Energy 111 (2016) 580–592

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Assessing global fossil fuel availability in a scenario framework

Nico Bauer [a, *], Jérôme Hilaire [a, b], Robert J. Brecha [c], Jae Edmonds [d], Kejun Jiang [e], Elmar Kriegler [a], Hans-Holger Rogner [f, i], Fabio Sferra [g, h]

[a] Potsdam Institute for Climate Impact Research (PIK), Germany
[b] Mercator Research Institute on Global Commons and Climate Change (MCC), Germany
[c] University of Dayton, Department of Physics, OH, United States
[d] Pacific National Northwestern Laboratory (PNNL), MD, United States
[e] Energy Research Institute (ERI), Beijing, China
[f] International Institute for Applied Systems Analysis (IIASA), Austria
[g] Centro Mediterraneo dei Cambiamenti Climatici (CMCC), Italy
[h] Climate Analytics, Germany
[i] Royal Institute of Technology (KTH), Sweden

ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form
20 May 2016
Accepted 24 May 2016

JEL code:
Q31
Q35
Q54

Keywords:
Shared socio-economic pathways (SSPs)
Fossil fuel sector
Coal
Oil
Gas
Integrated Assessment Models
Extraction cost

ABSTRACT

This study assesses global, long-term economic availability of coal, oil and gas within the Shared Socio-economic Pathway (SSP) scenario framework considering alternative assumptions as to highly uncertain future developments of technology, policy and the economy. Diverse sets of trajectories are formulated varying the challenges to mitigation and adaptation of climate change. The potential CO_2 emissions from fossil fuels make it a crucial element subject to deep uncertainties. The analysis is based on a well-established dataset of cost-quantity combinations that assumes favorable techno-economic developments, but ignores additional constraints on the extraction sector. This study significantly extends the analysis by specifying alternative assumptions for the fossil fuel sector consistent with the SSP scenario families and applying these filters (mark-ups and scaling factors) to the original dataset, thus resulting in alternative cumulative fossil fuel availability curves. In a Middle-of-the-Road scenario, low cost fossil fuels embody carbon consistent with a RCP6.0 emission profile, if all the CO_2 were emitted freely during the 21st century. In scenarios with high challenges to mitigation, the assumed embodied carbon in low-cost fossil fuels can trigger a RCP8.5 scenario; low mitigation challenges scenarios are still consistent with a RCP4.5 scenario.

1. Introduction

One of the factors considered of key importance for determining future CO_2 emissions and the cost of climate-change mitigation policies is the size and the costs of recoverable fossil-fuels [1,2]. However, assumptions of resource availability are subject to deep uncertainties that are difficult to quantify. These uncertainties, by which are meant not only physical quantities but also the conditions under which these resources might be extracted, are particularly crucial for the assessment of long-term projections of the energy system, economic development and environmental problems including global climate change. When mitigation scenarios are presented and discussed, it is necessary that the underlying assumptions about fossil fuel availability are transparent and the uncertainties are clearly communicated.

The Shared Socio-Economic Pathways (SSPs) provide a systematic framework for scenarios that are differentiated by socio-economic challenges to (i) mitigation of and (ii) adaptation to climate change (see Fig. 1 and Ref. [3,4]). The five SSPs describe plausible alternative trends in the evolution of society over a century time scale [4]. The Middle-of-the-Road scenario family projects moderate growth pathways and medium assumptions for key parameters, which define medium challenges to mitigation and adaptation. The other SSPs represent deviations from this baseline, with the goal of mapping out increasing or decreasing challenges for mitigation and adaptation. A variety of factors have been

* Corresponding author. PO Box 601203, 14412 Potsdam, Germany.
E-mail address: nico.bauer@pik-potsdam.de (N. Bauer).

http://dx.doi.org/10.1016/j.energy.2016.05.088
0360-5442/

Acronym

Technical terms

BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
CAC	cumulative availability curve
CECC	cumulative extraction cost curve
CCS	carbon capture and storage
CO_2	carbon dioxide
EMF-27	27th model comparison round of the stanford energy modeling forum
ERR	economically recoverable reserve
GEA	global energy assessment (database)
GEA+	up-dated GEA database
GHG	greenhouse gas
IAM	integrated assessment model
IPCC	intergovernmental panel on climate change
ORIP	original resource in place
RCP	representative concentration pathway
SRES	special report on emission scenarios
SSP	shared socioeconomic pathway
SOM	supporting online material
TRR	technical recoverable reserve
USGS	United States Geological Survey
WEC	World Energy Council

Regions

ASIA	Asia
OECD	Members of Organization for Economic Cooperation and Development
REF	Reforming Economies
LAM	Latin America
MAF	Middle East and Africa

Units

US$/GJ	US$ deflated to 2005 per GigaJoule (10^9 J)
EJ	ExaJoule (10^{18} J)
ZJ	ZetaJoule (10^{21} J)

Fig. 1. General framework for the development of the shared socio-economic pathways [3].

identified to be crucial for determining the SSPs and are assessed in detail in the SSP context including population [5], economic growth [6], urbanization [7], and are pivotal for interpreting the SSPs. The availability of fossil fuels is also identified as a key factor [3] for baseline emissions, mitigation strategies and costs. Interpretation of the SSPs then requires quantitative assumptions; in the case of the fossil fuel sector these assumptions include not only overall amount and relative regional distribution of the resources, but also future extraction costs.

The SSPs, which are a follow-up to the SRES scenarios [10], are related to the Representative Concentration Pathways (RCPs) [8], which serve as input assumptions to physical climate models. SSPs and RCPs are major components of a new scenario framework [9].

The main goal of this study is to construct consistent fossil fuel sector assumptions matched to the SSPs. The methodology consists of a qualitative step and a quantitative step (similar to [4–6]). The *qualitative* step is to translate the *basic* SSP narratives as provided in Ref. [3] into *extended* SSP narratives and qualitative assumptions of fossil fuel availability taking into account technological, political and economic uncertainties. The *quantitative* step is to formulate a unique database of fossil fuel quantities and extraction costs and then apply the set of scaling factors consistent with the qualitative assumptions of the SSPs to derive the quantitative fossil fuel availability.[1] This work provides a needed extension of the seminal work of Rogner [11], in which, for example, estimates were made of resources in place, without regard to socioeconomic conditions that would or would not result in extraction of these resources. The current work starts with the assumption that a more careful consideration of technological, political and economic forces is crucial to understanding the availability of physical resources. The rationale for using the SSP framework to derive assumptions of fossil fuel availability is that the SSP narratives guide the reasoning and the choice for the set of these assumptions. The approach aims at covering a reasonable range in the uncertainty space of fossil fuel sector assumptions within a broader framework of other uncertain dimensions about long-term socio-economic development, without claiming that any given scenario is a *prediction* of future development, but rather a plausible projection consistent with the corresponding narrative.

The remainder of the paper is organized as follows. Section 2 discusses the fossil-fuel extraction sector in the context of Integrated Assessment Models. Section 3 reviews fossil-fuel sector uncertainties that make diversified assumptions necessary. Section 4 introduces the SSP narratives with a special focus on the fossil-fuel sector. Section 5 provides the method and summarizes the results for the quantified scenario assumptions. Finally, Section 6 is a concluding discussion of the constructed scenarios. A detailed Supporting Online Material (SOM) supplement contains all data and assumptions used for this study.

2. Fossil fuels in the context of integrated assessment

Integrated Assessment Models (IAMs) are tools to derive quantitative scenarios given a set of input assumptions. There are four main reasons in the SSP context to put strong emphasis on the scenario assumptions regarding the fossil fuel sector used in IAMs. First, baseline scenarios without limitations on GHG emission [12] usually assume energy to be supplied by relatively cheap fossil fuels leading to high emissions [1,2,12,13,14]. Assumptions about fossil

[1] The approach to assess the economic fossil fuel availability to supply them at the market place is separable from specific climate policies like emission taxes.