Projection of world fossil fuels by country

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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° 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].

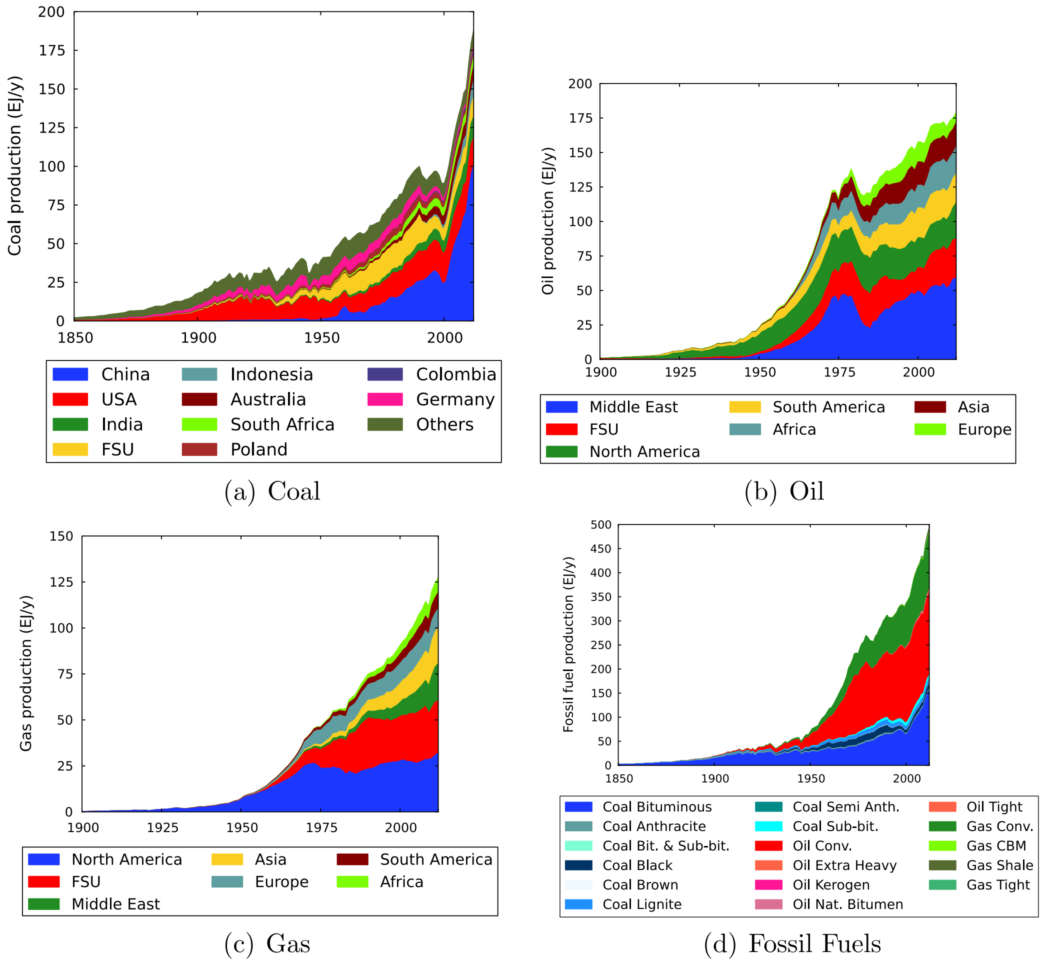


Fig. 1. World historic fossil fuel production.

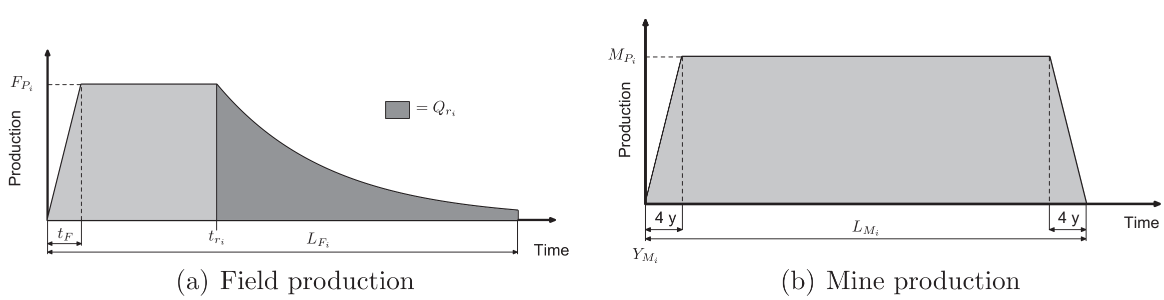


Fig. 2. Idealised production from fields and mines.

neither an input nor output in the model and is not used in the modelling approach. The projections presented here are dynamic, meaning the supply and demand interact with each other. This interaction is achieved by taking the percentage difference between supply and demand. If supply is higher than demand the model provides a signal to decrease supply and increase demand (and vice versa).

3.1. Supply – Oil and gas fields

The production for a region is calculated as the sum of the production from all idealised fields. The production of individual idealised fields has a one year ramp up to a plateau period, followed by an exponential decline in production, as shown in Fig. 2. There remain two things to calculate, the number of fields on-line over time, and the URR of the individual fields. The number of fields on-line $n(t)$ is determined by Eq. (1)

$$n(t) = \left\lceil r_F n_T \frac{Q(t)}{Q_T} \right\rceil \tag{1}$$

where n_T is the total number of fields to be placed on-line, r_F is a rate constant, Q_T is the URR of the region, and $Q(t)$ is the cumulative production. The calculation of the URR of the individual field, is determined via the calculation of the exploitable URR. The exploitable URR, is the sum of the URR in fields (or mines) that have already been brought on-line. The exploitable URR $Q_e(t)$ is estimated via Eq. (2),

$$Q_e(t) = Q_T\left(\frac{n(t)}{n_T}\right)^{r_Q} \tag{2}$$

where r_Q is a rate constant. The URR of an individual field brought on-line in year t, $Q_F(t)$ is determined as:

$$Q_F(t) = \frac{Q_e(t) - Q_e(t-1)}{N(t) - N(t-1)} \tag{3}$$

3.2. Supply – Coal, natural bitumen, extra heavy and kerogen mines

As with fields, the production for a mining region is calculated from the sum of the individual idealised mines' production. The idealised mines have a four year ramp up and ramp down period, with a steady production rate in between, as shown in Fig. 2. The life of an individual mine and its production rate is dependent on the year the mine is brought on-line as described in Eqs. (4) and (5).

$$L_M(t) = \frac{L_H + L_L}{2} + \frac{L_H - L_L}{2}\tanh(r_t(t - t_t)) \tag{4}$$

$$M_P(t) = \frac{M_H + M_L}{2} + \frac{M_H - M_L}{2}\tanh(r_t(t - t_t)) \tag{5}$$

where r_t and t_t are rate and time constants, M_L, M_H is the minimum and maximum mine production rates, and L_L, L_H are the minimum and maximum mine lives. The method for determining the rate and time constants is described in Mohr [10] It remains to calculate the number of mines brought on-line in year t. This is achieved via calculating an estimated exploitable URR $Q_E(t)$ as:

$$Q_E(t) = \frac{Q_T - Q_{T1}e^{-r_T}}{1 - e^{-r_T}} - \frac{Q_T - Q_{T1}}{1 - e^{-r}}e^{-r_T\frac{Q(t)}{Q_T}} \tag{6}$$

where Q_{T1} is the URR of the first mine brought on-line in the region and r_T is a rate constant. The number of mines brought on-line is determined by increasing the number of mines on-line until the actual exploitable URR is larger than the estimated exploitable URR.

3.3. Demand

The demand used in the model is calculated by multiplying the population by the per-capita demand. The global population $p(t)$ (in billions) is assumed to stabilise at 11 billion [107] based on the following equation:

$$p(t) = \frac{11 - 0.82}{[1 + 1.5\exp(-0.023 \times 2(t - 2014))]^{1/2}} + 0.82 \tag{7}$$

The per-capita demand, $D(t)$ is calculated as:

$$D(t) = \begin{cases} 60\exp(0.025(t - 1973)); & \text{if } t < 1973 \\ 60; & \text{if } t \geqslant 1973 \end{cases} \tag{8}$$

While per capita demand for fossil fuels has been shown to be steady between 1980 and 2005 [10] the per capita demand has been increasing in recent years due to the increases in Chinese demand. The demand estimate calculated here therefore should be considered a low estimate of future demand.

4. Fossil fuel URR

The Ultimately Recoverable Resources (URR) is defined as the total amount of the fossil fuels that can be recovered from the resource in the ground before production starts [108]. Specifically, to be counted as part of the URR the fossil fuel needs only to be (or assumed to be) economically and technologically recoverable at some point in time. It is possible that some of the URR is left unexploited, if for instance, climate change policies result in limitations to fossil fuel extraction. Furthermore, the fossil fuels does not need to be economically or technically recoverable currently (e.g. natural gas hydrates are not exploited due to a lack of a technological breakthrough). As a result of the uncertainty as to if a specific deposit of a fossil fuel will ever become economically and technically recoverable, three URR estimates will be used, namely a Low estimate (to attempt to define a reasonable lower bound on the URR) a High estimate (to obtain an upper bound on the URR) and the Best Guess estimate that the authors believe to be the most accurate estimate of the URR.

Table 1
URR by continent (EJ).

Continent	Fuel	Low	BG	High
Africa	Coal	467	988	1014
Africa	Gas	1032	3713	6225
Africa	Oil	1623	2044	3022
Asia	Coal	7338	12,353	16,400
Asia	Gas	2260	4995	9171
Asia	Oil	1458	2094	6048
Europe	Coal	2461	2675	2980
Europe	Gas	791	1482	2681
Europe	Oil	599	666	1525
FSU	Coal	1669	1669	4445
FSU	Gas	2671	4103	10,061
FSU	Oil	3557	4047	4599
Middle East	Coal	2	2	28
Middle East	Gas	3357	4406	5088
Middle East	Oil	5159	4606	8033
North America	Coal	2350	4337	6342
North America	Gas	2894	5359	8139
North America	Oil	4468	7547	12,238
South America	Coal	182	381	384
South America	Gas	922	3753	5341
South America	Oil	3149	4456	7723
Total	Coal	14,469	22,406	31,593
Total	Gas	13,927	27,810	46,707
Total	Oil	20,013	25,460	43,188
Total	Fossil fuels	48,409	75,676	121,488

The URR estimates for the world are compiled from a variety of sources.[2] There are three estimates of the URR, namely Low, Best Guess (BG) and High. The Low URR attempts to replicate estimates from Laherrère, Campbell and Rutledge [111,114,117,129]. These authors tend to have URR estimates at the low end of literature range, for example Rutledge estimates a URR of 680 Gt for world coal (similar to the Low estimate used here of 663 Gt). The High estimate is predominately based on the World Energy Council survey of energy for Coal and BGR survey for oil and gas [109,121]. The Best Guess (BG) URR is the value the authors believe to be the most likely. For 58% of regions the value use has been the same as the Low estimate, and 34% of time it was the high estimate. The remaining 8% were typically either a literature estimate was used (e.g. Geoscience Australia for Australia) or a value in between the high and low estimates. The reference or basis for each country and fuel source estimate is provided in the Electronic supplement. The summary of the URR estimates by continent and by mineral are shown in Tables 1 and 2.

The URR of fossil fuels was partitioned into over 900 different region/fuel types. Typically the URR was broken down into the country, fuel and fuel subtype (e.g. Extra heavy oil in Venezuela). However, four countries were deemed important for the scenarios namely: China for creating the recent rapid expansion in world coal production, USA and Canada for the recent boom in

[2] [10,18,54,78,83,84,97,109–128].

Table 2
URR by Mineral (EJ) (with comparison estimates from Mohr 2010 in italics).

Fuel	Type	Low		BG		High		Mass unit
		(EJ)	Mass	(EJ)	Mass	(EJ)	Mass	
Coal	Anth.	430	14	519	17	425	14	Gt
Coal	Bit.	10,889	454	14,777	616	19,527	814	Gt
Coal	Bit./sub-bit.	25	1	25	1	30	2	Gt
Coal	Black	1575	61	1579	61	3038	117	Gt
Coal	Brown	114	9	255	20	283	22	Gt
Coal	Lignite	844	89	2909	306	5582	588	Gt
Coal	Semi-Anth.	23	1	61	2	80	3	Gt
Coal	Sub-bit.	568	34	2281	138	2629	159	Gt
Coal	Total	14469	663	22,406	1161	31,593	1718	Gt
Coal	*Mohr 2010*[10]	*15,337*	*702*	*19,350*	*961*	*28,064*	*1536*	*Gt*
Gas	CBM	872	830	1097	1045	1945	1852	tcf
Gas	Conv.	11,125	10,595	13,138	12,512	22,539	21,466	tcf
Gas	Hydrates	–	–	4602	4383	12,638	12,036	tcf
Gas	Shale	1350	1286	7013	6679	7059	6723	tcf
Gas	Tight	579	551	1960	1867	2526	2406	tcf
Gas	Total	13,927	13,264	27,810	26,486	46,707	44,483	tcf
Gas	*Mohr 2010*[10]	*14,168*	*13,493*	*17,651*	*16,810*	*26,928*	*25,646*	*tcf*
Oil	Conv.	14,203	2479	14,596	2547	21,122	3686	Gb
Oil	Extra Heavy	1433	250	1728	302	3470	606	Gb
Oil	Kerogen	9	2	4406	769	11,098	1937	Gb
Oil	Nat. bitumen	2422	423	2616	457	3807	664	Gb
Oil	Tight	1947	340	2114	369	3691	644	Gb
Oil	Total	20,013	3493	25,460	4443	43,188	7537	Gb
Oil	*Mohr 2010*[10]	*16,100*	*2810*	*23,803*	*4154*	*37,568*	*6556*	*Gb*
Fossil fuels	Total	48,409		75,676		121,488		
Fossil fuels	*Mohr 2010*[10]	*45,605*		*60,804*		*92,560*		

unconventional oil and gas production, and Australia which was identified previously as having a likely strong future growth in coal production [18]. For these reasons these four countries were modelled in greater detail, generally making projections at a state/province level. A pdf document containing all the URR's used in the scenarios with the associated reference is contained in the Electronic supplement.

5. Results and discussion

The results and discussion will focus only on the main findings of the projections, by fuel type and scenario. Comparisons to other literature projections including the IPCC scenarios will be made. The detailed projections of China, USA, Canada and Australia are presented and discussed. A set of comprehensive reports showing the results of the scenarios by country, fuel type as well as the associated CO_2 emissions are provided in the Electronic supplement.

5.1. Low scenario results by fossil fuel

The projections of the Low scenario aggregated to continent level are shown in Fig. 3, and peak year and rate data is in Table 3.

5.1.1. Coal

The projection from the Low coal scenario indicates that world coal production may peak before 2020 (2018) due overwhelmingly to Chinese production. China contributed 50% of the worlds coal production in 2012 (on a mass basis) and is anticipated to peak in the near future. The sharp decline in coal production after the Chinese peak is projected to be only slightly mitigated by strong growth in Australia, India and USA.

5.1.2. Oil

The Low scenario indicates that oil production may already be in a bumpy plateau, with declining production anticipated to start shortly after 2050. The low scenario indicates the bumpy plateau is due to unconventional oil production partially offsetting the declines in conventional oil. The unconventional oil production is forecasted to predominantly come from Canadian natural bitumen, USA tight oil and Venezuelan extra heavy oil.

5.1.3. Gas

Unlike coal and oil, the Low gas projection is projected to have strong growth in production until 2050, driven predominantly by increases in Middle East, Asian and African conventional resources. These anticipated increases offset slow declines in US production which is projected to fall due to both conventional and unconventional (shale and CBM) production. With the steep declines in Chinese coal production anticipated, natural gas in Asia is likely to have strong demand in the near future. However Asia's gas is not projected to be sufficient to offset Chinese coal declines. Asia's gas production is projected to have a modest growth in the future, its production is currently around 25 EJ/y. So while Asian gas production is anticipated to increase, it is likely to be less than the Chinese Coal production of 100 EJ/y in 2012.

5.2. High scenario results by fossil fuel

The projections of the High scenario aggregated to continent level is shown in Fig. 4, and peak year and rate data is in Table 3.

5.2.1. Coal

For coal, the High scenario is similar to that of the Low, with a projected sharp near-term peak in global coal production driven by Chinese production. The subsequent decline however is anticipated to be less steep. The projection indicates that the slow post peak decline is due to USA, Australia and Former Soviet Union (FSU) which are projected to have strong growth in the latter half of this century. From 2050 onwards, the quality of coal being produced is projected to decrease with production more heavily focused on lignite and sub-bituminous coals rather than the currently dominant bituminous coals.

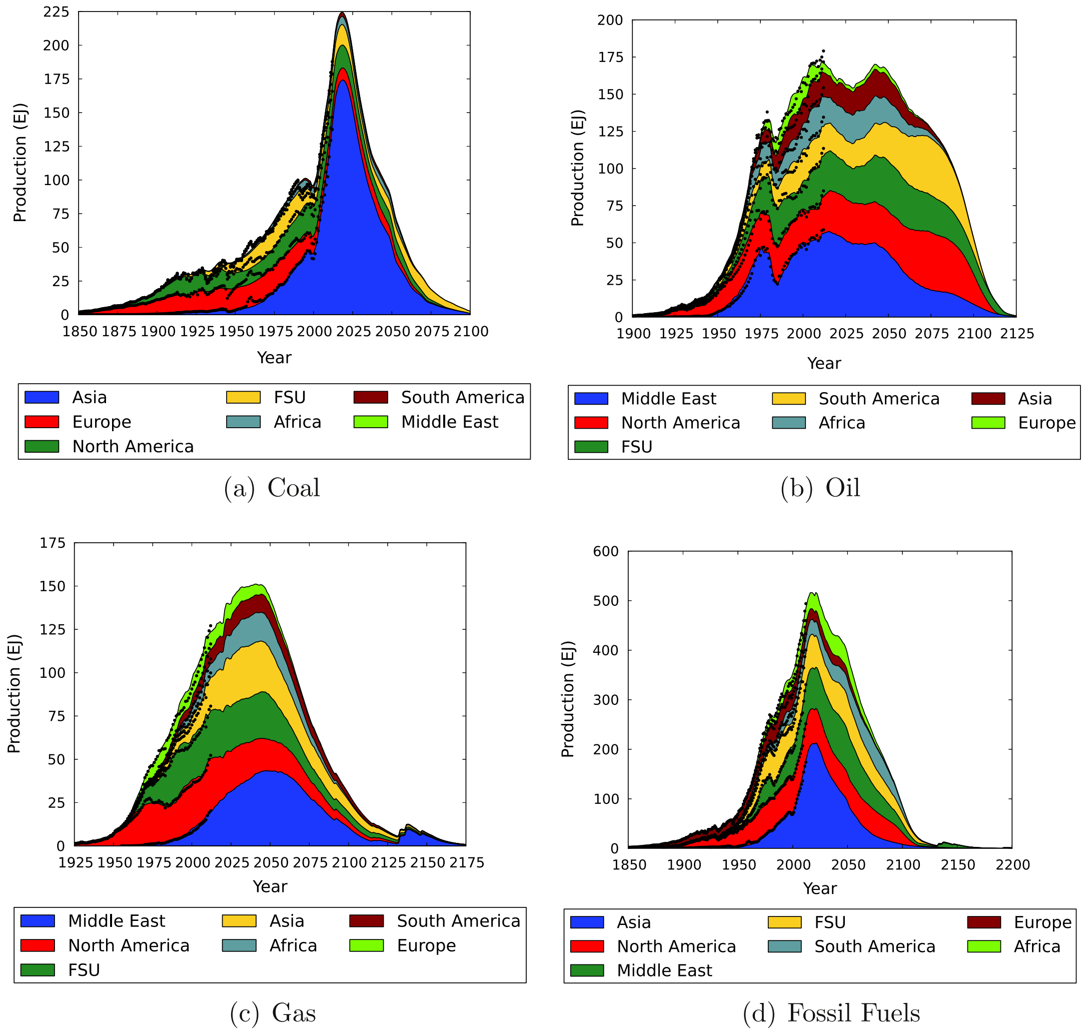


Fig. 3. Low scenario by continent (black dots represent actual historical production).

Table 3
Peak year by mineral.

Name	Low		BG		High	
	Peak year	Peak rate (EJ/y)	Peak year	Peak rate (EJ/y)	Peak year	Peak rate (EJ/y)
Coal Anthracite	1918	3.2	1919	3.2	1918	3.1
Coal Bituminous	2018	189.6	2021	207.8	2025	231.0
Coal Bit. and Sub-bit.	2018	0.3	2018	0.3	2024	0.3
Coal Black	1987	16.2	1987	16.2	2070	26.0
Coal Brown	2062	1.6	2080	3.1	2066	2.5
Coal Lignite	2032	8.5	2114	28.1	2162	37.02
Coal Semi Anthracite	2026	0.8	2033	1.9	2036	2.5
Coal Sub-bituminous	2011	9.3	2070	33.2	2069	22.4
Coal Total	2018	224.5	2021	245.9	2024	274.9
Oil Conventional	2005	166.4	2006	167.0	2041	208.9
Oil Extra Heavy	2078	29.7	2081	29.5	2093	52.2
Oil Kerogen	2036	0.1	2100	46.4	2133	120.0
Oil Natural Bitumen	2075	43.3	2081	42.1	2092	51.8
Oil Tight	2049	32.2	2083	27.7	2100	52.8
Oil Total	2011	172.6	2011	174.7	2100	271.3
Gas Conventional	2031	124.0	2037	134.8	2068	218.8
Gas CBM	2061	10.5	2063	11.5	2097	15.1
Gas Hydrates			2143	59.6	2173	144.5
Gas Shale	2061	17.0	2127	56.8	2141	48.5
Gas Tight	2064	8.5	2134	19.0	2140	18.6
Gas Total	2041	151.2	2052	193.6	2068	288.2
Total	2021	516.4	2023	577.5	2049	743.1

Table 4
Conversion factors used [10,133].

Fuel	Sub-Fuel	Mass conversion EJ/Gt	Mass to CO_2e conversion (Mt CO_2/Gt)
Coal	Anthracite	30	2122
Coal	Bituminous	24	2026
Coal	Sub-bituminous	16.5	1510
Coal	Lignite	9.5	1126
Coal	Semi Anthracite	29	2107
Coal	Bituminous and Sub-bituminous	20	1768
Coal	Black	26	2107
Coal	Brown	13	1318
Oil	Conventional	5.73	434.2
Oil	Tight	5.73	434.2
Oil	Natural Bitumen	5.73	434.2
Oil	Extra Heavy	5.73	434.2
Oil	Kerogen	5.73	610
Gas	Conventional	1.05	54.6
Gas	CBM	1.05	54.6
Gas	Shale	1.05	54.6
Gas	Tight	1.05	54.6
Gas	Hydrates	1.05	54.6

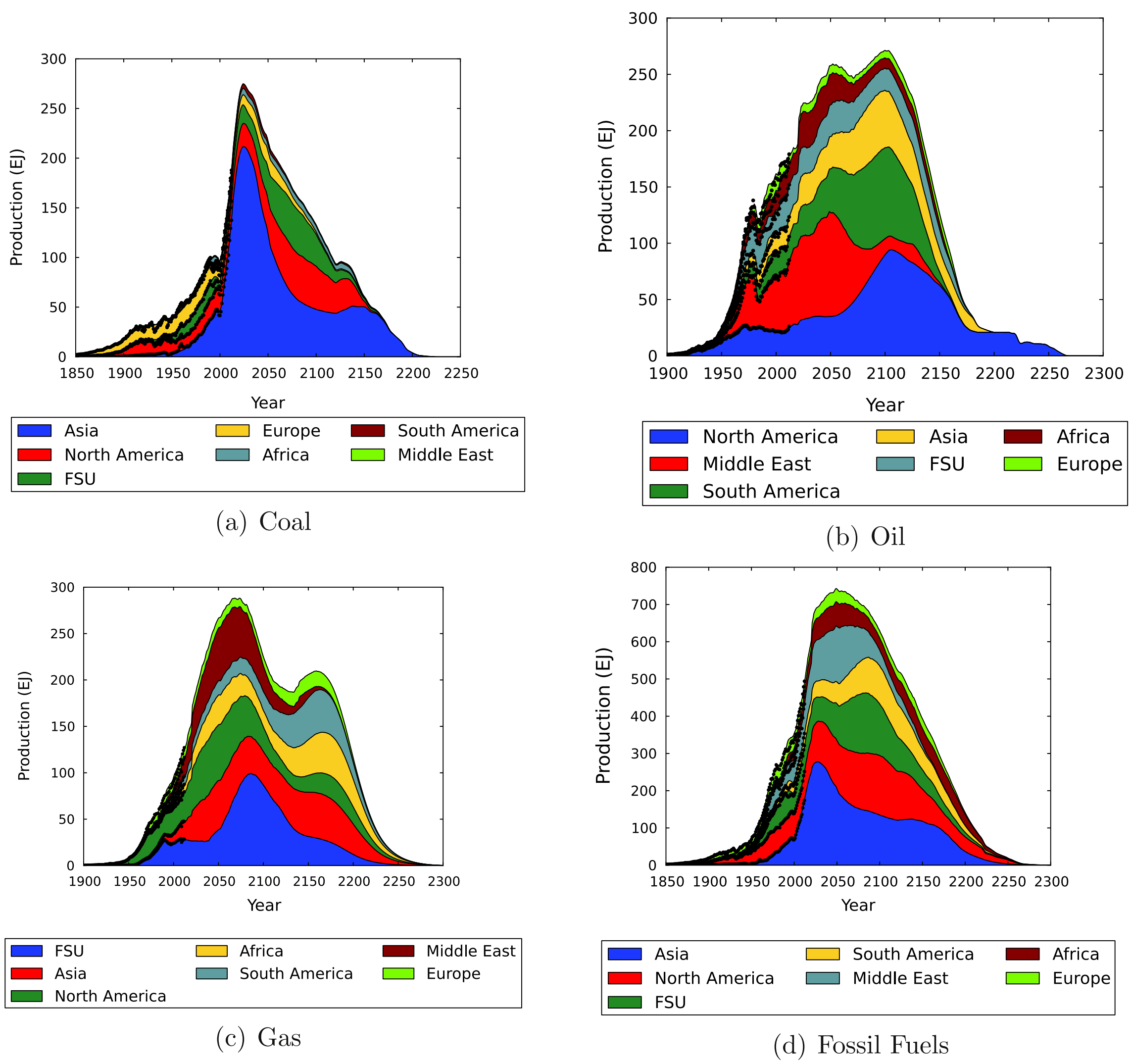


Fig. 4. High scenario by continent (black dots represent actual historical production).

5.2.2. Oil

Oil production in the High scenario is forecast to have a strong short-term growth followed by moderate growth to 2100. The short term growth is projected to be driven by Asia, FSU and African conventional production, followed by medium term growth from the Middle East. Longer term unconventional oil production is forecast to offset conventional declines, predominantly due to USA kerogen, with Canadian natural bitumen, Venezuelan

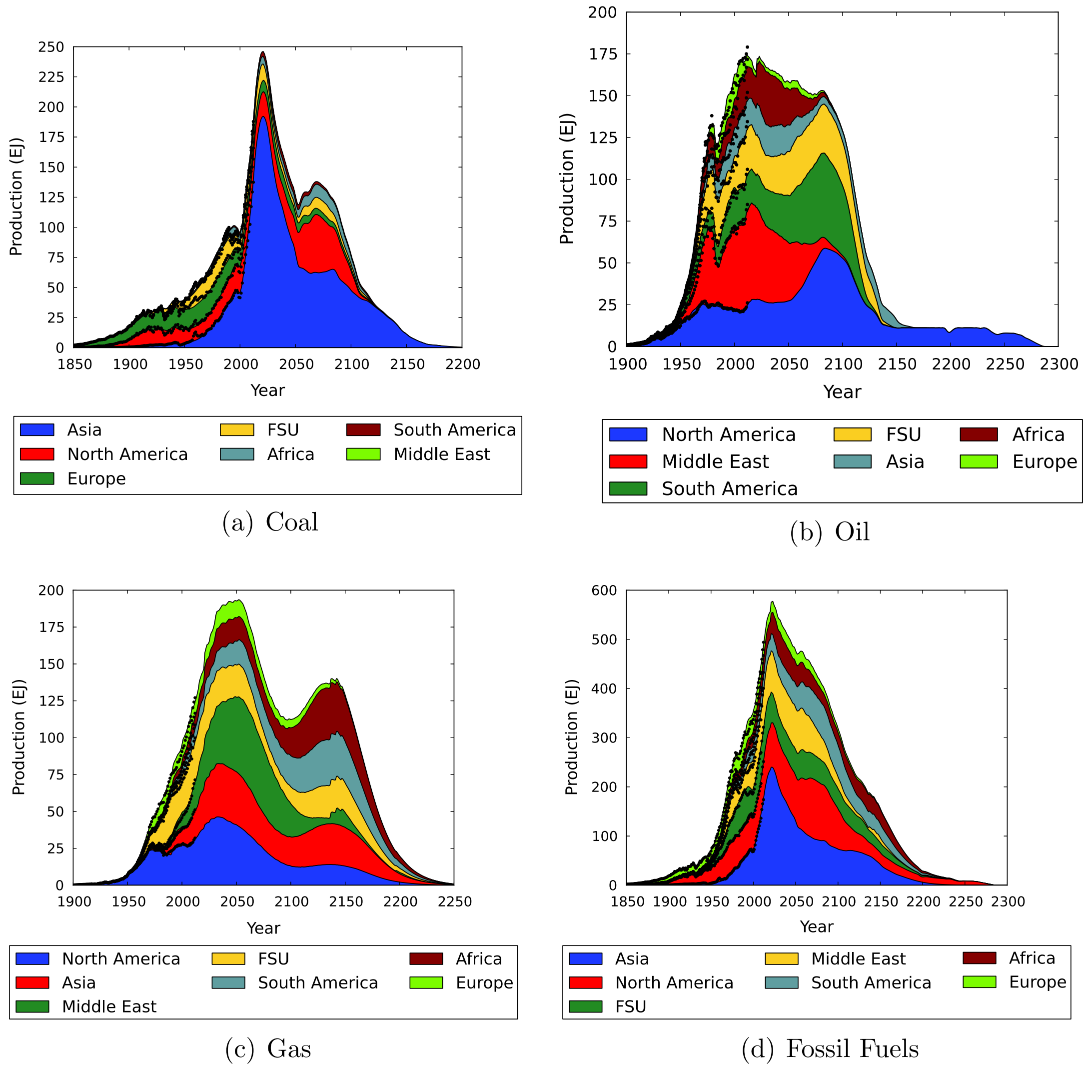


Fig. 5. BG scenario by continent (black dots represent actual historical production).

extra heavy oil and world tight oil production. While global production is anticipated to peak in 2100, the growth from 2025 onwards is likely to be subdued. The projection is heavily dependent on the rapid growth in kerogen oil in the USA. Historically kerogen minerals were exploited for synthetic oil production such as in Australia, and kerogen is currently exploited in Estonia as an energy source for power stations. However, kerogen is only being exploited as a source of liquid fuel in small quantities in countries such as China, Brazil and Estonia [109]. Given the limited current production in kerogen, any projection of future kerogen oil production needs to be taken with considerable caution. Production from kerogen oil could easily fail to materialise due to delays in technological advances needed to reduce the cost of the oil, or due to scarcity in fresh water needed to process the kerogen into a synthetic crude oil.

5.2.3. Gas

Gas production is anticipated to have strong continuing growth in conventional gas, with conventional production projected to peak in 2068. The growth in conventional production is forecast to be dominated by Asia, Middle East and North America. After conventional gas peaks, gas hydrates are anticipated have strong growth before peaking in the latter half of the 22nd century. The hydrates projection needs to be treated with considerable caution, as methods of extracting natural gas hydrates are still being researched. It is uncertain when or even if, technological advances will make gas hydrates extraction technically and economically feasible.

5.3. BG scenario results by fossil fuel

The projections of the BG scenario aggregated to continent level are shown in Fig. 5, and peak year and rate data is in Table 3.

5.3.1. Coal

As with the Low and High scenarios, worldwide coal production is anticipated to peak in 2021 due to Chinese coal production, followed by a steep decline. The decline is partially slowed by a forecast increase in production from Australia, USA and India. Unlike the High scenario, however, FSU production is not anticipated to rapidly increase to slow the decline. The increase in production from Australia, USA and India is projected to causes world production between 2050 and 2100 to plateau at a level roughly half that of current production.

5.3.2. Oil

Conventional oil production is projected to be at peak production currently, primarily due to Saudi Arabia peaking. Although

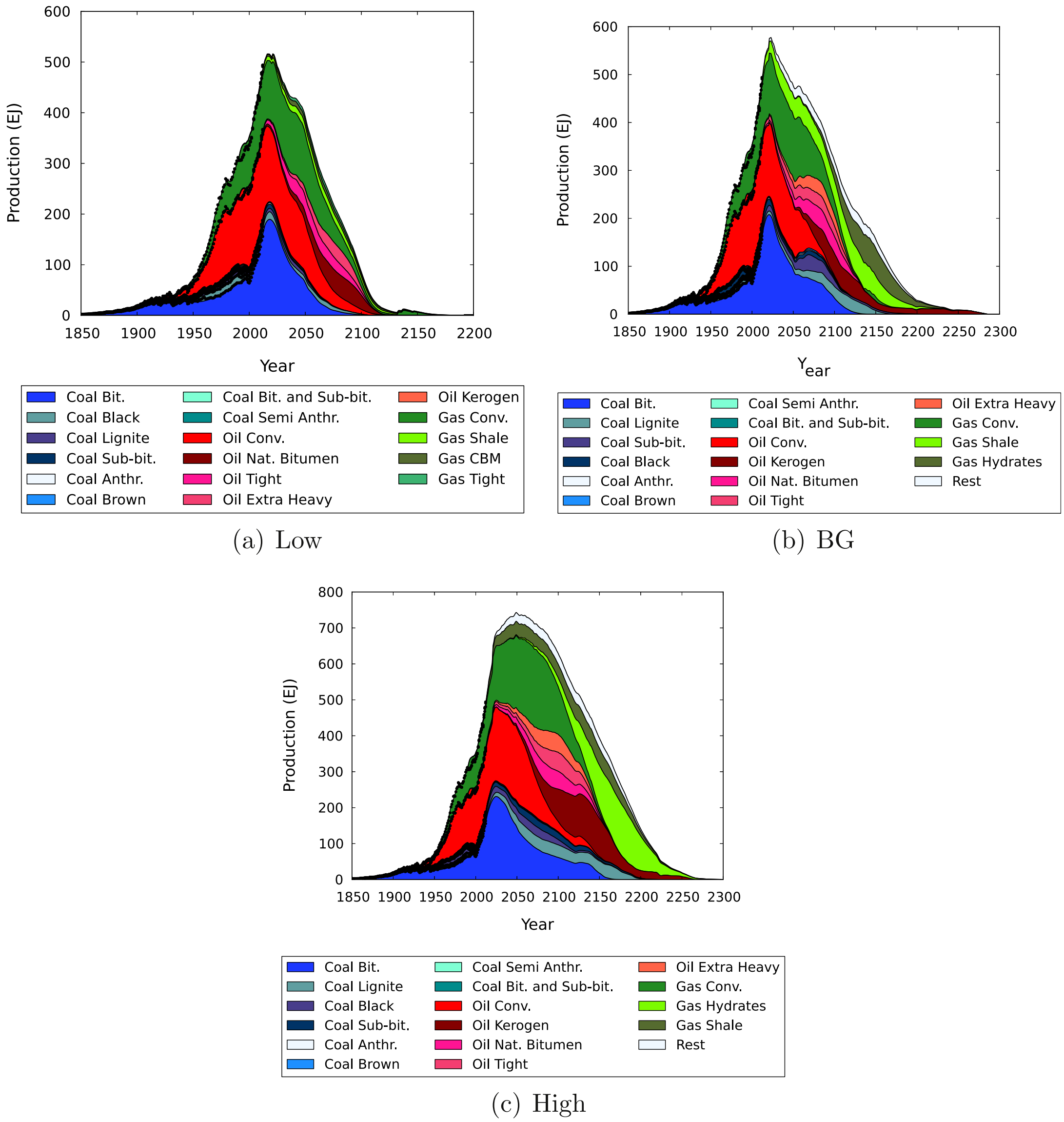


Fig. 6. Fossil fuel projection by mineral type (black dots represent actual historical production).

Canadian natural bitumen, Venezuelan extra heavy oil and USA kerogen all contribute strongly post peak. Growth in unconventional oil is anticipated to be insufficient to offset conventional oil declines. It does however enable a slower decline/plateau which is forecast to be maintained to 2100. By 2100, conventional oil is projected to have essentially ceased production, and unconventional oil is dominated by North America, Venezuela and FSU production. After 2100 steeper declines in oil production are projected due to unconventional oil resources being exhausted.

5.3.3. Gas

As with the Low and High scenarios, natural gas production is anticipated to have strong growth in production. Gas production is forecast to ultimately reach a plateau around 2040–2050. The increases are partially due to continuing conventional gas production growth, and partially due to booming shale gas production predominantly in North America. Hydrates, and to a lesser extent shale gas are forecasted to contribute to a second peak in production in the 22nd century. As with the High case, projection of hydrates needs to be taken with considerable caution. Hydrates could be delayed if technical advances are slow in developing or unfavourable economically; alternatively the recent shale gas boom in North America highlights that technical advances could happen suddenly if a technical breakthrough occurs.

5.4. Total fossil fuel projections

The total fossil fuel projections are shown in Fig. 6, and peak year and rate data are in Table 3.

5.4.1. Low

In the Low case the near term peak in Chinese coal production, plus the slowly declining oil production from 2014 onwards, is forecast to trigger the peak in world fossil fuels. Declining coal and oil production is not anticipated to be mitigated by increasing gas production.

5.4.2. High

In the High scenario, the near term peak in coal production is anticipated to be partially offset by increasing oil and gas production resulting in a broad plateau in production at slightly over 700 EJ/y between mid 2030s to mid 2040s. Initially the projected plateau is due to increasing conventional oil and gas production, followed later by unconventional oil. Natural gas hydrates, though

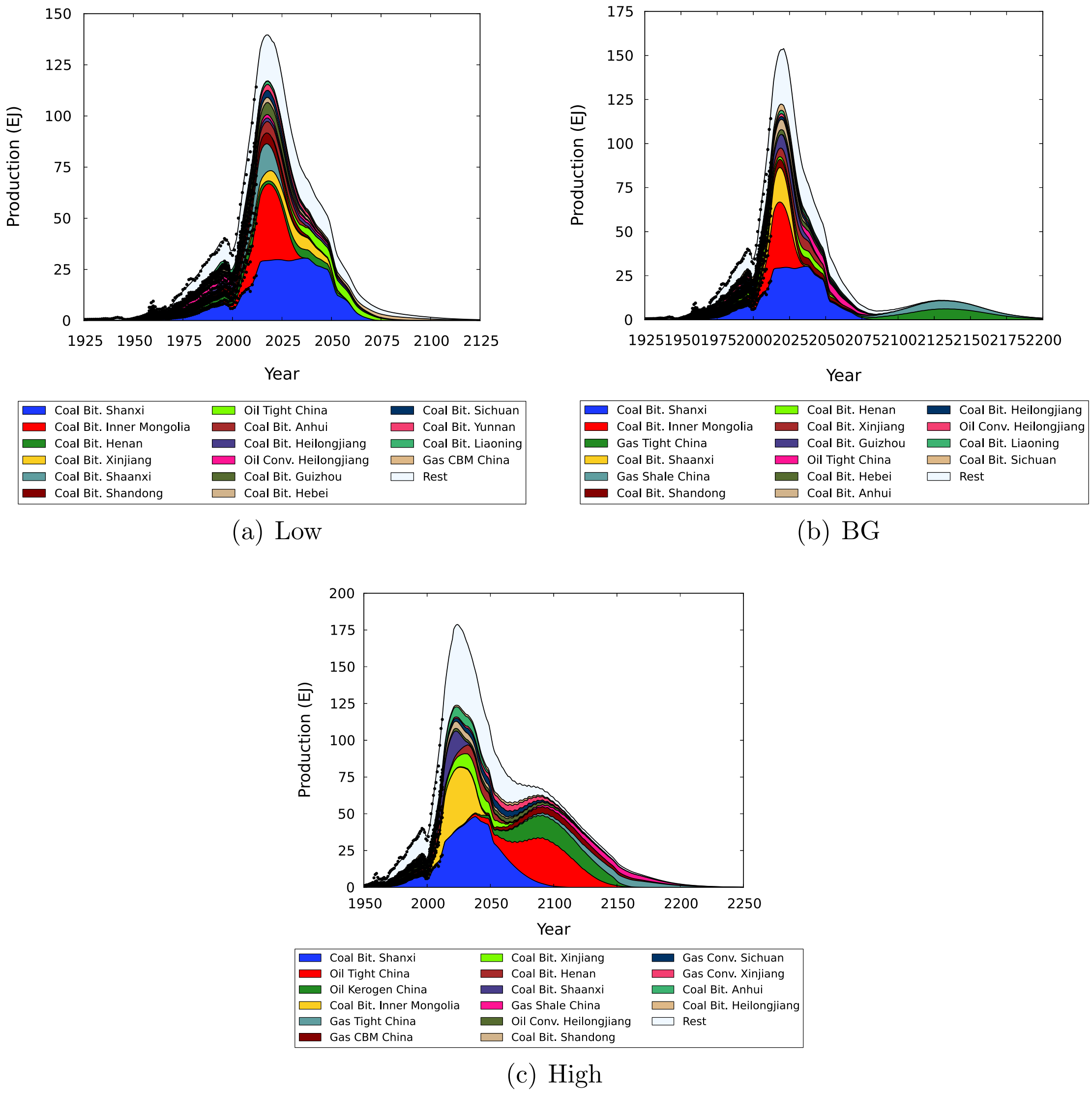


Fig. 7. Chinese fossil fuel projections (black dots represent actual historical production).

anticipated to make large contributions to supply post peak, only act to slow the total fossil fuel decline. The ease with which the world could substitute oil and gas offset declines in coal production is uncertain.

5.4.3. BG

The BG scenario indicates a similar sharp projected peak and decline that is similar to the Low scenario, again due to Chinese coal production. Increasing gas production and reasonably stable oil production are anticipated to not be able to mitigate the sharp decline in coal production. However, the forecast indicates that the decline is less steep than in the Low scenario. Post 2100, the scenario suggests that the majority of fossil fuel production will come from unconventional sources (kerogen, hydrates and shale gas) and from lower quality resources such as lignite. The BG scenario projects that fossil fuels will be mostly exhausted post 2200, compared to just after 2100 in the Low scenario.

5.5. Four key countries

Four countries (China, USA, Canada and Australia) were modelled on the state/province level and are shown in Figs. 7–10. The projections for these countries are briefly described.

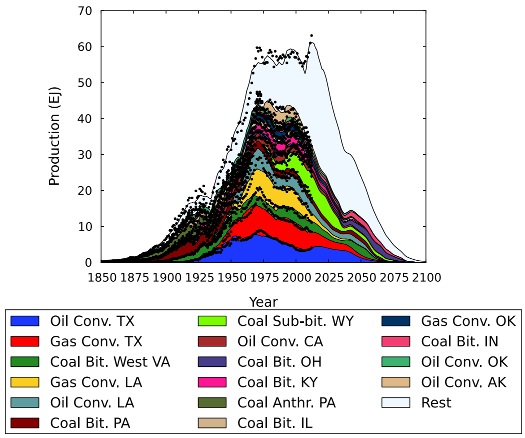
5.5.1. China

As described previously, Chinese coal production is a key driver of both total global fossil fuel based energy production and greenhouse gas emissions. Chinese fossil fuel production is dominated by coal from Shanxi and Inner Mongolia in all of the Low, Best Guess and High scenarios, with only the High scenario showing an additional contribution of note from tight oil and kerogen from around 2050. The peak in Chinese fossil fuel energy production is closely clustered in the vicinity of 2025 across all URR estimates. China has limited reserves of conventional gas and oil, although with some prospects in the post 2050 era of becoming a substantial tight oil and kerogen producer in the High scenario.

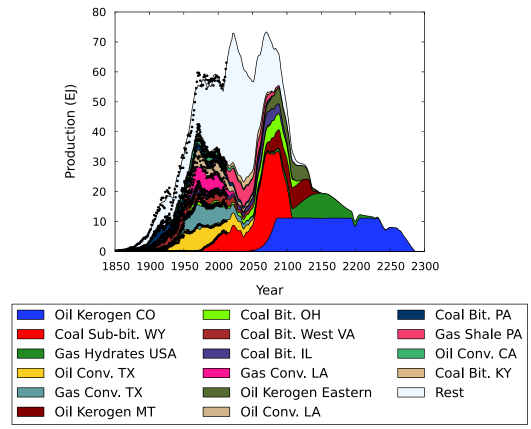
5.5.2. USA

The USA fossil fuel base is one of the most substantial, comprehensive and complex, making narrow range predictions of resource URR challenging. There is substantial variation among all fossil fuels between the Low, High and Best Guess URR estimates driven by uncertainty as to if large scale unconventional oil/gas reserves and currently minimally exploited coal reserves will be effectively brought to market.

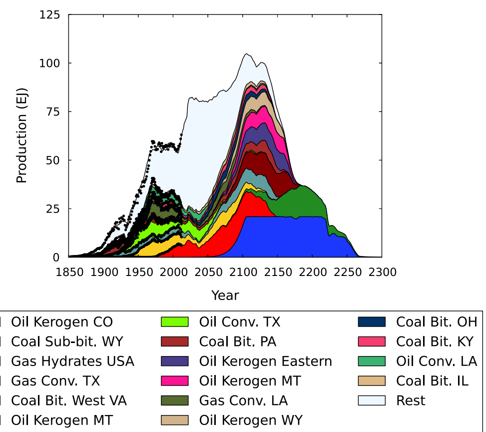
The USA situation is projected to be dominated by a continuing decline in conventional oil and gas along with a shift in the near



(a) Low



(b) BG



(c) High

Fig. 8. USA fossil fuel projections (black dots represent actual historical production).

term to shale gas and tight oil. The low estimate downplays the development of resources with limited historical precedent and hence downplays the unconventional shift and predicts a continuing energy decline. The best guess and high assessments assume new technology and infrastructure development and point to a rapidly increasing role for unconventional oil and gas in the short to medium term.

The BG and High projections indicate that fossil fuel in the US can remain stable or increase to 2100. The increase or plateau in these scenarios is initially due to the exploitation of USA shale gas and tight oil which peak in the 2020–2030 time frame, after which coal re-emerges as the dominant US fossil fuel. Fossil fuel production post 2100 in the best guess and high assessments are dependent on kerogen and to a lesser extent methane hydrates, however the limited production and technical gains necessary to see wide spread production creates considerable uncertainty in kerogen and methane hydrates production.

5.5.3. Canada

Canadian fossil fuel reserves are dominated by substantial natural bitumen resource along with a more moderate amount of shale and tight gas. These resources result in the projections showing Canada to be a significant oil and gas producer for the remainder of the century, peaking in 2075–2091. In all of the assessments the peak is anticipated to be relatively asymmetrical, with production declining rapidly after the peak. Shale and tight gas production capability is relatively consistent over the lifetime of the bitumen resource.

5.5.4. Australia

Australia's fossil fuel projections are dominated by substantial coal and significant amounts of both conventional and unconventional gas production. The Low assessment projects coal production to be limited to the currently exploited bituminous coal resource of eastern Australia, while the BG and High assessments indicate that the substantial lignite resource (predominately in Victoria) could also be heavily exploited. Gas from both conventional and unconventional sources is projected to have significant production for the remainder of the century. Tight oil in the Low scenario and Kerogen in the BG and High scenario are projected to be the biggest sources of oil production in Australia.

5.6. Overall findings

The biggest message from these projections is the importance of Chinese coal production in influencing the peak in world fossil fuels. Coal production is predicted to sustain several more years of high growth, then abruptly peak and decline sharply in all scenarios. Oil is likely to have either already started plateauing in production, or will have only modest growth into the future. Natural gas is the only fossil fuel that is likely to have a strong growth potential in the short to medium term. Under the high scenario fossil fuels will continue to grow for 10 more years, before entering a plateau that remains for over 50 years. The best estimate of resource availability for future production indicates production will peak before 2025 and decline thereafter in a steady fashion. The speed and timing of production of some unconventional fuels

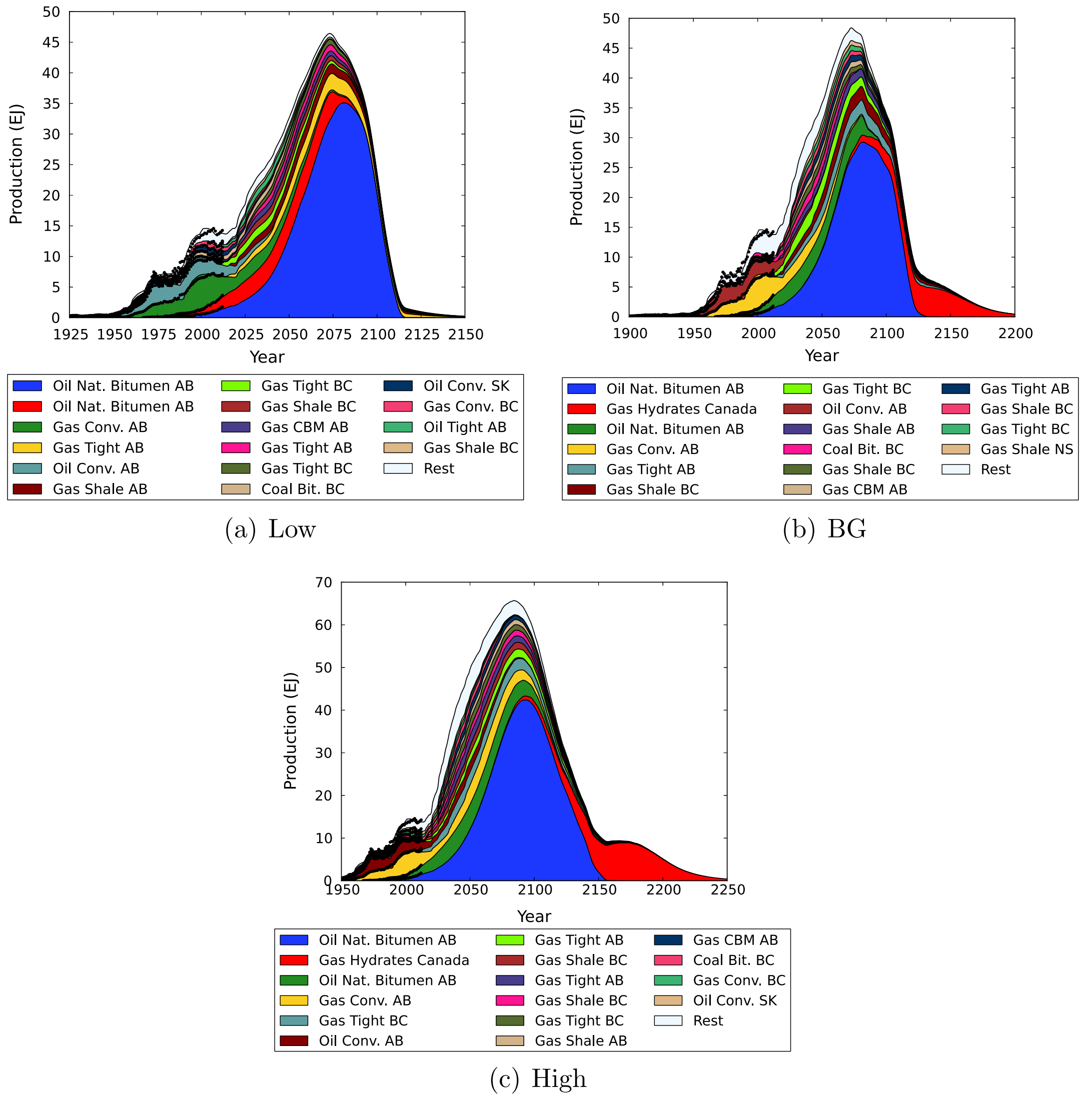


Fig. 9. Canadian fossil fuel projections (black dots represent actual historical production).

such as kerogen and hydrates are difficult to predict due to the current limited or non-existent production levels of these fuels. However, the results presented here indicate that even with an early start date and fast uptake of these fuels, they are largely unable to ensure fossil fuel production continues to increase.

The projections presented here differ form Mohr [10] in that more recent URR estimates have been applied, which particularly for unconventional oil and gas sources has seen substantial changes in recent years due to technological breakthroughs. Second, the results here include four critical countries (China, USA, Canada and Australia) projected at the state/province level to increase the detail in the projections. Next, additional unconventional resources have been included here that were absent in Mohr 2010, namely methane hydrates and tight oil. These changes have created different findings compared to Mohr 2010 with the best guess URR of 75.7 ZJ approximately 25% higher than 60.8 ZJ in Mohr 2010. This updated analysis indicates that production may plateau for longer and peaks may happen later. For instance, world oil production in Mohr 2010 was likely to peak before 2020, with only the high scenario indicating unconventional oil could rise quickly enough to create a plateau in production. In comparison, the results here indicate that the Low and BG will have plateaus in production due to rapidly rising unconventional sources coming on-line at a similar rate to conventional declines, and the High scenario has modest growth in oil production to 2100. Similarly coal is now estimated to peak before 2025, compared to before 2020 in Mohr 2010. Finally, Mohr 2010, indicated all fossil fuels would peak before 2030 due predominately to Chinese coal production peaking before 2020 and steeply declining after a short plateau. In this updated analysis, although Chinese coal production is not projected to have a plateau in production, the High scenario peaks around 2050.

The results from the herein paper are contrasted with Maggio and Caggiola [6] who use a Hubbert curve approach to peak modelling. They find peak years for coal between 2042 (using a similar URR to this paper) up to 2062 for their higher scenario in contrast to 2018–2024 for low and high scenarios in this paper and 2014–2019 in Mohr [10]. Unlike coal, for gas Maggio and Caggiola [6] find earlier peak years than this paper, namely a peak/plateau year of 2024 for their low estimate and 2046 for their high estimate, compared to 2045 (low) to 2073 (high) in this paper and 2033–2060 in Mohr [10]. Finally for oil Maggio and Caggiola [6] predict peak years of 2009–2021 whereas this paper estimates a range between 2011 and 2100 (and Mohr [10] between 2005 and 2101).

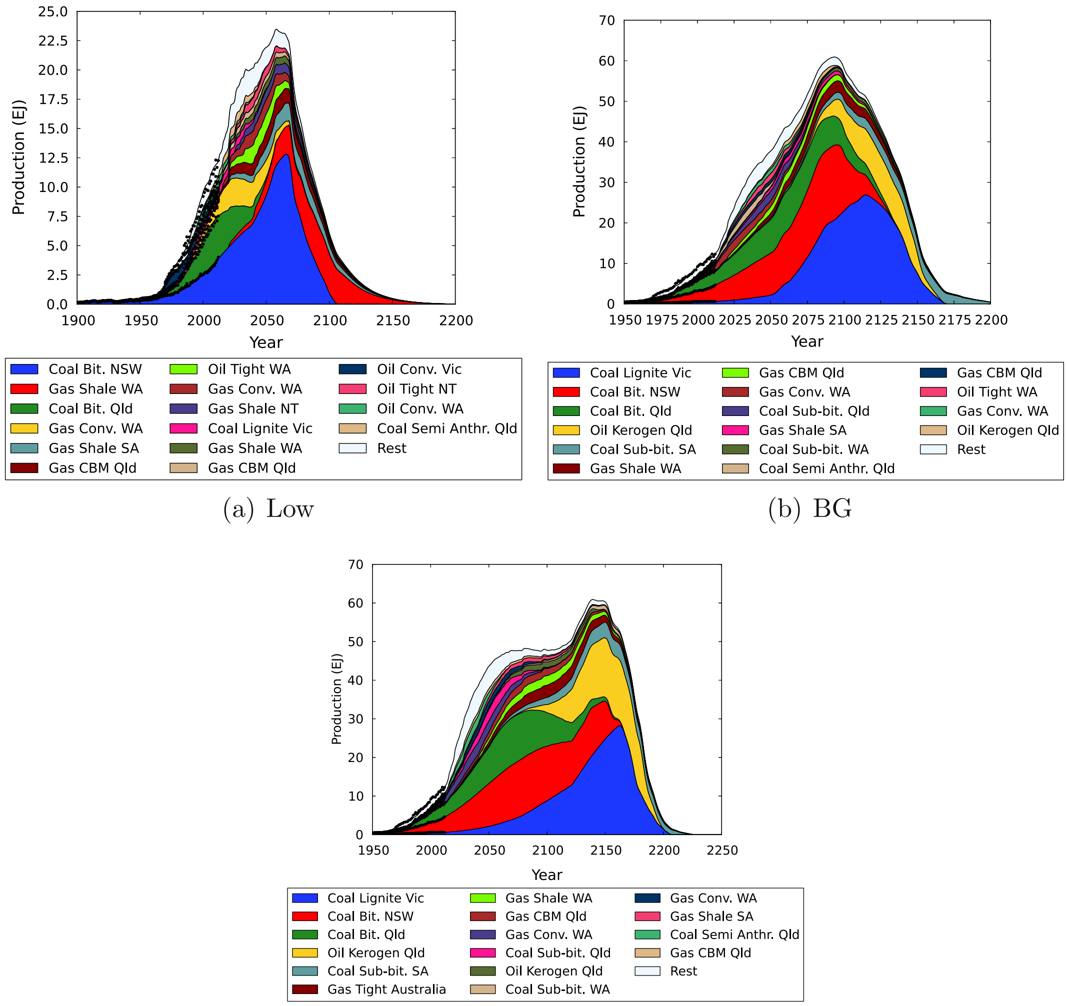


Fig. 10. Australian fossil fuel projections (black dots represent actual historical production).

5.7. Comparison to IPCC emission projections

The projections can also be compared and contrasted with the IPCC projections. The projections were converted to CO_2e units[3] and are shown in Fig. 11 along with IPCC projections[4] of emissions related to fossil fuel use [130,3,131]. Fig. 11 highlights that our BG projection is broadly consistent with the Low emissions scenarios (B1 IMAGE and RCP4.5) while our Low URR projection shows emissions considerably lower than these scenarios. The B1 IMAGE and RCP4.5 projections grow slower and peak higher than the Low and BG scenarios by 2070 and the RCP4.5 scenario shows flat production by 2100; but they decline at a similar rate and in between the Low and BG projections. Only the low emissions scenario (RCP2.6) is lower than our projections. Our High URR case broadly tracks the medium emissions scenarios (A1 AIM and RCP6.0) used for climate change projections. The A1FI and RCP8.5 scenarios are projected to continue to have strong growth in fossil fuel production, reaching over 100 Gt CO_2e by 2100 (when their projection ends). By comparison, our High URR scenario peaks at 50% of this amount (slightly over 50 Gt CO_2e). A possible explanation for this difference could

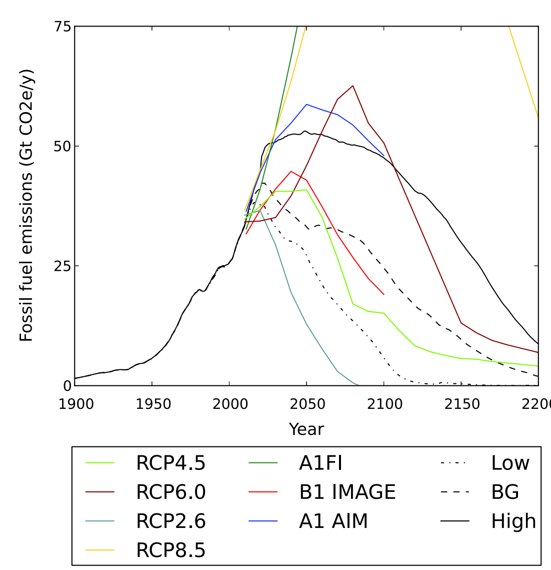


Fig. 11. Corresponding projections of CO_2e fossil fuel emissions, compared to some IPCC scenarios [130,3,131].

[3] Using conversion factors shown in the appendix (Table 4).

[4] Note while, on page 94 of the IPCC AR5 report the emissions are stated as fossil fuels, it appears to include cement and natural gas venting though these represent around 4% and less than 1% of fossil fuel emission currently [3].

be related to what is measured. The scenarios here present fossil fuel emissions, however the estimate in the IPCC appears to include cement and vented natural gas emissions, which currently represent around 5% of total fossil fuel emissions. The proportion of emissions particularly from cement could potentially grow substantially in the future which may explain some of the discrepancy, but it is unlikely that the RCP 8.5 or A1Fl scenarios are possible with the current URR estimates. The A1Fl scenario is based on the assumption that the world can consume vast amounts of coal, oil and gas [130], with others [132] concluding that the assumption is overly optimistic and does not assume constraints or limitations to fossil fuel production prior to 2100. Assuming cement and vented natural gas remains around 5% of total fossil fuel emissions, then the medium scenarios (A1 AIM and RCP6.0) would better reflect an upper limit to fossil fuel related CO_2e emissions.

6. Conclusion

Coal, oil and gas production have been projected into the long term to determine possible future fossil fuel trajectories. These projections include unconventional sources of oil and gas, and have been developed by country and by subfuel type. Four countries (China, USA, Canada and Australia) were examined in detail with projections made at the state/province level. Over 900 different regions and subfuel situations were modelled using GeRS-DeMo and feature three URR scenarios of Low (48,409 EJ), High (121,488 EJ) and Best Guess (75,676 EJ).

All three scenarios indicate that the consistent strong growth in world fossil fuel production is likely to cease after 2025. The Low and Best Guess scenarios are projected to peak before 2025 and decline thereafter. The High scenario is anticipated to have a strong growth to 2025 before stagnating in production for 50 years and thereafter declining. The reason for the projected lack of growth in fossil fuel production after 2025 is due to Chinese coal production peaking. In the Low and BG scenarios other major coal producing countries such as Australia and USA or unconventional oil and gas production are projected to be unable to mitigate the Chinese coal declines. The High scenario is forecast to maintain a high production level by a combination of increased production from natural gas and stable production from oil. Of all the fossil fuels only natural gas is anticipated to have strong growth in production in the future. In order to ensure that the world can continue to steadily increase energy consumption without a significant disruption to energy supplies post 2025, alternative forms of energy need to be sourced. Further, the projections have been compared to IPCC's scenarios, which indicate that the A1Fl intensive fossil fuel production and RCP8.5 scenarios are unlikely to eventuate given the current fossil fuel availability. A plausible upper limit on fossil fuel emissions would be the medium emissions (A1 AIM and RCP6.0) with a BG future emissions corresponding to low emissions scenarios (B1 IMAGE and RCP4.5).

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Appendix A. Supplementary material

The electronic supplement contains the inputs, model and outputs of the models. A set of comprehensive reports showing the results of the scenarios by country, fuel type as well as the associated CO_2e emissions are also provided. The modelled results are also presented in excel files for ease of use. The collated production statistics used are also available in the electronic supplement. Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fuel.2014.10.030.

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