global society. This is quantitatively expressed and codified by IAM scenarios in terms of GDP per capita that continues to increase.

These scenarios can be expressed in their most basic form with the Kaya (1989) identity as in Equation 7.1 where $F$ is emissions, $P$ is population, $G$ is GDP and $E$ is energy. The Kaya identity decomposes GHG emissions based on population, GDP per-capita ($G/P$), energy per capita ($E/P$) and the carbon intensity of that energy ($F/E$). In this chapter we focus on how $G/P$ influences $E$ and $F$. Though the scenarios produced by IAMs are far more complex than this one single equation, they are essentially designed to answer questions related to how each factor in Equation 7.1 evolves in the future, effectively determining the physical significance ($F$) of socioeconomic outlooks ($P$ and $G$).

\[
F = P \times \frac{G}{P} \times \frac{E}{G} \times \frac{F}{E}
\]  

(7.1)

This style of reasoning can be viewed within the tradition of integrated global change scenarios originated by Thomas Malthus in 1798 with his anonymous publication of, *An Essay on the Principle of Population as it affects the future Improvement of Society, with Remarks on the Speculations of Mr. Godwin, M. Condorcet, and other Writers*. Though much has been written about Malthus’ future scenario of human prosperity and population growth in relation to human-environment interactions (a few examples are Hansen and Prescott, 2002; Hoyle, 1986; Nordhaus, 1973) this book was the young Malthus’s philosophical means of responding to the utopian ideals of his era, while also addressing a foremost policy debate of the time on the English Poor Laws.

Malthus applied his long-run vision of the relationship between wealth, human behavior and the environment to explicitly influence a present-day policy debate. Thus, Malthus’ scenario of global change is relevant to this thesis because it demonstrates an early attempt to shape perceptions of future uncertainties by linking socioeconomic aspirations with physically consistent developments in the context of a contemporary policy discourse. This chapter argues that today’s socioeconomic scenarios for global change research are used to maintain the same style of reasoning, and continue in the Malthus (1798) archetype. To develop this inquiry, we first review the context of the original Malthus (1798) scenario in Section 7.1. Then, the parallel analogues in today’s global change scenarios are considered in the subsequent sections by understanding how these relationships affect the ideation, classification and codification of energy-economy models.
7.1 Malthus (1798): a global change archetype established

In An Essay on the Principle of Population (1798) Thomas Malthus develops one of the first integrated assessments of population, wealth and resources. Malthus’ model draws on three simple postulates: (i) population cannot increase without a means of subsistence, (ii) population increases whenever subsistence is available and (iii) the power of population growth cannot be checked without misery or vice (1798, Chapter 1). Thus, Malthus projects that under conditions of increasing equality of per-capita incomes, the constraints on population growth are reduced, further accelerating the ‘hare’ of exponential population growth which eventually generates demand that outstrips the ‘tortoise’ of expanding subsistence for the ever-greater number of humans.

To illustrate the model laid out by this Principle of Population, Malthus produces a scenario by drawing on data from the United States, where the population was measured to grow at 2.8% per year, and then extends it to the entire globe:

Taking the population of the world at any number, a thousand millions, for instance, the human species would increase in the ratio of $1, 2, 4, 8, 16, 32, 64, 128, 256, 512, \ldots$ and subsistence as $1, 2, 3, 4, 5, 6, 7, 8, 9, 10, \ldots$. In two centuries and a quarter, the population would be to the means of subsistence as 512 to 10: in three centuries as 4096 to 13, and in two thousand years the difference would be almost incalculable...

However, this scenario cannot be viewed outside of the context of its intended object of discourse. As Malthus clearly notes in the subtitle to his first edition, his work was designed as a contribution to a discourse on ‘the future improvement of society’, inspired by conversations between he and his father on infinite progress and human perfectibility (James 1979; Fishlow 1958). By producing this scenario in the context of his broader work, Malthus sought to develop an argument that grounded utopian visions of his era on prospects for unlimited human improvement within his vision of reality. These utopian scenarios were of distinct popularity at the time given the humanitarian discontent with the horrors of the French Revolution because they provided hope for something better (James 1979). Malthus applied his scenario to this context as described by Donald Winch in Malthus: A Very Short Introduction (2013):

Demography in the modern sense of the term, however was never Malthus’ sole concern, and it is certainly not the only reason for the persistent attention paid to his writings. From a broader, more political perspective, Malthus’ main claim to fame rests on his decisive attempt to undermine the doctrine of human perfectibility and utopian speculations of an egalitarian nature. He still serves as the figure most responsible for revealing the anxieties that are supposed to lie at the heart of political and economic liberalism. He marks the moment when optimism regarding the prospects for social improvement turned sour and fatalistic, serving to dampen hopes by reminding us of the narrow limits within which any progress is possible with the result that his population

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92 The later editions of Malthus’ Essay also adopted moral restraint as an option to check the power of population, and drew from extensive empirical data gathered during travels in Europe. Therefore the ‘positive checks’ that reduce population are extended from the first edition to include those that increase the death rate and the ‘preventative checks’ are those that reduce the birth rate (Fishlow 1958).
theory has become the hallmark of all that is sombre and dismal about the laws political economy. (p.3)

It was Malthus’s ‘dismal’ anti-utopian vision of the connection between wealth and the physical world that established the foundation for his perspective on the contemporary debate regarding the English Poor Laws. Malthus’ global change scenario evoked a powerful image that catalyzed popular debate as it related to utopian and moderate outlooks for human improvement, serving to unite coherent strands of argument related to English Poor Law reform (Fishlow 1958; Huzel 1969; Digby 1986). In the words of Fishlow (1958), Malthus, “extended his principle, valid as a long run tendency, into a short run immutable law.”

As Fishlow (1958) details, the English Poor Laws provided a legislative context for improving conditions of the poor across Britain which was challenged in 1795 as a series of poor harvests led to rapid increases in the price of wheat. With wages that had not changed to meet the higher costs of subsistence, there was rising discontent across the nation, and the magistrates who administered the Poor Laws elected to increase the amount of money given to the poor as a means of subsidizing wages up to subsistence levels. This form of increased support for the poor was contentious because opposition groups viewed it as a distortion of the market, and a diversion of wages that could otherwise go to support laborers (Digby 1986). Thus, it was into this policy debate into which Malthus submitted the original edition of the Essay and its population model in 1798.

Malthus’ Essay argued that relief offered by the Poor Laws must contend with the root problem inherent in his Principle of Population model. Namely that, despite benevolent intent, a standard minimum level of provisions would increase rates of early marriage, thereby producing a consonant increase in birth rates, which would keep population growing. These faster rates of population growth would then exacerbate the ratio of population to subsistence, further intensifying the misery of the lower classes.

Huzel (1969) describes Malthus’ application of this Population model to the policy debate on the Poor Laws:

Malthus concluded that the Poor Laws acted as a bounty on population and thus operated as the fundamental cause of surplus labour in the countryside. “The poor-laws”, he stated, “tend in the most marked manner to make the supply of labour exceed the demand for it.” The root cause of poverty and its increase via population growth lay, then, with the individual labourer encouraged to marry and reproduce without means of support, rather than with general economic conditions. (p.431)

When the Poor Laws were decisively reformed in 1834 they adopted core elements of Malthus's arguments, demonstrating the influence of his Population model as a guide for policy development. In reflecting on the ‘success’ of Malthus’s model, Digby (1986) writes, “It was neither the originality nor the consistency of his views on social welfare which gave them such relevance. Rather they

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93 Malthus argued initially that the Poor Laws should have been abolished, however he later articulated more of a reformist stance (James 1979).

94 It is not the intent of this chapter to fully detail the influence of Malthus's global change scenario on the English Poor Law reform of 1834, as Digby (1986), Fishlow (1958) and Huzel (1969) provide a far more comprehensive analysis than can be provided here. The key motivation for recounting Malthus’s scenario here is because it is important to identify its distinct structural form which connects policy aspirations for equity to worst-case ecological outcomes.
commanded support because of their apparent inevitability when linked to his principle of population." Malthus' biographer later wrote that the Essay had, "influenced public opinion and legislation about the destitute poor almost as powerfully as the Wealth of Nations has influenced commercial policy" (Fishlow 1958).

Therefore, in Malthus's population model we can see the creation of an important global change scenario archetype: one which employs a quantitative model to influence a policy discourse by linking aspirations for increased equality with physically consistent worst-case ecological consequences.

7.2 Maintaining Malthus (1798) in today's global change scenarios

Malthus' scenario archetype continues today in the many IAM scenarios based on outlooks for income and energy convergence between the economies of developing nations with those of developed nations, which results in catastrophic levels of climate change (Clarke et al., 2014; Crespo Cuaresma, 2017; Grübler et al., 2004; Nakicenovic et al., 2000; Nakicenovic et al., 2003). Many IAM scenarios base their projections for future energy demand on income elasticity formulations calibrated with an empirically consistent point-estimate from the past. Therefore, vastly expanded per-capita incomes lead to considerable growth in demand for energy services within the basic blueprint of past technological infrastructures.

In the following sections, we can see how IPCC AR5 and SSP scenarios employ this basic scenario archetype, where increased income and energy equality between developed and developing nations leads to high levels of energy demand met by coal, connecting desirable socioeconomics goals with catastrophic climate change that reach 4˚ of warming by end of the century (approximately RF = 7.1 W/m² – the AR5 WGIII median scenario RF). This dynamic is particularly notable in the case of transportation, which we can consider in more detail in Section 7.4 with the structure of the GCAM model.

As employed in Chapters 3, 5 and 6, The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Working Group III database (2014) contributes a ready case study of highly detailed IAM scenarios from a wide range of models within a standardized framework. To understand how IAMs represent future socioeconomics and resulting energy use, we can draw from the AR5 WGIII database reference cases that report necessary data for analysis. The IAMs considered in this chapter are detailed in Table 7.1. 95 We can first analyze these on a global scale, and then detail their GDP and energy-use projections per region to understand the degree of convergence they project.

95 The AR5 WGIII scenarios reporting data on GDP in market exchange rates (MER - US$2005 per person) and global population are used to calculate GDP per capita outlooks in Figure 7.1a. Sixteen models provide sufficient detail on GDP and population through year-2100 (BET, EC-IAM, FARM, GCAM, GRAPE, ISGM, IMACLIM, IMAGE, MERGE, MESSAGE, MiniCAM, POLES, REMIND, SGM, TIAM, WITCH). Data for passenger transportation service scenarios in Figure 7.1b are reported in billion passenger kilometers travelled (PKT) per year. Seven models provide passenger transportation scenarios (AIM, BET, DNE21, the Ecofys energy model, GCAM, IMACLIM and POLES). Data on the final energy used in transportation in Figure 7.1c are reported in exajoules per year (EJ/year). Seven models provide passenger transportation final energy service scenarios (AIM, BET, ENV-Linkages, GCAM, IMACLIM, POLES, TIAM).
Figure 7.1 summarizes these IAM generated scenarios with time-series plots of their projections for global economic development (Figure 7.1a), transportation demand (Figure 7.1b), and final energy for transportation services (Figure 7.1c). Each figure indexes these scenarios to their base year of 2005, and individual scenario runs are depicted by a gray dotted line with transparency that allows overlap to indicate a higher concentration of scenarios with darker shading. Ranges are overlaid on each plot to note the maximum and minimum values (black), 80th (green – 80%), 20th-percentile values (orange – 20%) and the median value (blue) across each set of reference cases. This color convention is used throughout the text. Population scenarios are included in Appendix B.

Consistent with the shared outlook for global income convergence, most of the economic development scenarios cluster in a narrow range at the end of the century, between the 20% and 80% values of 4.6-times to 5.5-times base year levels. Increasing per-capita incomes correspond with much higher levels of transportation demand: AR5 database scenarios reach a median level of annual transportation demand 4.8-times higher than base year by 2100 (Figure 7.1b). These outlooks collectively imply gradual improvements in the energy efficiency of transportation service delivery despite significant growth in total passenger numbers that would contribute to congestion: the median projection for annual final energy for transportation only grows by 190% from 2005 (Figure 7.1c).

Though 60% of the WGIII reference case scenarios do not report explicit values for passenger transport demand, outlooks for liquid fuel supply provide an insight into levels of mobility projected by IAM reference cases that include detail on total liquids production. In 2015 transportation used 56% of total liquid supply (International Energy Agency, 2016) and for the past four decades liquid fuels have been phased out of electricity generation and heating wherever possible. Thus, outlooks for total liquids production higher than today’s levels imply greater demand for transportation.
### Table 7-1 - AR5 WGIII scenarios: models and variables considered

<table>
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<th>Model</th>
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<th>Final Energy</th>
<th>Transportation</th>
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<td></td>
<td></td>
<td>Transportation</td>
<td>Passenger</td>
<td></td>
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Figure 7.1a  IPCC AR5 WGIII database scenarios of global GDP per capita – time-series of individual scenarios (gray), the sample maximum and minimum (black), median (blue), 80th-percentile (green) and 20th-percentile (orange)
Figure 7.1b  IPCC AR5 WGIII database scenarios of transportation service demand – time-series of individual scenarios (gray), the sample maximum and minimum (black), median (blue), 80th-percentile (green) and 20th-percentile (orange)

Figure 7.1c  IPCC AR5 WGIII database scenarios of final energy for transportation services – time-series of individual scenarios (gray), the sample maximum and minimum (black), median (blue), 80th-percentile (green) and 20th-percentile (orange)
7.2.1 Regional socioeconomics: varying rates of convergence between regions

The IPCC WGIII database encompasses socioeconomic and energy scenarios for five distinct world regions: OECD, Economies in Transition (EIT), Asia, Middle East and Africa (MAF), and Latin America (LAM). The individual nations composing these regions are listed in Appendix A.

The median AR5 scenario for OECD GDP per-capita in year-2100 is 3.7-times higher than in 2005, reaching $120,000 per person (Figure 7.2a). The base year OECD level sets a baseline to which other regions converge: $34,300 of GDP per person, represented as a black horizontal line in the subsequent figures.

The median projection for EIT GDP-per person converges with the OECD by 2070 and ends the century at a level twelve times higher than today (Figure 7.2b). In Asia, the median scenario does not converge until the end of the 21st-century, as regional per-capita incomes must grow more than twenty times their current level to do so (Figure 7.2c). For the Middle East and Africa, only very few scenarios reach convergence this century, and the median scenario does not converge until early in the 22nd century, by year 2120 (Figure 7.2d). This slower rate of convergence results because even though the median growth rate of the African and Middle East economy is 4% per year, this is not fast enough to compensate for a population that expands from 1.1 to 4 billion people. The median scenario for Latin America achieves convergence around 2070, following a similar profile to the EIT countries (Figure 7.2e).
Figure 7.2a IPCC AR5 WGIII database scenarios of regional GDP per-capita: OECD – time-series of individual scenarios (gray), median (blue); individual scenarios are shaded with transparency so more overlap leads to darker lines; (right axis) multiple of 2005 base year
Figure 7.2b  IPCC AR5 WGIII database scenarios of regional GDP per-capita: Economies in transition – time-series of individual scenarios (gray), median (blue); individual scenarios are shaded with transparency so more overlap leads to darker lines; (right axis) multiple of 2005 base year; (black reference line) OECD base year
Figure 7.2c  IPCC AR5 WGIII database scenarios of regional GDP per-capita: Asia — time-series of individual scenarios (gray), median (blue); individual scenarios are shaded with transparency so more overlap leads to darker lines; (right axis) multiple of 2005 base year; (black reference line) OECD base year
Figure 7.2d  IPCC AR5 WGIII database scenarios of regional GDP per-capita: Middle East and Africa – time-series of individual scenarios (gray), median (blue); individual scenarios are shaded with transparency so more overlap leads to darker lines; (right axis) multiple of 2005 base year; (black reference line) OECD base year
7.2.2 Convergence scenarios lead to higher demand for transportation fuels

These socioeconomic outlooks correspond with much greater demand for transportation fuels, so that IAM scenarios for the year-2100 reach up to 270 million barrels per day of oil equivalent (mbdoe), and a median value of 140 mbdoe (Figure 7.3a). Many of these liquid fuel production scenarios project levels of demand that extend beyond the available supply from oil, and so a synthetic fuel backstop technology is deployed when they exceed what Malthus would have called the ‘subsistence’ level for oil (Chapter 4).

As IAMs characterize the future energy backstop resource with coal (Chapters 3-5), they collectively anticipate high levels of coal based liquid fuel production, so that annual coal-to-liquids (CTL) supply reaches up to 260 mbdoe before year 2100, with a median value of 45 mbdoe (Figure 7.3b). The average IPCC AR5 scenario uses 40% of its liquid fuels from coal at the end of the century (Figure 7.4b). Socioeconomic projections for most of the world’s population converging at the OECD’s income level and relying on a coal backstop serves to link aspirational economic growth targets with severe levels of climate change. This scenario archetype is further illustrated by the corresponding outlooks for primary energy convergence.

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96 Scenario data for total liquids and coal based liquids (Figure 7.3a-c) are reported in EJ/year for 9 IAMs (BET, EC-IAM, GCAM, GRAPE, IMACLIM, MERGE, MESSAGE, POLES, REMIND, TIAM). Available scenario years for each data set are reported in decadal blocks and missing years are interpolated.
Figure 7.3a  Global liquid fuel production: AR5 WGIII scenarios – Liquid fuel use in AR5 WGIII IAM reference cases, million barrels of oil equivalent per day (mbdoe) with time-series of individual scenarios (gray), series maximum-minimum (black), median (blue), 80th-percentile (green) and 20th-percentile (orange)
Figure 7.2b  Coal-to-liquids production: AR5 WGIII scenarios – million barrels of oil equivalent per day (mbdoe) with time-series of individual scenarios (gray), series maximum-minimum (black), median (blue), 80th-percentile (green) and 20th-percentile (orange)
Socioeconomics of global income convergence also produce outlooks for gradual convergence in energy resource use among regions. The bulk of IPCC AR5 scenarios suggest limited change in OECD per-capita resource use over the coming century, as the median scenario maintains approximately 200 GJ/person from 2005-2100, and most scenarios cluster within a narrow range around this level (Figure 7.3a). Energy resource use in the other regions gradually converge toward this level.

Scenarios for the EIT region show the highest degree of primary energy convergence before 2100 due to overall projections for a falling population (Figure 7.3b). The other three regions have an implied energy resource convergence sometime in the 22nd-century. The median scenario for Asia converges at OECD levels of energy resource use by 2130 (Figure 7.3c). Implied median energy resource convergence years for MAF and Latin America are 2180 and 2140 respectively (Figures 7.3d and 7.3e).

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**Figure 7.2c** Proportion of liquid fuel supply from coal backstop supply: AR5 WGIll scenarios – with time-series of individual scenarios (gray), series average (black)

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It is important to note that the base year in some regions for some IAMs do not match because it appears the regional definitions are not internally consistent for a number of models, such as POLES, MERGE, EC-IAM, etc… This thesis merely takes these model output ‘at face value’ and does not attempt to correct the heterogeneity in their underlying regional compositions since those assumptions are not readily available and would require provisional decisions on behalf of the analyst.
Figure 7.3a  IPCC AR5 WGIII database scenarios of regional primary energy resource use per-capita: OECD – time-series of individual scenarios (gray), median (blue); individual scenarios are shaded with transparency so more overlap leads to darker lines; (right axis) multiple of 2005 base year
Figure 7.3b  IPCC AR5 WGIII database scenarios of regional primary energy resource use per-capita: Economies in Transition – time-series of individual scenarios (gray), median (blue); individual scenarios are shaded with transparency so more overlap leads to darker lines; (right axis) multiple of 2005 base year; (black reference line) OECD base year
Figure 7.3c  IPCC AR5 WGIII database scenarios of regional primary energy resource use per-capita: Asia – time-series of individual scenarios (gray), median (blue); individual scenarios are shaded with transparency so more overlap leads to darker lines; (right axis) multiple of 2005 base year; (black reference line) OECD base year
Figure 7.3d  IPCC AR5 WGIII database scenarios of regional primary energy resource use per-capita: Middle East and Africa – time-series of individual scenarios (gray), median (blue); individual scenarios are shaded with transparency so more overlap leads to darker lines; (right axis) multiple of 2005 base year; (black reference line) OECD base year
In the previous section, we could identify the link IPCC’s 5th Assessment socioeconomic scenarios develop between equity targets and catastrophic ecological outcomes by studying the general orientation of hundreds of individual scenarios. However, these IAM scenarios were not developed with explicit narratives of future society in mind - a gap which the Shared Socioeconomic Pathways (SSP) intend to fill. The precise storylines of future society framed by the SSPs help to further distinguish a clear representation of the Malthus scenario archetype applied in global change research.

The SSPs (as detailed in Chapter 5) provide storyline narratives for potential development pathways of future society, numbered SSP1 through SSP5. Each of these five SSP narratives describe preferences and tendencies of a future world trajectory and its representative agents, shaping model

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98 After the publication of the original IPCC narrative-based IAM scenarios in the Special Report on Emission Scenarios (SRES) in 2000, there was a rich dialogue between economists and the scenario architects on issues of income convergence which mainly centered on one key point: two economic historians argued that since the convergence gap was measured in market exchange rates, it was specified as too large, and so IAMs overestimated the amount of growth needed to ‘close the gap’, and therefore overestimated 21st-century energy use and GHG emissions, arguing that purchasing power parity convergence scenarios should be applied instead (Castles and Henderson, 2003a; 2003b; Holtsmark and Alfsen, 2005; Mckibbin et al., 2004; NakiEnoviEt al., 2003). This chapter is not analyzing convergence scenarios within the context of whether they are historically consistent or constitute likely future projections.
parameters and scenario outputs. Though each of the SSPs lead to different types of IAM scenarios for energy use, GDP and population growth, they directly adopt the Malthus structure of argumentation by setting the upper bound for future business-as-usual climate change with SSP5-RCP8.5 – a scenario that leads to the ‘best’ outcomes for global equity, and the lower bound with SSP4-RCP6.0 – a scenario defined by global inequality. 99

7.3.1 SSP5: The best-case scenario for global equity is the only SSP world that leads to RCP8.5, the worst-case climate scenario

The overarching SSP5 narrative offers a storyline for a future global society focused on rapid growth, income convergence and ‘fossil fueled development’, summarized by Riahi et al. (2017) as:

This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

Notably, the SSP5 narrative is the only future world among the SSPs that leads to RCP8.5 consistent scenarios. The SSP5 world results in a global energy supply where richer citizens prefer fuels in liquid form as opposed to other solid or gaseous fuels, and actively discourage development of renewables. Bauer et al. (2017) describe the global energy trends of an SSP5 world as:

Energy demand growth is strongly coupled to economic growth, particularly in the transportation sector due to materially intensive lifestyles with a strong preference for intensive material consumption patterns including high transportation demand. Technological development in the fossil fuel sector, including CCS based mitigation technologies, is rapid and social acceptance is high. Non-biomass renewables, however, are subject to low social acceptance.

7.3.2 SSP4: The worst-case scenario for global equity is the only BAU SSP world that leads to climate change less than 4˚C

The overall theme of SSP4 is of global inequality, where regional GDP per-capita does tend toward convergence, but much slower than in other scenarios, and described by Riahi et al. (2017) as:

Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge-and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly

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99 IAM reference case scenarios that illustrate the SSP1 narrative of green growth provide an even lower outlook for future climate change, averaging 5.5 W/m² which is coupled with fast convergence outlooks for GDP among regions. However, while this is a ‘reference case’ scenario without explicit climate policies, it is difficult to argue it is a ‘business-as-usual’ outlook since it is for an explicit transition toward ‘green growth’. Therefore, the SSP2, 3, 4 and 5 scenarios are more consistent with what could be described as a BAU world.
educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high-income areas.

This development narrative leads to a world energy supply articulated by Bauer et al. (2017) with this description:

Final energy demand is moderately coupled to economic activity, which results in large disparities in energy consumption because of slow income convergence. In poor countries the use of traditional bio-energy remains important. Technological improvements in conventional oil and gas extraction are high, but policies are restrictive in high-income countries because of local pollution problems. There are significant technologica improvements in nuclear power. Investments are risky because of generally volatile markets… In SSP4 the business elite develops advanced technologies in the energy sector, but broader diffusion is slow and energy access is a pressing, yet unresolved, issue.

7.3.3 Income, primary energy and transportation convergence of SSP5 and SSP4 scenarios

The SSP5 and SSP4 global development and energy narratives guide IAM projections to narrowly illustrate increasing global equity with high-carbon energy use. In this section, we compare the marker scenarios for SSP5 and SSP4 developed by the REMIND and GCAM IAMs. Figure 7.4a compares the SSP5 and SSP4 projections for GDP per-capita, demonstrating how the narrative of global equity leads to rapid growth in all world regions so that Asia, the Middle East and Africa, and Latin America approach OECD per-person incomes, which also expand five-times over. Though GDP per person grows rapidly in SSP4, there is only a slow income convergence in other regions toward the base year OECD level, rather than the final year OECD end-point as in SSP5.

The primary energy resource use scenarios for SSP5 show end-of-century convergence at two levels: (i) an OECD level of 300 GJ/person, and (ii) 225 GJ/person in the rest of the world (Figure 7.4b). The SSP4 scenarios illustrate convergence between the OECD and the EIT, with a slow convergence in Latin America, while energy resource use stagnates in other regions and does not converge.

SSP5 and SSP4 narratives draw a link between growing incomes and higher demands for transportation, as shown by the liquid fuel outlooks in their corresponding IAM marker scenarios. In SSP5, most regions converge at 50-55 GJ/capita of final energy in the form of liquid fuels (Figure 7.4c). However, in SSP4 regional per person use of transportation fuels continues growing at a steady pace, but does not converge.
Figure 7.4a  SSP5 and SSP4 scenarios of regional GDP per-capita convergence – SSP5 scenarios (purple), SSP4 scenarios (orange), (black reference line) OECD base year from SSP5 (REMIIND model)
Figure 7.4b  SSP5 and SSP4 scenarios of regional GDP primary energy convergence – SSP5 scenarios (purple), SSP4 scenarios (orange), (black reference line) OECD base year from SSP5 (REMIIND model)
7.4 Model structures that produce the high-coal transportation future: a case study of GCAM-ref

The previous two sections have covered the ways global change scenarios apply the Malthus archetype in their initial concepts (ideation) and quantified model outputs (codification). In order to provide a complete discussion of this dynamic in the energy modeling literature, we can now consider the effect of model structure by providing a brief case study of transportation demand in the GCAM IAM and its default reference case (Chapters 2, 4 and 5).

Economic development in the GCAM reference case (GCAM-ref)\(^\text{100}\) projects a year-2100 GDP nine-times larger than 2005 (Figure 7.5a - blue circles) and a population that peaks around 9.2 billion people in 2070 (Figure 7.5b - green circles). This scenario is readily comparable to the SSP2 marker scenario (Fricko et al., 2017; Riahi and van Vuuren, 2016), so the SSP2 marker scenario outlooks for economic growth and population are also included in Figure 7.5a with light blue and green triangles.

Demand for transportation energy services in GCAM is formulated with constant elasticity from the general form in Equation 7.2a (Grübler et al., 2006; Kim et al., 2006), where \(d\) is service demand per-capita, \(i\) is per capita income, \(P\) is the aggregate service price and \(\alpha\) as a constant.

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\(^{100}\text{GCAM-ref is the unmodified reference scenario in GCAM v4.2 r6539 as applied in Chapter 4.}\)
The income elasticity $u$ and price elasticity $\rho$ calibrate levels of per-capita demand to full service costs, including fuels and capital. GCAM allows income and price elasticities for energy service demands to change per region and per period, however in GCAM-ref these remain at $u = +1.00$ and $\rho = -1.00$ in all regions from now until end of the century.

The transportation service price ($P$) for each mode is calculated from Equation 7.2b where $Cost_{fuel}$ is the fuel cost, $Efficiency$ is the fuel economy, $Cost_{nonfuel}$ captures costs of ownership, maintenance and operations, $LF$ is the load factor, $Wage$ is the wage rate and $Velocity$ is the average transportation speed. This formulation of service price with an income accelerator factor ($\frac{Wage}{Velocity}$) allows the opportunity cost of passenger time to influence modal choice so that higher incomes lead penalize slower transportation speeds.
Figure 7.5b  
GCAM-ref: global passenger travel demand by mode – aviation (green circles), road four wheeled vehicles (blue squares), bus (light blue triangles), road two wheeled vehicles (orange left triangle), rail (red right triangle), walking (yellow down triangle), cycling (pink diamond)

Figure 7.5c  
Cost of transportation services in GCAM-ref by mode – walking (light green triangle), cycling (yellow left triangle), bus (light blue diamond), road - two wheeled vehicles (yellow triangle), rail (red circle), aviation (green triangle) and road - four wheeled vehicles (blue square) indexed to 2005 prices for cost per passenger-kilometer ($/pkm)
Accordingly, the global representative agents of GCAM favor transportation modes with faster potential velocities. Throughout the century in GCAM-ref, personal travel by car grows more than 200% (Figure 7.5b - blue line) and air total passenger kilometers traveled (PKT) by more than 700% (green line). Per-capita aviation reaches 5,000 km by end of the century - equivalent to every person on the planet flying from Dubai to London each year. The cost penalty for slower transportation modes classified by GCAM-ref means that higher incomes also reduce interest in public transit, walking and cycling: after mid-century per-capita PKT for bus travel declines by 90% (light blue line), rail by 30% (maroon line), while walking and cycling falls 80% (yellow and pink lines).

Expanded levels of demand for car and air transportation, coupled with shifting from less energy-intensive modes leads to increasing demand for liquid fuels. Although price elasticities could conceptually influence the new equilibrium point on the transportation supply curve, the cost of aviation and car transport remain relatively constant resulting in domination of income effects for these modes (Figure 7.5c).

Because oil and gas resources in GCAM are considered less abundant than coal and biomass, synfuels become the key supply-side technology for transportation fuels once demand exceeds the ‘subsistence’ available from oil, as in the AR5 scenarios of Section 7.2. Expanded liquid fuel supply
is increasingly delivered from a burgeoning coal and biomass synfuel industry after 2030. CTL and gas-to-liquids (GTL) are the major synfuels, with a minor role for cellulosic ethanol and biomass-to-liquids (BTL) (Figure 7.5d). This leads GCAM-ref to report refinery inputs totaling more than 330 mbdoe in year-2100 from a diverse portfolio of liquid fuel options and an outlook for climate change well above 4˚ with total RCP forcing of RF = 7.7 W/m².

7.5 Summary

Beginning with his Essay (1798) Malthus created a model archetype that linked policy aspirations for an increasingly equitable society with an outlook for ecological catastrophe. Yet, Malthus’ scenario of a counterfactual utopia was not simply a mathematical projection, but a codification that synthesized his politics and morals (Section 7.1). This chapter has studied how the scenarios used in climate science use the same style of reasoning, because they shape perceptions of future uncertainties by linking best-case socioeconomic projections with worst-case climate change outcomes in order to affect the ongoing policy discourse (Section 7.2 and 7.3).

Malthus is viewed by many as the Cassandra who never was: with the advantage of hindsight we can now see the gradual decline in global fertility rates throughout the 20th-century (Alkema et al., 2011; Lutz, 2006; Lutz et al., 2014; Sleebos, 2003), and modern demographic projections are readily developed with a peak and decline in the populations of major regions (Raftery et al., 2012; United Nations DESA, 2015) and the total global population (KC and Lutz, 2014; Lutz et al., 2001). However, the structure of Malthus’s argument served its intended purpose in producing legislative changes shaped by his scenario. Malthus’s scenario of exponentially growing populations and slowly growing subsistence was not a permanent physical truth, but a physically consistent representation of the technology and society and the time, filtered through Malthus’ values to direct a dialogue on the role of institutions in developing a more equitable society.

Though Malthus elaborates his justifications for expectations of unabated population growth under conditions of ‘improvement unchecked by plague, famine or other undesirable future scenario possibilities’, in An Essay on the Principle of Population this perspective is summarized by his statement that, “The perpetual tendency in the race of man to increase beyond the means of subsistence is one of the general laws of animated nature which we can have no reason to expect will change.” (Chapter 17, 1798). Yet, the difficulty of framing any outlook for long-run human development must still contend with the challenges faced by Malthus’ model: how relevant is the quantitative data and expectations formed from past development trends for our expectations for future human societies?

Where Malthus imagined that increasing incomes over the long-run would reduce constraints on fertility, exacerbating population overshoot, modern IAM generated scenarios employ model structures which anticipate that higher incomes will only reduce constraints on transportation demand, leading to an ever-expanding desire for liquid fuels (Section 7.4). Thus, high-income scenarios in IAMs are synonymous with ambitious outlooks for transportation demand growth within the infrastructure of today’s contemporary technologies (Section 7.3 and 7.4). Though this paper merely presented the high levels of demand at face value, it is unclear whether such levels of transportation demand could ever be achieved in the context of congestion faced by today’s technologies for aviation and road transportation. Various changes in constraints, preferences and
technologies nullified Malthus’s quantitative scenario, even though these factors were not readily perceptible to him and his contemporaries. The IAM scenarios analyzed in this chapter shy away from imagining such boundary conditions in a way that raises to question the vision of energy use they sketch from utopian socioeconomic outlooks.

As quoted from Winch (2013) in Section 7.1, Malthus, “still serves as the figure most responsible for revealing the anxieties that are supposed to lie at the heart of political and economic liberalism.” Today’s IAMs merely continue this tradition by quantifying utopian socioeconomic scenarios that attempt to illustrate what would happen if a global population of 9 to 10 billion attempts to aspire toward the same lifestyles as those in the developed world with modest and gradual changes to today’s technologies.

Though many aspects of these scenarios may not appear plausible upon deeper reflection, the convergence targets may seem arbitrary, or perhaps undeserving of the dominant role they play in climate science and the IPCC process, they do reflect real-world aspirations that shape the discourse on energy use between developed and developing nations. In this regard, as Malthus challenged the vision of utopia painted by Godwin and Condorcet, many portions of his Essay also served to provide an honest reflection and candor on the logical contradictions in their arguments about human life under such conditions:

A writer may tell me that he thinks man will ultimately become an ostrich. I cannot properly contradict him. But before he can expect to bring any reasonable person over to his opinion, he ought to shew that the necks of mankind have been gradually elongating, that the lips have grown harder and more prominent, that the legs and feet are daily altering their shape, and that the hair is beginning to change into stubs of feathers. And till the probability of so wonderful a conversion can be shewn, it is surely lost time and lost eloquence to expatiate on the happiness of man in such a state; to describe his powers, both of running and flying, to paint him in a condition where all narrow luxuries would be contemned, where he would be employed only in collecting the necessaries of life, and where, consequently, each man’s share of labour would be light, and his portion of leisure ample… (Chapter 1, 1798)

Even if the dominant consensus is that the future of the global human population is one of global income convergence, where the only uncertain variable is the speed at which it takes place, citizens of the future would still face challenges from boundary conditions induced by the organizational complexity required to maintain such high levels of flying and driving. These constraints could readily lead wealthier people to use their time and money in more ways than waiting in traffic and at airports, or incentivize development of technologies such as autonomous vehicles that transform the basic blueprint of transportation services.

There is no doubt that higher incomes around the world will lead to more energy consumption, however it is equally difficult to argue that the multiple decades of sustained high oil prices illustrated by IAMs along these trajectories wouldn’t cause oil to compete with low-carbon options as well, in the form of efficient technologies, electric vehicles, and a reconfiguration of urban forms.

A middle-class lifestyle for the entire world population can provide a noble goal for energy modeling, yet recent developments in OECD nations reflect strong inherent discontents regarding the evolving definition of what a middle-class involves or entails. Thus, where world income and energy
convergence provides a benevolent target to which global change scenarios can aspire, they can also benefit from the advice of their original scenario architect:

But in cases where the perfection of the model is a perfection of a different and superior nature from that towards which we should naturally advance, we shall not always fail in making any progress towards it, but we shall in all probability impede the progress which we might have expected to make had we not fixed our eyes upon so perfect a model.

(Chapter 15, 1798)
Chapter 8: Conclusion

In contrast to the traditional view, for the more distant future, the use of coal on a much larger scale must be envisaged — compared to today’s circumstances, larger by a factor of perhaps 10… In the case of a real coal revival, it could happen that the main problems would be psychological (lack of dynamism—of confidence in the future—of coal organizations) or institutional, rather than physical or industrial... After the civilization of \textit{homo sapiens} and that of \textit{homo economicus}, we now have to shift progressively to the civilization of the intelligent mole.


Through the preceding seven chapters, this thesis has analyzed energy system uncertainties in the context of global environmental change research. This topic has been addressed through exploring various components of the models used to conduct global environmental change research (Chapters 2-4), the scenarios these models produce for application in the wider research community (Chapters 5 and 6), and the stories they tell (Chapters 5-7). And no single story has played a larger role in global change research than the belief that future technological change would tap into a high-carbon coal backstop (Chapter 3 and 4), represented as a \textit{return to coal hypothesis} by IAMs (Chapter 5). Though perhaps more appropriately, this narrative can be described as the story of \textit{becoming the intelligent mole}. Thus, conventions in 1970s energy-economy modeling established this story as a tradition that continues to shape the way climate science is practiced today.

In the wake of the 1970s energy crises, it seemed as if oil and gas were so severely limited, and the possibilities for energy demand were so vast, that coal appeared the only option which could feasibly satisfy the world’s growing want for electric power and liquid fuels (Edmonds and Reilly, 1983; Greenberger, 1983; Grenon, 1979; Häfele, 1981; 1980; Häfele et al., 1974). And it was in this context that the story of the intelligent mole gained traction: though a transition from hydrocarbons to renewable resources would be desirable, wind, solar or nuclear were simply too limited and costly to meet the projected rapidly growing demand for energy — therefore a transition to coal was on the horizon in just a few decades.

As the early global energy-economy models which told this story were adapted to study the greenhouse gas emissions that would result from such high levels of coal use, they played an important role in the early development of climate science (IPCC, 1990; Leggett et al., 1992; Williams, 1978). It is not the purpose of this thesis to examine that historical interaction in detail. However, we can note that with the publication of the IPCC’s First Assessment, expectations for the ‘best guess’ for business-as-usual were anchored at 4˚ of warming over pre-industrial levels (Chapter 3). Once this end-point was set, and the discourse surrounding climate science gained higher profile, the range of scenarios that produced 4˚ became inextricably embedded in the scientific discussion (Chapters 3, 5 and 6).

For over a decade RCP8.5 has been the most widely used description of ‘business-as-usual’ climate change in the scientific community. Before that it was the coal backstop predecessors to RCP8.5 - A2, A1F1, and its many previous iterations (Chapter 3). Yet, the mega-coal scenarios represented by RCP8.5 are now more difficult to clearly see as vestiges from the past, because they have become abstracted in a scenario architecture designed for climate model experiments based on specific year-2100 targets and atmospheric CO2 concentrations (Chapter 5). Even if the five SSP narratives and their fully integrated scenarios can aid in linking each RCP with descriptions of future society (and are intended to do so by their designers), allowing the plausibility of SSP5-RCP8.5 to be questioned, the story of the intelligent mole...
mole seems poised to live on for at least another decade in the process leading up to the next IPCC’s Assessment, and likely well beyond.

8.1 The story of the models produce a scientific meta-narrative

As discussed in Chapter 1 world models like IAMs operate on a global scale, where they can be appropriately interpreted as hypotheses about the future. These hypotheses can also be understood as storylines - implicitly as the elements of a model work together, or explicitly as with the SSP narratives analyzed in Chapters 5 and 7.

It is not uncommon for physical and social scientists to use models to tell stories. Morgan (2012) eloquently describes this dynamic in her discussion of the model produced by James Meade to illustrate the opaque world of Keynes’ General Theory:

[Economists] ask questions, use the resources of the model to demonstrate something, and tell stories in the process... For each question put to the model, the answer involves an implicit set of causal links, signaled by the order in which the tracing process is followed. This tracing allows consideration of whether each of the linked changes that occur are plausible ones in the context of the economic world portrayed in the model, but perhaps also in the context of the economic world that Meade lived in. These are the narratives of model usage: each answering argument to each question offers a narrative sequence of connected events as each change alters the value of some other element in the model... these narratives provide the correspondence links between the demonstration made with the model and the events, situations and process of change in the real world... In creating the model, economists represent or denote the situation in the world in such a way as to incorporate their theoretical claims or hypotheses about the world (e.g. the Keynesian account of the macroeconomy).

This thesis has examined the stories that models used in global change research tell about energy resources, and in doing so, studied the way these parables form the scientific meta-narrative around our anthropogenic influence on the Earth’s climate. In doing so, we have assessed the learning-by-extracting theory of energy resources (Chapter 2), the way it is used to describe a coal backstop (Chapter 3) and how this coal backstop influences climate change science and economics (Chapters 4 and 5). This allows these energy scenarios of re-carbonization (Chapter 6) based on rapid growth in coal combustion to be viewed as a technical means of providing a strong carbon signal, rather than purely as outlooks for possible developments in the global energy system.

This thesis has only addressed this meta-narrative in the context of how climate change is communicated by scientists when working with each other, not about the way the discourse proceeds between scientists and the public. Nowhere in this thesis was it stated that carbon emissions are not a problem, or that there is no reason for concern regarding future climate change, nor that climate policy is not needed. However, the arguments developed in these chapters have collectively identified that various traditions of global energy-economy modeling have narrowly constrained the scientific discourse on climate change, and that these conventions have been employed by downstream researchers because it overwhelms the uncertainties in their models.

At one time, these stories about a transition to coal were meaningful and plausible descriptions of the future global energy system, and so they could justifiably describe outlooks for business-as-usual. Yet, plausibility is not an eternal property of any model used in science, economics, or for understanding
uncertain developments in global energy supply and demand; plausibility is fundamentally ephemeral as articulated by Morgan (2012) with the following passage:

‘Plausible’, in contrast, captures the idea that the stories map adequately to certain characteristics of the phenomena in the real world that the models aim to describe and that economists seek to explain... We have seen that the elements in a narrative that make a model count as meaningful are contingent on local scientific knowledge: they depend on what economists of a certain time take to be a good explanation of human behavior or of the behavior of the whole economy; they depend on the theories and assumptions of the time and place and group of economists involved. But this is equally so of the plausibility of models in relation to the world, for what counts as plausible depends in part on the particular events to be explained. Where Depression era model narratives were plausible stories for the 1930s, and Keynesian stories told with models were seen as plausible to many economists and policy makers and the public during the 1950s and 1960s, they came to be seen as implausible during the stagnation of the 1970s, only to be resurrected, in certain respects, in the economic crisis at the end of the first decade of the twenty-first century. So what constitutes plausibility, like meaningfulness, is by no means a stable or universal criterion. In part, this is of course because, as we know from the history of economic science: economic theories, ideas, evidence, and methods change – just as for any other science. But we also find from historians of what happens in the economy (economic historians) that their subject matter is not necessarily stable – economies develop; there are crises, new phenomena to be explained, and old ones to be reevaluated. Plausibility, like meaningfulness, depends on both content and context.

The process of determining the plausibility of models and scenarios takes on a different meaning when used in complex interdisciplinary inquiries that span many nations and types of expertise. Where the economists studied by Morgan need to only assess other economic models as plausible, and to imbue them with the epistemic power to shape policy, models of the future energy system used for climate science are applied by many second and third order users. These downstream users do not necessarily have an intrinsic compass for assessing the plausibility of future fossil resources and technologies, and for them, there is no reason to doubt the story of the intelligent mole. This picture is further muddled by assigning physical relevance to aspirational socioeconomic scenarios through linking desirable equity goals with catastrophic ecological outcomes (Chapter 7).

Since these global change scenarios have conventionally ended in the year 2100, it is reasonable to expect that some hypotheses will be ruled out as that year approaches the present – this is a form of temporal constraint on hypotheses of future developments. Yet, the legacy intelligent mole storylines reincarnated as SSP5-8.5 and SSP3-7.0 could feasibly be assessed as inherently more plausible by their users because they resemble familiar intelligent mole scenarios from the past, like the original IPCC (1990) BAU scenario (Figure 8.1) - even when the energy research community could view them as absurd (see Chapters 3 and 6). A more plausible high-signal scenario may be best captured by the CO₂ forcing component of RCP6.0, combined with the forcing from other GHGs in the RCP8.5 scenario. Such an end-point target for IAM scenarios would end up around 6.6 W/m², consistent with the SSP2 scenarios reviewed in Chapter 6. However, there remains significant demand for forcing scenarios that fall into the range above 7.0W/m², as highlighted by the CMIP6 scenario design process which labels SSP3-RCP7.0 as ‘baseline’ and places the highest priority on SSP5-RCP8.5 (O’Neill et al. 2016). Such tensions highlight the tenuous nature of multi-user scenarios and the unique determinants of plausibility among disciplines.
Figure 8.1  Year 2100 forcing by component in RCP scenarios, IPCC (1990) BAU and their consistent hypotheses of the global energy system – cumulative bar plots for radiative forcing by component for RCP scenarios with carbon (red), methane (blue), nitrous oxide (yellow), halocarbons (green) and all positive components (purple); for RCP8.5 in 2020 as a proxy for today, RCP4.5, RCP6, RCP8.5, IPCC (199) business-as-usual, and a hypothetical modern worst case that combines the CO2 forcing component of RCP6.0 with the worst-case other GHG components of RCP8.5; (right column) list of 21st-century energy system development hypotheses consistent with each scenario.

In this sense, it is useful to view the alternative future visions described by the uncertainty space of SSPs (Chapter 5) as useful for studies of climate change, but as shown in Chapters 6 and 7, they only describe a narrow uncertainty range for future society, economic development and its global energy system – yet, this is the scope of future scenarios where climate change is an interesting problem for scientific research. The motivation for this is self-evident: achieving scientific equilibrium in matching research supply with research demand. In other words, a research need to focus inquiry and scientific discourse on an engaging object of study.

Today’s scenarios could be viewed as playing a similar role in the scientific community as did the intelligent mole storyline which served the research needs of the early unrefined GCMs which required a high signal-to-noise ratio (Chapters 3 and 5). These high coal scenarios provided the ideation and motivation that crystallized the historical pathway of theoretical and instrumental climate model development. So, as with the high-coal scenarios developed by the 1970s IIASA Energy Program, it may be that the real barrier to excising the coal backstop from global change research is not technical or physical, but psychological.

8.2 Journal submissions associated with this thesis

A portion of that barrier is demonstrated by the peer review process for work conducted as part of this thesis (Figure 8.2). The work in this thesis benefited from 33 reviews gathered through 23 submissions to 16 journals from November of 2015 through October 2017. Some brief excerpts of several reviews are.
provided in Appendix C for reference. It was somewhat surprising that this work was rejected a dozen times since peer reviewers found no major technical issues and all comments could have easily been addressed in a phase of revisions. Additionally, many editorial decisions to reject were accompanied by positive comments that found great value in the work. The rationale for most rejections was based on 'insufficiently positive response for reviewers for further consideration'. However, a few rejections were based on desk decisions due to journal scope, and these are understandable.

In hindsight, the collective reviewer response demonstrates that work on highly technical and opaque models (like IAMs) lead editors to send papers about these models to the model developers. This is an obvious outcome. If a paper is critical of their model, or its results, the reviewer's mood is soured from the start and the review is slanted negative. When work is critical of a broader body of literature produced by many modeling teams, over many years, there is a very low probability of garnering at least two positive reviews on any submission.

Therefore, it is no surprise that the Chapter 3 work on the coal backstop was published first – it is only weakly associated with IAMs, and is more about the economic interpretation of coal resource assessments and the revised meaning of a coal backstop energy supply. Chapter 5 on the return to coal took over two years to publish, and it was ultimately accepted by the journal Energy based on overwhelmingly positive reviews: the energy-focused academics looked at the work and thought it was valuable to discuss this topic.

As this data set demonstrates, publishing papers that challenge the meta-narrative of a research community is a long and protracted process. This carries an additional dimension for studies of model-based science: once researchers start seeing the world in the model as the lens through which they view meaningful research contributions, any single paper is defined within that world rather than its ability to discourse about the model in the world.

Figure 8.2  Timeline of journal submissions associated with this thesis – each chapter submission on the left column and its submission timeline marked as a black line
8.3 Research contributions of this thesis

This thesis concludes by summarizing the research contributions it has offered to the broader scientific community and the fields of global change research, energy systems analysis and energy economics.

8.3.1 Chapter 2 – Evaluating the learning-by-doing theory of long-run energy resources

Chapter 2 provided the first detailed empirical assessment of the Rogner (1997) theory of productivity gains for the oil and gas industries. It was found that Rogner’s original theory of endogenous non-price induced productivity gains accurately correspond to productivity improvements observed in operational expenditures, but poorly captured trends in capital expenditures. The Nordhaus (2009) theoretical critique of endogenous learning models for energy technologies was extended to consider the specific case of energy resource industries, producing a means of evaluating the operational definition of learning in oil, gas and coal production. A sensitivity analysis of various empirical learning rates was conducted with GCAM IAM. Alternate reference cases were developed based on these learning rates to determine their influence on climate policy. It was found that learning rates which produced faster oil depletion induced GCAM to substitute higher carbon resources in the form of unconventional oil and coal for liquid fuel demand.

8.3.2 Chapter 3 – The 1,000 GtC coal question: is a coal backstop still relevant?

Chapter 3 evaluated the historical economic concepts used to understand coal resources for long-term studies. The ideation of a vast coal backstop energy supply enabled by an equilibrium reserves-to-production ratio was revisited based on modern data. It was found that coal resource base data could be divided into two phases: legacy data which supported the vast coal backstop and modern data which did not. The reasons for this were explained. Underground coal gasification technology was detailed for its ability to potentially re-adopt a vision of coal as the ultimate source of energy security. It was identified that a number of long-term energy scenarios used in global change research still applied the concept of a vast coal backstop and that these needed to revisit their conceptual underpinnings. In summary, a coal backstop is determined an unlikely scenario for the future energy system and exceeding the overall amount of today’s identified coal reserves is considered very unlikely.

8.3.3 Chapter 4 – Empirically constrained supply and demand in IAM scenarios

Chapter 4 investigated the influence of empirically constrained supply and demand scenarios in the GCAM IAM. These scenarios were systematically developed and applied to produce outlooks for climate policy. It was found that the coal backstop is used in GCAM to provide high levels synthetic liquid fuels from coal, based on an ideation that the future energy system would need to rely on the high-carbon backstop resource. The empirically constrained outlook for coal and transportation demand reduced costs of moderate climate policy targets by as much as 70%. Costs to achieve a 1.5˚ policy goal in the constrained scenarios were roughly equivalent to those for a 2˚ policy goal in the original unconstrained GCAM.

8.3.4 Chapter 5 – Why do climate change scenarios return to coal?

Chapter 5 conducted a meta-analysis of the energy scenarios produced by the full suite of long-run IAMs used in the IPCC 5th Assessment Report to illustrate the Representative Concentration Pathway scenarios. It was found that they present uncertain developments in the future energy system with a return to coal hypothesis. An explanation for this model behavior was offered through analyzing the
Rogner (1997) theory used to structure supply curves for many IAMs. It was found that IAMs employ the Rogner learning-by-extracting theory in a way that induces a coal bias in their long-run energy outlooks. Accounting for this bias indicates that RCP8.5 is an exceptionally unlikely future energy system scenario. However, an analysis of the raw CMIP5 GCM outputs found that RCP8.5 is used to provide a strong carbon signal to noise ratio in GCMs, which provides specific benefits by overwhelming uncertainties in these models, so therefore its continued use is determined to be very likely.

8.3.5 Chapter 6 – General approaches to global change uncertainty with a structure-neutral phase space

Chapter 6 proposes that future energy scenarios used in global change research can be developed as a phase space based on their graphical and analytical solutions. This allows scenario uncertainties to be effectively understood and communicated, independently of model structure. Such an energy system phase space was developed for the Representative Concentration Pathway scenarios. This phase space was applied to conduct a k-means cluster analysis on the IPCC Fifth Assessment Working Group III database. The cluster analysis found three energy system scenario archetypes: (i) rapid recarbonization, (ii) moderate recarbonization, and (iii) slow recarbonization. Each of these scenario archetypes ran counter to the post-1965 baseline signal of gradual decarbonization, suggesting their climate policy outlooks may be miscalibrated. These AR5 scenarios were compared to the IEA Reference Case and the SSP scenarios. The SSP scenarios provided support for revising climate policy cost assessments: the 2˚ climate policy scenarios produced by energy system reference cases which followed the baseline trajectory of passive decarbonization showed carbon shadow prices that rarely increased above $30 per ton CO2. However, only the SSP1 scenarios emphasized a fossil resource other than coal, indicating the other scenarios are needlessly constrained to emulate specific end-point targets.

8.3.6 Chapter 7 – Maintaining Malthus (1798): a global change scenario archetype continues

Chapter 7 studied the socioeconomic outlooks of the AR5 and SSP scenarios, finding they follow a template originally developed by Thomas Malthus in the late 18th century. Malthus created a model of human population and resources to link aspirational equity goals with physically consistent worst-case outcomes in order to direct a policy discourse on the English Poor Laws. Accordingly, the AR5 scenarios are based on assuming that global levels of per-capita income and energy resource use converge, producing 4˚ of warming above pre-industrial levels. The SSP scenarios have applied the Malthus scenario archetype more directly by linking ‘best-case’ equity outcomes to the BAU scenario of SSP-RCP8.5 and the ‘worst-case’ equity outcomes to lower levels of climate change (SSP4-RCP6.0). It was found that transportation fuels play a major role in these income convergence scenarios, therefore the structural elasticity formulation for transportation demand in the GCAM IAM was analyzed in a case study. Based on this model classification, high per-capita incomes shift transportation from all other modes toward air travel fueled by coal-based liquids.
Chapter 9: Summary of implications for the ongoing climate policy discourse

The scientific discipline of climate modeling developed after the 1970s alongside legitimate concerns about long-term energy resource availability and the consequences of burning most fossil energy deposits in the Earth’s crust. Numerous long-run scenarios applied to illustrate this possibility were conventionally labelled ‘business-as-usual.’ These hypothetical visions became the basis of climate model experiments where atmospheric concentrations of CO2 more than tripled from pre-industrial levels. Subsequent projections of extensive CO2 emissions necessarily depicted outcomes consistent with combusting high levels of coal, because global energy demand was expected to outstrip available oil, gas, and all other supplies.

Research in climate science at this time was conducted in parallel with emerging anxieties about peaking oil production. As conventional oil output in the United States started to decline, analysts wondered which virtually unlimited and cheap resource could support trends of rapidly growing energy demand post-WWII. Available data on fossil energy deposits appeared to indicate that the total geologic occurrences of coal were virtually unlimited. Further, it was thought that during the decades ahead, rapid advances in coal production technology could allow humans to access deep and geographically remote deposits of coal, enabling far higher and more equitable levels of energy resource demand across the world. The contemporary economic policy models adopted coal as the high-carbon backstop resource, supporting outlooks for the very high scenarios of CO2 emissions used in climate science.

In the decades since then, coal combustion has grown significantly in rapidly industrializing countries such as China and India, but overall world coal production has continued to prove more costly and less abundant than expected. Every alternative to coal, other than nuclear power, has been far more competitive. Coal’s long-term climate impacts are borne in tandem with its more immediate human costs from conventional air pollution, tempering enthusiasm for constant combustion growth in any one region because of public health limitations. Any sustained rapid expansion in coal combustion has been eventually checked by overwhelming air pollution concerns. Hence, since the mid 20th-century coal’s market share of global energy supply has followed a general trend of gradual long-term decline, temporarily punctuated by relatively brief waves of initial adoption in developing regions. Observing this dynamic undermines plausibility of the vast coal combustion scenarios frequently used in the climate research literature, where future global energy supply is dominated by exceptionally rapid sustained growth in coal combustion. Acknowledging these findings emphasizes a more comprehensive approach to the baseline scenarios used in climate science and for policy recommendations to reduce CO2 emissions.

Therefore, the relevance of work in this thesis for the ongoing policy discourse on climate change can be summarized as follows:

- Projections of future climate change are contingent on underlying scenarios of fossil fuel use and corresponding oil, gas and coal resource estimates. Fossil CO2 emission projections have tended to emphasize extensive future coal combustion for consistency with conventions in climate model experiments. These high-coal scenarios have formed the scientific foundation for estimates of

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101 Even though the events leading to the contemplation of these scenarios, the oil crises of 1973 & 9, were anything but business-as-usual.
carbon budgets, assessed possibilities for achieving specific temperature goals, impacts of sea level rise and many other critical numbers in the climate policy debate (Chapters 3, 4, 5).

- Upper bound 21st-century global coal combustion estimates should be downgraded to account for ongoing refinements in our understanding of coal markets, standardized reserve definitions, improved data quality in major producing regions, production potentials and technology factors. Today’s recoverable coal estimates are approximately one-third of those assumed by the first IPCC Assessment in 1990. However, climate change scenarios developed for subsequent assessments have elected to maintain the original coal estimates from before the 1990s. Therefore, scenarios for policy targets to reduce fossil CO2 emissions should take great care to distinguish between CO2 emissions projected from coal that exceeds today’s world reserves versus those from other fossil fuels (Chapter 3).

- The plausible worst-case climate scenarios have conventionally been based on combusting all theoretically recoverable fossil deposits. These should be downgraded for consistency with empirical constraints developed from today’s best understanding of recoverable coal supplies and more abundant oil and gas (Chapters 3, 4, 6, 8).

- Economic models of the policies that could reduce industrial fossil fuel emissions have anticipated significant resistance to low carbon fuels and cleaner burning technologies because of potential swift innovation which could reduce the costs of adopting high-carbon technologies. Projections of climate policy costs are highly sensitive to assumptions about the difference in price between high-carbon and low-carbon fuels. Thus, if evidence supports the conclusion that a baseline future of high-carbon technologies will be more costly to implement than expected, the total net investment required to adopt low-carbon technologies will inherently cost less. Therefore, a more expensive coal supply in a ‘no policy’ baseline implies modestly higher baseline energy costs, and therefore a lower economic barrier for less carbon intensive alternatives (Chapters 2, 4, 5).

- The cost of investments needed to sustain rapid innovation in high-carbon technologies have traditionally been undercounted in the economics of climate policy scenarios. In reality, high-carbon fuels compete with lower carbon fuels for investment capital. More comprehensive accounting for the investments required to sustain high rates of innovation in high-carbon fuels suggests increased final long-run costs for fossil fuel dominant baselines. This reduces estimated cost differentials between carbon-intensive baselines and scenarios for adopting greater levels of lower carbon technologies (Chapters 2, 4).

- Displacing use of fossil fuels remains a significant challenge but has generally been presented as more difficult than necessary because vast cheap coal resources were assumed to always outcompete all other energy strategies over the long-run. Climate policy baselines have largely anticipated rapid innovation in high-carbon technologies such as coal-based liquid fuels and underground coal gasification. Achieving the rapid cost-reductions commonly projected for these technologies will require substantial explicit long-term policy support despite no evidence they are a worthwhile investment for affordable energy supply in the face of competition from all other energy technologies. Further, more than a century of failed experience indicates these technologies face significant unsolved technical barriers before they could reasonably scale, due to their intensity of water consumption, underground seam collapses and pervasive groundwater contamination (Chapters 2, 3, 4, 5).
• Therefore, we can conclude that unwarranted extensive use of hypothetically cheap high-carbon technologies in climate policy baselines have supported outlooks for needlessly high carbon prices to achieve any long-term climate policy goal. Energy policy baselines aligned with empirically consistent 21st-century developments in resource economics and carbon intensity trends suggest each dollar effectively applied to mitigate fossil fuel CO₂ emissions is likely to have a bigger impact than previously expected (Chapters 2, 4, 6).

• The socioeconomics of long-term climate scenarios are based on depicting a world of more than 9 billion humans living with current Western European or North American levels of material affluence (Chapter 7). While it is important and in many ways desirable to consider this possibility, a full scientific consideration of uncertainty must account for a wider range of potential developments, such as average global energy and material consumption that converges at significantly lower levels.

• Though worst-case energy production and combustion scenarios can play a useful role in climate risk assessments, empirically grounded long-term energy policy trends of gradual decarbonization and more efficient energy end-use need stronger representation in the baselines used to assess climate policy. These characteristics are consistent with more modest cost projections for a low-carbon transition to achieve climate policy goals such as those outlined in the Paris Agreement (Chapters 4, 6).
Bibliography


Averitt, 1975. Coal Resources of the United States, 1–139.


Couch, G., 2008. Coal to liquids (No. CCC/132), IEA Clean Coal Centre.


Deloitte, 2015. A look at the top issues facing the oil and gas sector 1–32.


Goldman Sachs, 2014. Top 400 Oil Cost Curve by Field.


Häfele, W., 1980a. IIASA’S World regional energy modelling. Futures 12, 18–34. doi:10.1016/S0016-3287(80)80004-8


IIASA, 2009. RCP Database v2.0.


IPCC WGIII, 2014. AR5 Scenario Database.


Lempert, R.J., Popper, S.W., Bankes, S.C., 2003. Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis. RAND.

Lewis, M.C., 2014. Toil for oil spells danger for majors, ESG Sustainability Research.


282


Pindyck, R.S., 2015. The Use and Misuse of Models for Climate Policy. NBER Working Papers.


Riahi, K., van Vuuren, D., 2016. SSP Database (Shared Socioeconomic Pathways) - Version 1.1.


285


van Ruijven, B., van Vuuren, D.P., 2009. Oil and natural gas prices and greenhouse gas emission mitigation. Energy Policy 37, 4797–4808. doi:10.1016/j.enpol.2009.06.037


Appendices

Appendix A - Aggregation of individual nations to the five region levels used in the AR5 database

The IPCC WGIII AR5 Database of scenarios provides projections for five world regions. These regions include the following nations:

I - OECD1990

This region includes the OECD countries in 1990.

Aland Islands, Andorra, Australia, Austria, Belgium, Canada, Channel Islands, Denmark, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Guam, Guernsey, Holy See (Vatican City State), Iceland, Ireland, Isle of Man, Italy, Japan, Jersey, Liechtenstein, Luxembourg, Monaco, Netherlands, New Zealand, Norway, Portugal, Saint Pierre and Miquelon, San Marino, Spain, Svalbard and Jan Mayen, Sweden, Switzerland, Turkey, United Kingdom, United States

II - EIT = Economies in Transition

This region is sometimes also referred to as Reforming Economies of Eastern Europe and the Former Soviet Union (REF).

Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Georgia, Hungary, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Macedonia, Malta, Moldova (Republic of), Montenegro, Poland, Romania, Russian Federation, Serbia, Serbia and Montenegro, Slovakia, Slovenia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan,

III - ASIA = Non-OECD ASIA

The region includes most Asian countries with the exception of the Middle East, Japan and Former Soviet Union states.

Afghanistan, American Samoa, Bangladesh, Bhutan, British Indian Ocean Territory, Brunei Darussalam, Cambodia, China, Christmas Island, Cocos (Keeling) Islands, Cook Islands, Fiji, French Polynesia, Heard Island and McDonald Islands, India, Indonesia, Kiribati, Korea (Democratic People's Republic of), Laos (People's Democratic Republic), Malaysia, Maldives, Marshall Islands, Micronesia (Federated States of), Mongolia, Myanmar, Nauru, Nepal, New Caledonia, Niue, Norfolk Island, Northern Mariana Islands, Pakistan, Palau, Papua New Guinea, Philippines, Pitcairn, Samoa, Singapore, Solomon Islands, South Korea, Sri Lanka, Thailand, Timor-Leste, Tokelau, Tonga, Tuvalu, US Minor Outlying Islands, Vanuatu, Viet Nam, Wallis and Futuna

IV - MAF - Middle East and Africa
This region includes the countries of the Middle East and Africa.

Algeria, Angola, Bahrain, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Congo (The Democratic Republic of the), Cote d'Ivoire, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Iran, Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Oman, Palestinian Territory, Qatar, Reunion, Rwanda, Saint Helena, Sao Tome and Principe, Saudi Arabia, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Swaziland, Syrian Arab Republic, Tanzania, Togo, Tunisia, Uganda, United Arab Emirates, Western Sahara, Yemen, Zambia, Zimbabwe

V - LAM = Latin America

This region includes the countries of Latin America and the Caribbean.

Anguilla, Antarctica, Antigua and Barbuda, Argentina, Aruba, Bahamas, Barbados, Belize, Bermuda, Bolivia, Bouvet Island, Brazil, British Virgin Islands, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Curacao, Dominica, Dominican Republic, Ecuador, El Salvador, Falkland Islands (Malvinas), French Guiana, French Southern Territories, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Sint Maarten, South Georgia and the South Sandwich Islands, Suriname, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, US Virgin Islands, Venezuela
Appendix B - AR5 population scenarios

Figure B.1  Population scenarios AR5 WGIII scenarios: World - with time-series of individual scenarios (gray), series median (blue)
Figure B.2  Population scenarios AR5 WGIII scenarios: OECD - with time-series of individual scenarios (gray), series median (blue)
Figure B.3  Population scenarios AR5 WGIII scenarios: Economies in transition - with time-series of individual scenarios (gray), series median (blue)

Figure B.4  Population scenarios AR5 WGIII scenarios: Asia - with time-series of individual scenarios (gray), series median (blue)
Figure B.5  Population scenarios AR5 WGIII scenarios: Middle East and Africa - with time-series of individual scenarios (gray), series median (blue)
Figure B.6  Population scenarios AR5 WGIII scenarios: Latin America - with time-series of individual scenarios (gray), series median (blue)
Appendix C - Excerpts of peer reviews collected from journal submissions related to material in this thesis

C.I - Chapter 5 – Return to Coal

Chapter 5 was originally rejected based on the argument that data for the SSP scenarios was from a preliminary database and therefore could not be used in a scientific study. These are recounted in the excerpt from the review:

The manuscript by Ritchie and Dowlatabadi is not acceptable for publication… the authors rely on data that is not published and that is, consequently, not properly cited. The data used refers to the Shared Socioeconomic Pathways (SSPs). The SSPs are in preparation and not published. Therefore, the study is based on data that cannot be replicated from the references provided by the authors. Therefore, the entire study is not substantiated.

And another reviewer remarked:

In a parallel process to the development of the RCPs, IAM modelling teams are systematically exploring which future pathways lead to the different forcing levels. The authors have acknowledged these scenarios, the SSPs, and have even included these throughout the paper. The problem with doing this though, is that the current results which have been published online for review purposes only have a disclaimer which states “…the current data cannot be used or quoted…”.

However, the data was already in use by papers that were in press and accepted at the time and so these comments were only applied to prevent critical scrutiny of the data.

At another journal, reviewers later argued that it was not appropriate to base a research paper on a meta-analysis of research results produced by other groups:

This article type is claimed to be a “research paper”, and yet there is almost no original research described in the paper. The paper is primarily descriptive of what other research groups have done, and it focuses on the results from various integrated assessment models which they have run for the representative concentration pathway (RCP) scenarios relied on in the 2014 IPCC Working Group III report. (The brief mention of the more recent SSP scenarios in the paper can be ignored, because these scenario results do not add anything of substance to the paper beyond the analysis of the RCP scenarios.) This paper is also very poorly written, and contains many poorly worded sentences which undermine the level of perceived expertise of the authors. But, at times, the authors seem truly confused, even though in the end clarifying those points of confusion really would not affect the substance of the paper because in other sentences the facts are basically stated correctly.

C.II - Chapter 2 – Learning-by-extracting

The original manuscript for Chapter 2 was rejected based a review that argued:

The authors argue, following an earlier manuscript by Nordhaus (2009), that these models significantly over-estimate the learning rates and are consequently over-optimistic with regard to future costs of fossil fuel supply. The authors do a good job of pointing out the difficulties of disentangling the effects of learning and other factors, such
as local geology and cost drivers, and the data that they collect is relevant. The criticism of IAM with regard to future fossil fuel supply is certainly correct... Given that IAMs project the future energy system for a century, some "averaging out" of the development cycles is simply necessary to obtain numerically tractable models. I would be very curious to see better approaches for representing the fossil fuel sector in large-scale applied models - but I believe that this manuscript does not deliver a good starting point for such a discussion.

C.III - Chapter 3 – 1,000 GtC Coal Backstop

A reviewer for the initial manuscript on which this chapter was based emphasized the importance of considering the potential need to access coal in the future:

Whether the BGR (2015) reported 18,000 Gt of hard coal reserves and resources can ever be produced is irrelevant and futile to debate - clearly the bulk will remain where they are for all kinds of reasons also correctly identified by the author(s)... But if push comes to shove, i.e., the global demand for energy services continues unabated and non-fossil alternatives and energy efficiency, etc. do not live up to expectations, coal may again be increasingly called upon (approximately the situation 20-30 years ago). The general view was that if the necessity arises, human engineering ingenuity would develop the prerequisite technology capability to tap these vast coal resources - hence the backstop coal... Btw, initial climate modeling and baseline scenarios date back to the early 1980s and consequently incorporated coal resources (in addition to reserves) as the logical backstop. In addition, early unrefined GCMs required a strong carbon signal that only could be only provided by large coal use throughout the 21st century. The use of coal as a backstop fuel may look anachronistic or even antagonistic given current climate, environmental and health concerns, economic realities, especially the performance of some renewables. Given the enormous resources flows of wind and solar energy as well as world's large fissile resource base, it might well be more appropriate to use any of these sources (and associated conversion technologies) as backstops rather than coal. This is a fundamental change compared to 30 years ago...