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Projection of world fossil fuels by country

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HIGHLIGHTS

- We model world fossil fuel production by country including unconventional sources.
- Four countries, China, USA, Canada and Australia modelled by state/province level.
- Three ultimately recouverable resources applied, that range from 48.4 to 121.5 ZJ.
- Scenarios suggest coal production peaks before 2025 due to China.
- Results suggest lack of fossil fuels to deliver high IPCC scenarios: A1Fl, RCP8.5.

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ABSTRACT

Detailed projections of world fossil fuel production including unconventional sources were created by country and fuel type to estimate possible future fossil fuel production. Four critical countries (China, USA, Canada and Australia) were examined in detail with projections made on the state/province level. Ultimately Recoverable Resources (URR) for fossil fuels were estimated for three scenarios: Low = 48.4 ZJ, Best Guess (BG) = 75.7 ZJ, High = 121.5 ZJ. The scenarios were developed using Geologic Resources Supply-Demand Model (GeRS-DeMo). The Low and Best Guess (BG) scenarios suggest that world fossil fuel production may peak before 2025 and decline rapidly thereafter. The High scenario indicates that fossil fuels may have a strong growth till 2025 followed by a plateau lasting approximately 50 years before declining. All three scenarios suggest that world coal production may peak before 2025 due to peaking Chinese production and that only natural gas could have strong growth in the future. In addition, by converting the fossil fuel projections to greenhouse gas emissions, the projections were compared to IPCC scenarios which indicated that based on current estimates of URR there are insufficient fossil fuels to deliver the higher emission IPCC scenarios A1Fl and RCP8.5.

1. Introduction

Fossil fuels are vital for our global energy needs, accounting for more than 80% of the world primary energy consumption [1]. Recent scenarios developed by the IEA [1], BP [2] and RCP [3] point to continuing growth in fossil fuel demand in the near future. These scenarios weave together a range of factors including demand, technology development, assumptions of policy agreements to reduce greenhouse gas emissions and changes in regional production capacity. While the development of global energy use and emissions scenarios are important, they are not immutable forecasts and must be bounded by geological limitations in fossil fuel Ultimately Recoverable Resources (URR). Time series estimates with geological limits representing an upper bound of fossil fuel supply at a global, national and province level are important for forecasting future greenhouse gas emissions.

Supply based geologically constrained estimates for the exploitation of finite resources including fossil fuels have received increasing attention in the literature e.g. [4–9]. A general feature of these assessments is that the extraction of any particular resource passes through a production growth phase, followed by a peak and inevitable decline as the resource becomes more technically, energetically and economically challenging to extract and deliver to market. While all estimates bound by exploitation of finite resources show this peaking behaviour if the time period is

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sufficiently long, the predictions of the timing and profile of the production peak can vary significantly between studies [10]. Global coal production for example was predicted to peak in 2011 by Patzek and Croft [7], while Höök et al. [11] forecast the peak will occur later between 2020 and 2050.

Developing production profile estimates for fossil fuels at a global, national or basin level depends on four key factors.

1. The accuracy of URR estimates for each fossil fuel source. Outdated estimates, political estimates and different classification systems (e.g. JORC, National Instrument 43–101) can result in a significant difference in the applied URR value e.g. the URR in conventional oil estimates ranges from 1800 to 4500 Gb [12,13].
2. The inclusion of new and emerging fossil fuel sources as they become technically and economically accessible. Most current peak studies mainly focus on the conventional fossil fuels, e.g. [9,12,14,15]. Only a few studies give their attention to unconventional fossil fuel, such as tight oil and shale gas, e.g. [8,16,17]. This can lead to an underestimate of the potential production growth in unconventional fuel.
3. The development of accurate estimates for the rate of change in production in response to supply and demand interactions. Algorithm type approaches such as the use of Logistic or Gompertz curves e.g. [6,11,18] constrain future growth based on historical growth data without reference to changes in future demand.
4. The sensitivity of predictions to stochastic events as they unfold into the future. Both production and demand are influenced by political, economic and physical events such as wars, recessions and natural disasters [10].

The last two points can be addressed by using the Geologic Resources Supply-Demand Model (GeRS-DeMo) [10,19]. GeRS-DeMo is an algorithm-based approach that allows supply and demand to interact and is able to model stochastic events relatively well. GeRS-DeMo generates a supply projection from a bottom-up analysis of mining and field extraction activities at a basin and country level that is influenced by the marginal difference between global supply and demand. By calculating production from a bottom-up approach, it is capable of projecting future supply from resources that have negligible or no production to date. GeRS-DeMo has been used to develop projections for coal, conventional and unconventional oil, conventional and unconventional gas, lithium, phosphorus, copper production and other minerals [8,10,18,20–24].

The purpose of this paper is to update the global fossil fuel limitation study of Mohr [10] and to specifically include an assessment of resultant fossil fuel related greenhouse gas emissions. The update includes latest URR estimates; these URR estimates are used to form three URR scenarios, a Low estimate of the URR, a High estimate of the URR and a Best Guess (BG) scenario. The update includes all currently recognised unconventional sources of fossil fuels, including some resource previously excluded in Mohr [10] e.g. methane hydrates. In addition, four countries that have substantial resources and hence are critical to forecasts (China – coal, USA – coal, unconventional oil and gas, Canada – unconventional oil and Australia – coal) are projected on a state/province level in a bid to increase the quality and depth of the projection forecast. The GeRs-DeMo approach assumes no global action to reduce global greenhouse gas emissions and no significant breakthroughs in alternative (non fossil fuel) energy technologies. The resultant models are therefore not intended as a prediction of future fossil fuel energy use, but instead estimate an informative picture of the upper limits to business as usual growth in fossil fuel use and its associated greenhouse gas emissions. In particular, GeRS-DeMo assumes that all of the URR is exploited into production. The supply of fossil fuels in the future could be lower than predicted by the model, if, for example, demand is reduced due to climate change policies, or by alternative energy sources out-competing fossil fuels.

2. Overview of fossil fuels and historical production

2.1. Overview of fossil fuels

Coal qualities are often split into four categories namely anthracite, bituminous, sub-bituminous and lignite [25]. A fifth category, semi-anthracite, is used to describe a small number of resources that are part way between anthracite and bituminous coals. The term black coal refers to anthracite and bituminous coals and brown refers to sub-bituminous and lignite coals.

Coalbed methane (CBM) is methane generated and trapped within coal seams [26]. Methane hydrates are methane trapped in ice typically located on the sea floor [27]. Tight gas is natural gas in sandstone and limestone with a permeability below 0.1 mD [28,29]. By comparison, the permeability of conventional oil and gas reservoirs is between 0.1 and 100 mD [30]. Shale gas is natural gas found in organic rich source rocks, which typically have low permeability [29]. Conventional gas is any natural gas in a porous geologic formation that can readily flow to a well [26,31].

Extra heavy oil and natural bitumen both have an API gravity of $<10^\circ$ but extra heavy has a viscosity of <10,000 cP whereas natural bitumen has a viscosity of >10,000 cP. Tight oil is chemically conventional crude oil found in reservoirs with a low permeability (below 0.1 mD) [30]. Kerogen oil is a synthetic crude oil created from kerogen rich source rock [32]. Conventional oil is any crude oil source that is not unconventional and includes deepwater, and natural gas liquid sources. Note the term shale oil is not used here, as its definition is conflicted and typically is either used to mean kerogen oil or tight oil found in organic rich source rocks.

2.2. Global historical production, by country

Global coal, oil and gas production statistics by country have been collated from a variety of sources.[1] Fig. 1 shows the historical production by continent and fueltype. Coal production before 2000 was below 100 EJ/y, however due to booming Chinese production, production rapidly increased to 187 EJ/y by 2012. By comparison conventional oil production between 2005 and 2012 has been stable between 166 and 170 EJ/y. Although growth in unconventional oil (primarily in North America) is strong, total oil production in 2012 was only 179 EJ/y meaning that in 2011 coal production overtook oil production for the first time since the early 1960s. Natural gas production has been steadily growing since the 1950s. Production in the past 5 years has seen growth gaining pace due to unconventional gas production from North America. Older versions of coal and gas statistics were published elsewhere [8,106]. The Electronic supplement to this article has the collated production statistics.

3. Modelling methodology

The model used to create the projections is the Geologic Resources Supply-Demand Model (GeRS-DeMo). The model has been described in detail in [10], and briefly elsewhere [20–23]. The model has two components, supply (from either mines or oil/gas fields) and demand. Note, that the price for fossil fuels is

[1] Coal from [33–68]. Oil from [33–36,41,45,50,53,54,58,61,65–90]. Gas from [33–35,45,54,58,61,66,68–70,78,81,83,90–105].