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Long term forecasting of natural gas production

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ABSTRACT

Natural gas is an important energy source for power generation, a chemical feedstock and residential usage. It is important to analyse the future production of conventional and unconventional natural gas. Analysis of the literature determined conventional URR estimates of 10,700–18,300 EJ, and the unconventional gas URR estimates were determined to be 4250–11,000 EJ. Six scenarios were assumed, with three static where demand and supply do not interact and three dynamic where it does. The projections indicate that world natural gas production will peak between 2025 and 2066 at 140–217 EJ/y (133–206 tcf/y). Natural gas resources are more abundant than some of the literature indicates.
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1. Introduction

Natural gas is a flammable gas consisting predominately of methane found naturally in basins around the world. There are two main categories of natural gas namely, conventional and unconventional natural gas. Unconventional natural gas includes, coal bed methane, shale gas, tight gas, aquifer gas, biogenic and methane hydrates. In particular, coal bed methane is natural gas produced from coal seams (Energy Information Administration, 2010), likewise aquifer gas is from water aquifers (Doherty), tight gas is natural gas trapped in sandstone formations with a permeability of <0.1 mD (Fletcher, 2005), shale gas is a poorly defined term referring to a gas that is from an organically rich and fine grained deposit (Rokosh et al., 2009), biogenic gas is natural gas generated at a shallow depth from the degradation of organic material (Campbell and Heaps, 2009), finally, methane hydrates are natural gas trapped in ice crystals (Collett, 2001). Conventional natural gas is considered to be natural gas sourced from rocks that is not one of the previously mentioned unconventional natural gases. Natural gas does not include man-made synthetic gases (such as syngas) or a predominately methane gas produced from landfill sites or manure or decomposing vegetation.

Natural gas is widely used around the world for a variety of applications including: power generation, chemical industry feedstock, transportation and for residential use. Production in 2008 was ~ 113 EJ/y (~ 108 tcf/y) (EIA International Energy Statistics, 2011; BP Statistical review of world energy, 2010) and consumption is expected to increase to 164 EJ/y (156 tcf/y) in 2035 (EIA, 2010). Is this future consumption possible?

The importance of natural gas has resulted in eight long term projections of future natural gas production in the literature. Table A.1 has the forecasted peak year and rate of production along with the year the estimate was made. Table A.1 also shows the Ultimately Recoverable Resources[1] (URR) values used in the projections. First the projection by Edwards (1997) estimated that natural gas production would peak at 115 EJ/y in 2040, this projection is no longer valid due to the production currently at the forecasted peak production rate. With the exception of Zhang et al. (2010) all of the remaining projections forecast natural gas will peak at or before 2021 (Campbell and Heaps, 2009; Al-Jarri and Startzman, 1997; Al-Fattah and Startzman, 2000; Imam et al., 2004; Guseo, 2006; Laherrère, 2007). The projection by Zhang et al. (2010) forecasts a peak in 2030–2035. The importance of natural gas, and the considerable amount of effort, time and money needed to replace natural gas with alternative means that it is critical to determine whether natural gas will peak in less than a decade or around 2030–2035 (or a different date altogether).

The aim of this study is to determine when and at what rate natural gas production will peak. To achieve this first, a review of natural gas projections in the literature will be presented. Next, URR values for both conventional and unconventional natural gas will be estimated, by low, BG and high values. Next the model used to create the natural gas projections will be described. Finally the natural gas projection will be presented and compared with literature studies and possible future implications will be discussed.

2. Natural gas projections

Conventional natural gas production for the world has been projected to peak between 2008 and 2040 (Campbell and Heaps,

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[1] Defined as the sum of all historic and future production.

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2009; Edwards, 1997; Al-Jarri and Startzman, 1997; Al-Fattah and Startzman, 2000; Imam et al., 2004; Guseo, 2006; Laherrère, 2007). The studies used Hubbert curves (Al-Jarri and Startzman, 1997; Al-Fattah and Startzman, 2000; Imam et al., 2004; Laherrère, 2007), Generalised Bass model (Guseo, 2006), constant decline rate (Campbell and Heaps, 2009) and unknown method were believed to be a Hubbert curve (Edwards, 1997). Edwards (1997) modelled world conventional gas production and assumed a URR of 12,200 EJ and a peak date of 2040 at $\sim$115 EJ/y. Al-Jarri and Startzman (1997) also modelled world conventional production and used a URR of 7400 EJ and a peak date of 2011 at 108 EJ/y. Al-Fattah and Startzman (2000) and Imam et al. (2004) modelled conventional natural gas production by country and estimated a peak of 2014–2017 at 104 EJ/y with a URR of 10,560 EJ and a peak of 2019 at 93EJ/y with a URR of 9680 EJ respectively. Guseo (2006) modelled conventional world gas production by assuming a URR of 7700 EJ determined a peak in 2008–2014 at $\sim$105 EJ/y. Laherrère (2007) estimated a URR of 10,500 EJ and projected a peak date of 2020 at 140 EJ/y. Campbell and Heaps (2009) modelled natural gas production by country and determined the peak in 2021 at 113 EJ/y. Recently, Zhang et al. (2010) modelled world natural gas production and used multicycle Hubbert curves to show it would peak in 2030–2035 at $\sim$137 EJ/y ($\sim$130 tcf/y) (Zhang et al., 2010). Table A.1 summarises the conventional natural gas literature.

World unconventional gas production for the world has only been examined in the literature by Campbell and Heaps (2009) and Laherrère (2006). In particular, Campbell and Heaps (2009) projected unconventional gas as well as methane hydrates and biogenic gas and estimated a production to plateau in 2030 at 15 EJ/y. Laherrère (2006) projected unconventional gas (including aquifer gas and methane hydrates) to peak around 2057 at $\sim$26 EJ/y.

3. Literature ultimately recoverable resources estimates

3.1. Conventional natural gas URR

The literature indicated that world conventional natural gas has a URR of 7400–17,660 EJ, as shown in Tables A.1 and A.2. In addition, WEC 2010 estimate that the proved recoverable resources are 6880 EJ which if combined with cumulative production of 2860 EJ create a URR estimate of 9740 EJ. Three scenarios where chosen, which were similar to the estimate in Mohr (2010). The only difference from the previous estimate was that a newer version of the BGR report (Rempel et al., 2009) was used here. In particular, the Low scenario assumed estimates in general from Campbell and Heaps (2009) and Laherrère (2006). In places the estimate is from Rempel et al. (2009) due to insufficient information. The low URR estimate was 10,700 EJ (10,200 tcf), which is very similar to some of the lower URR estimates in the literature (Campbell and Heaps, 2009; Al-Fattah and Startzman, 2000; Laherrère, 2007). The high scenario assumed the estimate from Rempel et al. (2009), which is the highest known URR estimate in the literature, with cumulative production added for countries that have ceased producing natural gas. The only change comes to the estimate for USA, it is indicated that the USA URR estimate by the BGR contains significant amounts of unconventional gas in it as well (Mohr and Evans, 2010). For this reason, a lower URR estimate for the USA is selected instead of the BGR estimate. Finally the Best Guess (BG) scenario assumes the authors best estimate, and the source of the estimate for countries with $>$50 EJ is explained in Table A.3. The BG URR estimate assumed a URR of 12,900 EJ (12,300 tcf) and is similar to the estimate by Edwards (1997).

3.2. Unconventional natural gas URR

The unconventional natural gas URR estimates are arranged by type. First coalbed methane is described, next shale gas and finally tight gas.

3.2.1. Coalbed methane

Kuuskra and Stevens (2009) have recently estimated that the coalbed methane URR for the world by country is 870 EJ (830 tcf) (Kuuskra and Stevens, 2009). Literature typically reports coalbed methane resources instead of URR values and a summary of these resource estimates are shown in Tables A.4 and A.5. As shown in these tables, the estimates for coal resources vary significantly from 3100 to 25,200 EJ, however, if Scott and Balin (2004) high estimate is ignored then the range becomes 3100–13,900 EJ. In this article it is assumed that the high estimate from Scott and Balin is an outlier.

Due to the large range in the resource estimates three URR values will be used to in a bid to cover the large range. First, the low scenario assumes the 870 EJ URR estimate from Kuuskra and Stevens (2009), low is believed to represent an adequate minimum coalbed methane resource estimate. Next, the high URR estimate assumes Cramer et al. (2009) low resource estimate of 5070 EJ is completely recoverable. This should be viewed as an optimistic assumption as typical recovery fractions for coalbed methane range from 20% to 33% (DPI, 2005; Soot, 1991; Stringham, 2007). Finally, the BG assumed a URR of 2533 EJ and was justified in Table A.6.

3.2.2. Shale gas

Shale gas resources have been estimated for the world by region by Cramer et al. (2009) and Rogner (1997) as shown in Table A.7. The estimate by Cramer et al. was heavily influenced by the ground breaking work by Rogner. In North America, however, several studies have estimated the ultimately recoverable resources (e.g. Kuuskra and Stevens, 2009; Theal, 2009; FERC, 2010; Dawson, 2010; Henning, 2010; Skipper, 2010) as shown in Table A.8. In particular, Kuuskra and Stevens (2009) indicate that North American resources are 5400 EJ and the recoverable portion is 750 EJ, which indicates an overall recovery of around 15% of resources.

The URR was determined separately for North America and the rest of the world. The estimate for North America have been described in a previous paper (Mohr and Evans, 2010) and was based on the estimates from Kuuskra and Stevens (2009), Theal (2009), FERC (2010), Dawson (2010), Henning (2010), and Skipper (2010) as shown in Table A.9. For the rest of the world all three URR scenarios assumed, the resource estimate by Rogner (1997) was correct, and a 15% recovery was assumed as this is the approximate overall recovery of resources as indicated in North America by Kuuskraa and Stevens. As Rogner (1997) only has regions, the totals were split into various countries as explained in Table A.10. In the future, it is likely that the URR value assumed for the rest of the world will be considered too high or low. However, it is impossible to reduce the uncertainty due to the limited amount of literature on shale gas resources in the world.

3.2.3. Tight gas

Tight gas reserves have been estimated for the world by total to be between 740 and 1850 EJ, with the splits by region as shown in Table A.11 (http://www.total.com/static/en/medias/topic1026/tight-gas-reservoirs_2007.pdf). In addition worldwide tight gas resources have been determined to be approximately 8000 EJ (see Table A.12) (Cramer et al., 2009; Rogner, 1997). The low scenario assumed the low reserve estimate by Total, the BG assumed the

Table 1
Conventional natural gas URR in ZJ for the world by country.

CTY	Conventional			CBM			Shale			Tight			Total		
	L	BG	H	L	BG	H	L	BG	H	L	BG	H	L	BG	H
DZA	0.23	0.23	0.29							0.01	0.01	0.04	0.24	0.24	0.33
NGA	0.26	0.26	0.33									0.12	0.98	0.26	0.46
Rest	0.38	0.42	0.44	0.03	0.01	0.01	0.25	0.25	0.25			0.04	0.66	0.68	0.74
AF	**0.87**	**0.92**	**1.06**	**0.03**	**0.01**	**0.01**	**0.25**	**0.25**	**0.25**	**0.01**	**0.02**	**0.21**	**1.16**	**1.19**	**1.52**
AUS	0.23	0.20	0.20	0.13	0.23	0.30	0.37	0.37	0.37	0.08	0.20	0.11	0.81	1.00	0.98
CHN	0.21	0.21	0.51	0.11	0.32	1.26	0.57	0.57	0.57	0.16	0.41	0.06	1.05	1.50	2.39
IDN	0.24	0.30	0.30	0.05	0.01	0.35				0.01	0.02	0.09	0.30	0.33	0.74
Rest	0.53	0.63	0.65	0.02	0.02	0.02	0.05	0.05	0.05			0.03	0.6	0.70	0.75
AS	**1.21**	**1.34**	**1.66**	**0.31**	**0.57**	**1.93**	**0.99**	**0.99**	**0.99**	**0.25**	**0.63**	**0.29**	**2.76**	**3.54**	**4.86**
NOR	0.16	0.27	0.31										0.16	0.27	0.31
Rest	0.54	0.65	0.73	0.04	0.11	0.25	0.09	0.09	0.09			0.06	0.66	0.85	1.12
EU	**0.70**	**0.92**	**1.04**	**0.04**	**0.11**	**0.25**	**0.09**	**0.09**	**0.09**			**0.06**	**0.82**	**1.11**	**1.43**
FSU	**2.31**	**3.45**	**7.62**	**0.25**	**1.45**	**2.00**	**0.10**	**0.10**	**0.10**	**0.09**	**0.22**	**0.16**	**2.75**	**5.22**	**9.88**
IRN	1.21	1.50	1.50										1.21	1.50	1.50
QAT	1.13	1.13	1.05										1.13	1.13	1.05
SAU	0.48	0.48	0.73							0.05	0.13	0.04	0.53	0.61	0.77
ARE	0.18	0.31	0.31										0.18	0.31	0.31
Rest	0.33	0.50	0.52				0.21	0.21	0.21				0.54	0.70	0.73
ME	**3.33**	**3.93**	**4.12**				**0.21**	**0.21**	**0.21**	**0.05**	**0.13**	**0.04**	**3.59**	**4.26**	**4.36**
CAN	0.33	0.33	0.64	0.10	0.18	0.79	0.10	0.43	0.68	0.15	0.21	0.33	0.67	1.15	2.43
USA	1.31	1.31	1.31	0.15	0.17	0.21	0.33	0.62	1.26	0.43	0.49	0.66	2.22	2.60	3.44
NA	**1.63**	**1.63**	**2.75**	**0.24**	**0.35**	**1.00**	**0.43**	**1.05**	**1.93**	**0.58**	**0.70**	**0.98**	**2.87**	**3.73**	**6.67**
BRA	0.02	0.02	0.10				0.34	0.34	0.34				0.36	0.36	0.44
VEN	0.24	0.24	0.33									0.07	0.24	0.24	0.40
Rest	0.08	0.09	0.10	0.01	–	0.01							0.08	0.09	0.10
SA	**0.65**	**0.73**	**0.89**	**0.01**	–	**0.01**	**0.34**	**0.34**	**0.34**	**0.01**	**0.02**	**0.21**	**1.00**	**1.09**	**1.45**
Tot.	**10.71**	**12.92**	**18.32**	**0.87**	**2.49**	**5.18**	**2.40**	**3.02**	**3.91**	**0.98**	**1.72**	**1.94**	**14.96**	**20.15**	**29.35**

high reserve estimate of Total and the high scenario assumed that resource estimates by Cramer et al. and Rogner, and assumed a 15% recovery. The URR estimates used for the three scenarios are shown in Table A.13.

3.2.4. *Other sources*

Due to the limited and/or contradictory information on the resource size of other unconventional sources of natural gas, this article will examine only coalbed methane, shale gas and tight gas unconventional sources. It is reasonable to assume that in the future, production from methane hydrates and other unconventional sources may occur. It is likely that these resources will take a decade or more to be exploited.

3.3. *URR summary*

A summary of the URR values selected is shown in Table 1.

4. Model analysis

The demand–production interaction model is described in Mohr (2010). Briefly, a URR is assumed for a given country,[2] with production capability based on historical production for North Sea gas production. Production is further influenced by demand interactions.

4.1. *Production*

Production of natural gas is determined from individual countries. Countries generally contain one or more natural gas basin, e.g. Carnarvon basin in Western Australia and the Bass Strait for Australia. These basins contain individual fields where natural gas is extracted. In order to project the production for a country, it is necessary to determine the production from basins and fields. The production of natural gas for the world, is determined as the sum of all the fields' productions in a basin, for all the basins in a country, and for all the countries in the world.

4.1.1. *Basins*

First, the total number of basins n_{R_T} is inputted into the model, and the number of basin that have been placed on-line $n_R(t)$ is determined by the square root of the cumulative production. Mathematically this is

$$n_R(t) = \left\lceil \sqrt{\frac{Q(t)}{Q_T}} \right\rceil \tag{1}$$

where $Q(t)$ is the cumulative production of the country and Q_T is the URR of the country. At the start year it is assumed that one region is on-line. The URR of the i-th basin, $Q_{R_{T_i}}$, is calculated by:

$$Q_{R_{T_i}} = Q_\varepsilon(i) - Q_\varepsilon(i-1) \tag{2}$$

where $Q_\varepsilon(i)$ is defined as:

$$Q_\varepsilon = Q_T \frac{1-e^{(-r_\varepsilon (i/n_{R_T})^2)}}{1-e^{(-r\varepsilon)}} \tag{3}$$

where r_ε is a rate constant. This profile ensures that the size of the first basins is small, the middle[3] basins is large and finally the last basins is small. The equations developed were justified by examining North American oil production by states (Mohr,

[2] Which has a number of basins and fields.

[3] I.e. ones around $n_{R_T}/2$.

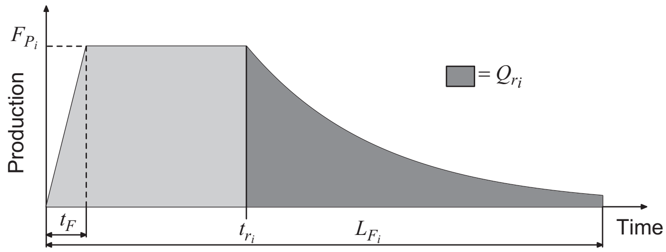

Fig. 1. Field profile assumed in the model (Mohr, 2010).

2010). With the size and start year of the basin known the production for the basin is determined from these inputs as described below.

4.2. Fields

The production of a basin is determined from the production of individual fields in the basin. The number of fields on-line, URR of the fields and the production profile of the fields need to be determined in order to calculate the production of the basin.

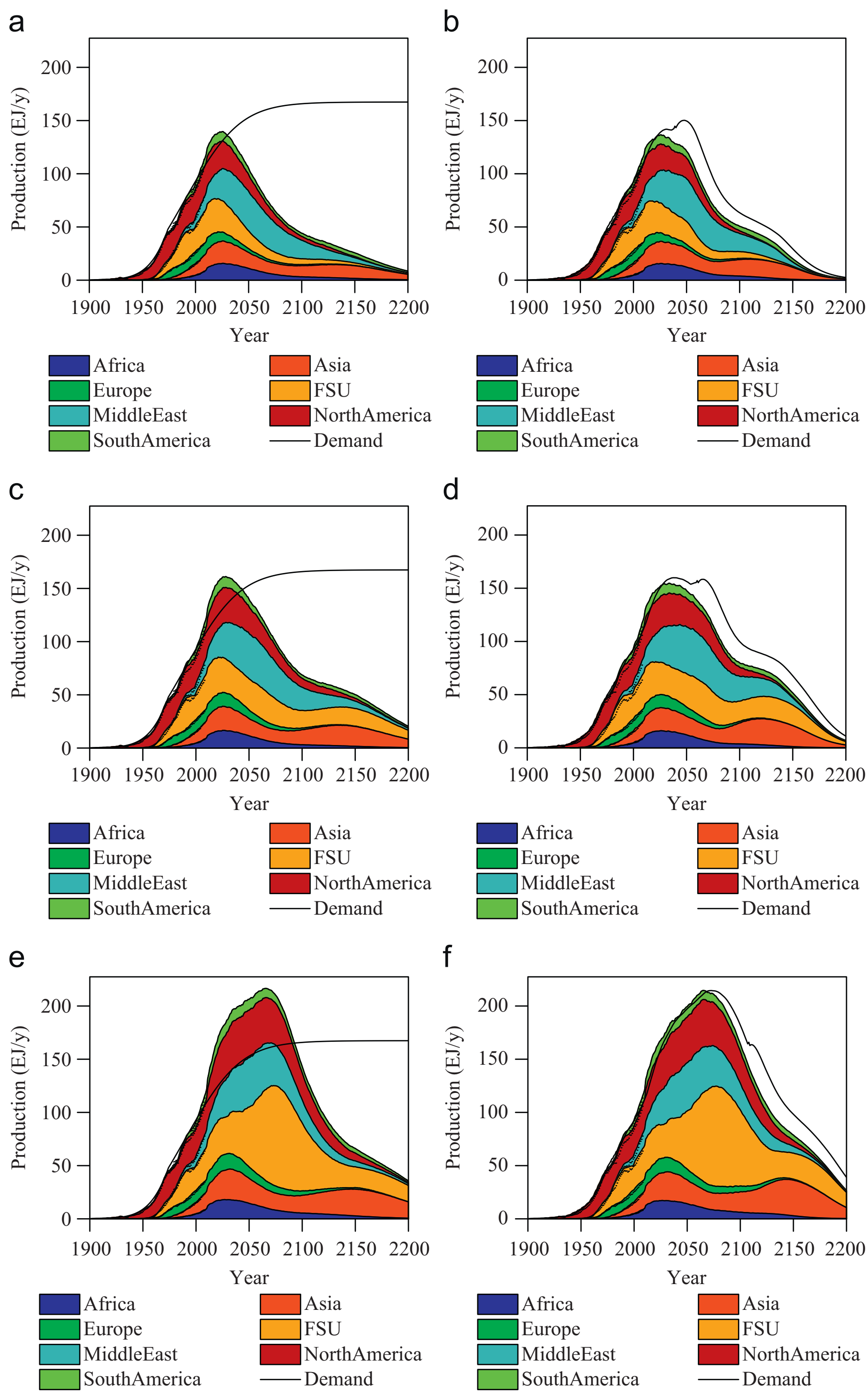

Fig. 2. Natural gas projections for the world by continent. (a) Static low, (b) dynamic low, (c) Static BG, (d) dynamic BG, (e) static high, and (f) dynamic high.

The number of fields on-line $n_F(t)$ was assumed to be proportional to the cumulative production of the basin $Q_R(t)$, that is:

$$n_F(t) = \left\lceil r_F n_{F_T} \frac{Q_R(t)}{Q_{R_T}} \right\rceil \quad (4)$$

where r_F is a rate constant, n_{F_T} is the total number of fields in the basin and Q_{R_T} is the URR of the basin.

The URR of fields in a basin varies, hence the model has to change the size of the fields. The URR of a new field determined by assuming the cumulative discovery verses cumulative number of fields on-line follows a power law relationship that is:

$$\frac{Q_D(t)}{Q_{R_T}} = \left(\frac{n_F(t)}{n_{F_T}}\right)^{0.35} \quad (5)$$

where $Q_D(t)$ is the cumulative URR in the first $n_F(t)$ fields. If the i-th field is brought on-line in year Y_{F_i} then the URR of the i-th field Q_{T_i} is determined by:

$$Q_{T_i} = \frac{Q_D(Y_{F_i}) - Q_D(Y_{F_i}-1)}{n_F(Y_{F_i}) - n_F(Y_{F_i}-1)} \quad (6)$$

The production profile of the field is assumed, initially ramp up over 1 year to a maximum production level F_{P_i}, which is maintained until the year t_{r_i} is reached where after it exponentially declines until production reaches 1% of the maximum production level as shown in Fig. 1. The field profile can be expressed

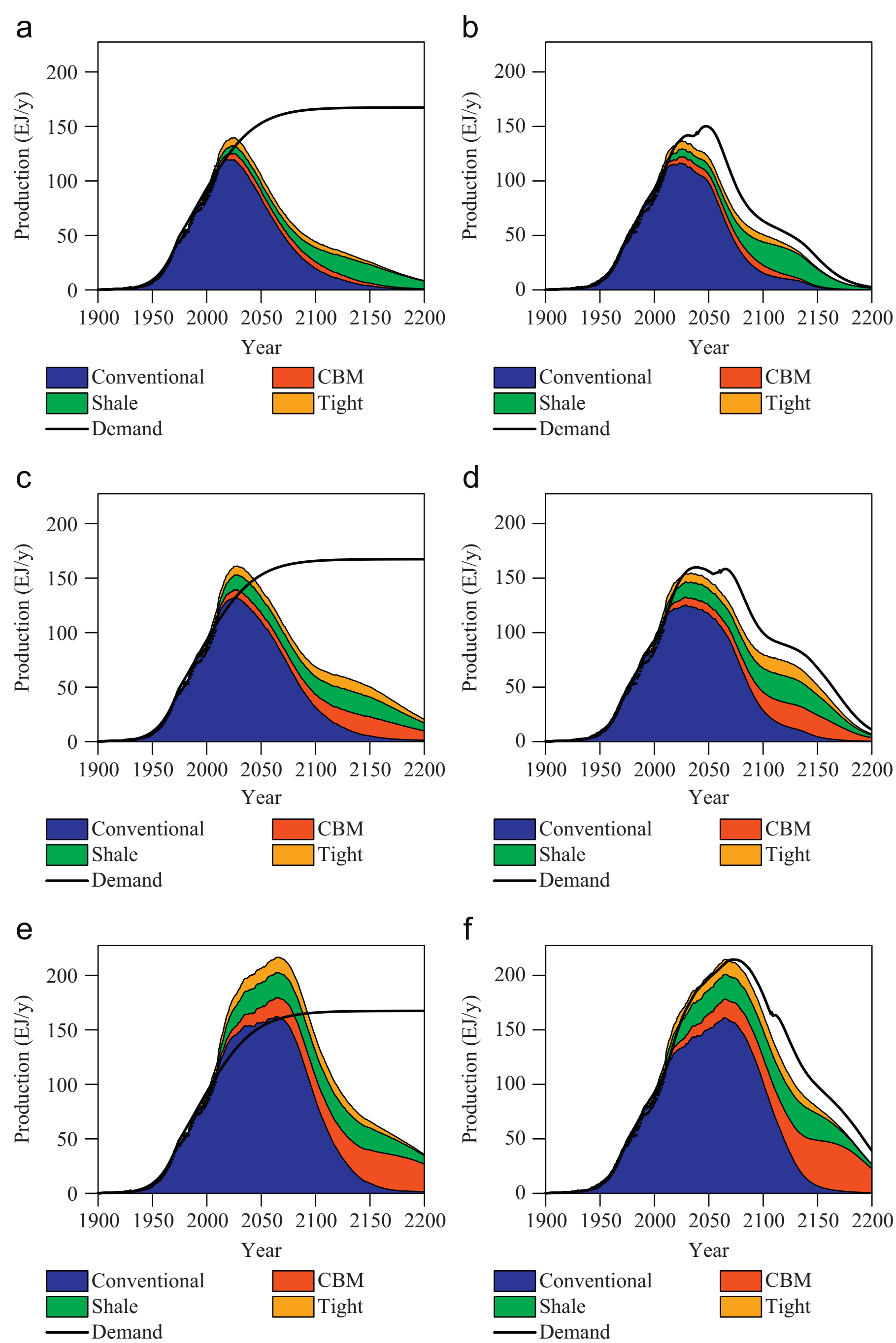

Fig. 3. Natural gas projections for the world by type. (a) static low, (b) dynamic low, (c) static BG, (d) dynamic BG, (e) static high, and (f) dynamic high.

mathematically as (Mohr, 2010):

$$P_{F_i}(t) = \begin{cases} 0 & \text{if } t < Y_{F_i} \\ \frac{F_{P_i}}{t_F}(t - Y_{F_i}) & \text{if } Y_{F_i} \le t < Y_{F_i} + t_F \\ F_{P_i} & \text{if } Y_{F_i} + t_F \le t < t_{r_i} \\ F_{P_i} e^{((-F_{P_i}(1-0.01)/Q_{r_i})(t - t_{r_i}))} & \text{if } t_{r_i} \le t \le t_{r_i} - \frac{\log(0.01)Q_{r_i}}{F_{P_i}(1-0.01)} \\ 0 & \text{if } t > t_{r_i} - \frac{\log(0.01)Q_{r_i}}{F_{P_i}(1-0.01)} \end{cases} \quad (7)$$

with t_{r_i} equal to:

$$t_{r_i} = \frac{Q_{T_i} - Q_{r_i}}{F_{P_i}} + \frac{t_F}{2} + Y_{F_i} \quad (8)$$

where Q_{r-i} is the URR remaining when production begins to decline. The maximum production, F_{P_i}, and URR remaining when production declines, Q_{r_i}, are assumed to be proportional to the URR of the field.

The justification for these equations was based on analysis of the UK North Sea oil and gas statistics (Mohr, 2010). The equations above can be used to replicate the production from an oil or gas region (e.g. the UK component of the North Sea).

4.3. Demand

The demand can be determined in two ways dynamic and static. The static demand is dependent on time only, whereas the dynamic demand is a modification of the static demand where constraints on natural gas production also influence the demand. The simpler static demand is described here, and the dynamic demand is described in Appendix.

The static demand for natural gas $D_G(t)$ is defined as:

$$D_G(t) = f_G(t)\tilde{D}(t)p(t) \quad (9)$$

where $p(t)$ is the world population, $\tilde{D}(t)$ is the per capita demand for fossil fuels and $f_G(t)$ is the natural gas fraction of fossil fuel demand. The population projection adopted in this study is the same as that used previously (Mohr, 2010), i.e.

$$p(t) = \frac{(10-0.82)\times 10^9}{[1+e^{(-0.046(t-2015.8))}]^{1/2}} + 0.82\times 10^9 \quad (10)$$

The per capita demand projection used was identical to that in Mohr's (2010) thesis namely:

$$\tilde{D}(t) = \begin{cases} 62e^{(0.02502(t-1974))} & \text{if } t < 1974 \\ 62 & \text{if } t \ge 1974 \end{cases} \quad (11)$$

Table 2
Natural gas peak years for the static scenarios.

Type	Peak year			Max production		
	Low	BG	High	Low	BG	High
Africa	2026	2026	2027	15.8	16.6	18.1
Asia	2025	2025	2034	21.1	22.7	29.0
Europe	2004	2026	2028	11.6	13.0	15.0
FSU	2015	2016	2077	32.6	35.6	94.4
Middle East	2049	2049	2052	37.7	43.1	46.9
North America	2016	2023	2046	28.7	34.0	45.1
South America	2021	2022	2024	9.3	10.7	11.6
Total	2025	2028	2066	139.6	161.2	216.6
Conventional	2019	2025	2066	119.6	132.4	162.2
CBM	2040	2141	2166	7.0	17.8	32.5
Shale	2136	2134	2117	18.0	19.5	23.5
Tight	2031	2128	2080	7.5	10.8	14.6
Total	2025	2028	2066	139.6	161.2	216.6

Finally, the natural gas fraction of demand was determined previously (Mohr, 2010) to be:

$$f_G(t) = 0.135\tanh(0.03(t-1960)) + 0.135 \quad (12)$$

5. Results and discussion

The model projections are shown in Figs. 2 and 3, and Tables 2 and 3 summarise the peak years and rates. The projections for each country and continents are presented in Supplementary material.

Table 3
Natural gas peak years for the dynamic scenarios.

Type	Peak year			Max production		
	Low	BG	High	Low	BG	High
Africa	2026	2026	2027	15.7	16.1	17.2
Asia	2026	2123	2150	20.8	24.6	33.8
Europe	2004	2027	2028	11.8	12.4	13.9
FSU	2013	2013	2077	32.2	34.6	93.3
Middle East	2049	2056	2052	40.4	44.6	45.8
North America	2010	2018	2064	27.1	31.0	44.8
South America	2021	2023	2024	9.1	10.2	11.0
Total	2026	2034	2065	136.7	154.7	214.6
Conventional	2023	2029	2065	116.4	125.5	161.0
CBM	2077	2130	2159	8.5	22.1	43.8
Shale	2117	2121	2133	24.3	24.3	28.1
Tight	2078	2113	2095	7.7	13.9	15.2
Total	2026	2034	2065	136.7	154.7	214.6

Table A.1
Conventional natural gas production peak year and rate estimates.

Reference	Year	URR (EJ)	Peak year	Peak prod. (EJ/y)
Edwards (1997)	1997	12,200	2040	115
Al-Jarri and Startzman (1997)	1997	7400	2011	108
Al-Fattah and Startzman (2000)	2000	10,560	2014–2017	104
Imam et al. (2004)	2004	9680	2019	93
Guseo (2006)	2006	7700	2008–2014	105
Laherrère (2007)	2007	10,500	2020	140
Campbell and Heaps (2009)	2009	10,130	2021	113
Zhang et al. (2010)	2010	Unknown	2030–2035	~137

Table A.2
Literature conventional natural gas URR estimates in EJ for the world by region (Mohr, 2010).

Region	Al-Fattah and Startzman (2000)	Rempel et al. (2009)	Campbell and Heaps (2009)	IEA (2009)	Imam et al. (2004)	Laherrère (2006)
Africa	500	1062	673	1112	474	840
Asia	840	1656	1048	1260	779	1208
Europe	588[a]	1036	649	1000[a]	563	840
FSU	3570[b]	7624	2210	5634[b]	3071	2000
Middle East	2625	4116	3318	5004	2437	3000
North America	1995	2752	1601	2372	1652	1575
South America	441	893	630	927	702	840
World	**10,560**	**19,140**	**10,130**	**17,310**	**9680**	**10,550**

[a] Western Europe.
[b] Eastern Europe + FSU.

Table A.3
Conventional natural gas URR in EJ for the world by country.

Country	Low	BG	High	Country	Low	BG	High
Algeria	231[C]	231[C]	290[B]	**Europe**	**697**	**917**	**1036**
Angola	53[L]	55[B]	55[B]	**FSU**	**2310**[L]	**3449**[M]	**7624**[B]
Egypt	105[L]	135[B]	135[B]	Iran	1208[C]	1503[B]	1503[B]
Libya	105[L]	105[L]	88[B]	Iraq	131[C]	270[B]	270[B]
Nigeria	263[L]	263[L]	334[B]	Kuwait	74[C]	74[C]	94[B]
Rest	117[C,L,B]	126[C,L,B]	161[B]	Oman	63[C]	63[C]	74[B]
Africa	**873**	**915**	**1062**	Qatar	1134[C]	1134[C]	1051[B]
Australia	231[C]	196[B]	196[B]	Saudi Arabia	478[C]	478[C]	725[B]
Bangladesh	55[B]	52[H]	55[B]	UAE	179[C]	314[B]	314[B]
Burma	52[B]	52[B]	52[B]	Rest	63[C,B]	90[C,B]	86[B]
China	210[C]	210[C]	507[B]	**Middle E.**	**3330**	**3926**	**4116**
India	79[C]	89[B]	89[B]	Canada	333[H]	333[H]	637[B]
Indonesia	242[C]	301[B]	301[B]	USA	1313[J]	1313[J]	1313[J]
Malaysia	116[C]	173[B]	173[B]	**North America**	**1628**	**1628**	**2752**
Pakistan	68[C]	85[B]	85[B]	Argentina	79[C]	106[B]	106[B]
Rest	162[C,B]	184[H,C,B]	251[B]	Bolivia	68[C]	58[B]	58[B]
Asia	**1214**	**1341**	**1656**	Brazil	21[C]	21[C]	95[B]
Germany	50[C]	48[B]	48[B]	Mexico	105[C]	142[B]	142[B]
Greenland	0	104[B]	104[B]	Trinidad	53[C]	65[B]	65[B]
Netherlands	173[C]	173[C]	171[B]	Venezuela	242[C]	242[C]	326[B]
Norway	158[C]	265[H]	311[B]	Rest	78[C,B]	85[C,B]	102[B]
Romania	58[C]	60[H]	84[B]	**South America**	**645**	**729**	**893**
UK	131[C]	131[C]	153[B]	**World**	**10,708**	**12,915**	**18,321**
Rest	126[P,C,B]	136[P,H,B,C]	166[P,B]				

H=Hubbert linearisation, P=Cumulative production, B=Rempel et al. (2009), M=Mohr and Evans (2007), L=Laherrère (2009), C=Campbell and Heaps (2009), J=Laherrère (2004).

Table A.4
Coalbed methane resources in EJ for the world by continent (Mohr, 2010).

Continent	Region	Scott and Balin (2004)	Rogner (1997)
Africa		28–58	42[a]
Asia	Australia[b]		504
	North[c]	678–3528[d]	1302
	Subcontinent[e]		42
Europe	Eastern Europe		126
	Western Europe	169–282	168
FSU		4200–16,922	4242
North America		999–4602	3,234
South America		16–34	42
World		**6300–25,200**	**9702**

[a] Sub-Saharan Africa.
[b] Australia and Japan; Japanese resources are believed to be very small relative to Australian resources.
[c] Vietnam to Mongolia.
[d] All of Asia.
[e] Afghanistan to Bangladesh.

Table A.5
Coalbed methane resources in EJ for the world by country (Mohr, 2010).

Country	Campbell and Heaps (2009)	Aluko (2001)	Boyer and Qinghao (1998)	Cramer et al. (2009)	Kuuskra and Stevens (2009)
South Africa		37	32[a]	5–32	95–231[b]
Australia	525	297–519	315–525	297–593	525–1050[c]
China	1050	1112–2039	1113–1302	1260–1364	735–1334
India		37	32	15–74	74–95
Indonesia		< 37		354–476	357–473
Germany		111	105	19–111	
Poland		111	105	13–115	21–53
UK		93	63	63–107	210[d]
Turkey					53–116
Russia	4200	741–4300[e]	630–4200	1887–2928	473–2100
Kazakhstan			42	44–63	42–63
Ukraine			63	63–2835	179
Canada	3150	222–2817	210–2835	691–3204	378–483
USA	525	408	360–435	199–1809	525–1575
Other			32	161–177	53
World	**9450**	**3169–10,508**	**3101–9769**	**5070–13,889**	**3717–8012**

[a] Southern Africa.
[b] Southern Africa, includes carbonaceous shales.
[c] Includes New Zealand.
[d] Western Europe.
[e] FSU.

The static projections indicate that total natural gas production for the world will peak between 2025 and 2066 with a peak rate of 139.6–216.6 EJ/y (133–206 tcf/y). The static Cases 1 and 2 scenarios have a sharp peak with no continent dominating the production of natural gas. For the static Case 3 scenario the FSU, Middle East and North America dominate the future supply of natural gas and the production remains in a broad plateau of above 200 EJ/y for ~40 years (2041–2080). The dynamic projections indicate a similar peak rate and year with the peak estimated at 2026–2065 at 136.7–214.6 EJ/y (130–204 tcf/y). However, the peak shapes are reversed with dynamic Cases 1 and 2 scenarios showing a broad plateau and Dynamic Case 3 having a sharp peak.

The projections presented only partially confirm previous literature results. First, the projections (Al-Jarri and Startzman, 1997; Al-Fattah and Startzman, 2000; Guseo, 2006) that highlighted a conventional peak of 2008–2017 at 104–108 EJ/y are not replicated in any of the scenarios. Although static Case 1 peaks in 2019 the same as Imam et al. (2004), Imam et al. projection estimates a peak rate of 93 EJ/y which is approximately ~ 28 EJ/y lower than the static Case 1 scenario. Both the static and dynamic Case 1 scenarios, which indicate a peak in 2019 and 2023 at 120 and 116 EJ/y respectively agree well with the projection by Campbell and Heaps (2009) who estimated a peak in 2021 at 113 EJ/y. This result is unsurprising given that the URR values assumed for Case1 were based on Campbell and Heaps (2009) estimate, but does to an extent validate the empirical modelling technique employed by Campbell and Heaps. Finally static Case 2 projection of a peak in 2025 at 132.4 EJ/y is reasonably similar to that of Zhang et al. (2010) and Laherrère (2007) who estimated a peak in 2030–2035 and 2020 at 137 and 140 EJ/y respectively.

Table A.6
Coalbed methane URR in EJ for the world by country.

Country	Low	BG	High	Comments on BG
South Africa	32[a]	9	5	Resource from Aluko (2001) with 25% recovery
Africa	**32**	**9**	**5**	
Australia	126[b]	231	297	URR from Brown (2008)
China	105	315	1261	Low resource of Cramer et al. (2009) with 25% recovery
India	21	19	15	High resource of Cramer et al. (2009) with 25% recovery
Indonesia	53	9	354	Resource from Aluko (2001) with 25% recovery
Mongolia		0	1	Low resource from Cramer et al. (2009) with 25% recovery
Asia	**305**	**574**	**1928**	
Bulgaria		2	6	Resource from Cramer et al. (2009) with 25% recovery
Czech Republic		3	2	High resource of Cramer et al. (2009) with 25% recovery
Germany		26	19	Resource from Boyer and Qinghao (1998) with 25% recovery
Hungary		1	6	High resource of Cramer et al. (2009) with 25% recovery
Netherlands		7	30	Resource from Cramer et al. (2009) with 25% recovery
Poland	5	26	13	Resource from Boyer and Qinghao (1998) with 25% recovery
Turkey	11	28	111	Resource from Boyer and Qinghao (1998) with 25% recovery
UK	21[c]	16	63	Resource from Boyer and Qinghao (1998) with 25% recovery
Europe	**37**	**109**	**250**	
Kazakhstan	11	11	45	Resource from Boyer and Qinghao (1998) with 25% recovery
Russia	210	732	1887	High estimate of Cramer et al. (2009) with 25% recovery
Ukraine	26	709	63	High estimate of Cramer et al. (2009) with 25% recovery
FSU	**247**	**1452**	**1995**	
Canada	95	175	788[d]	URR from Stringham (2007)
USA	147	171	210[e]	URR from Mohr and Evans (2010)
North America	**242**	**346**	**998**	
Mexico	11[f]	2	5	High resource of Cramer et al. (2009) with 25% recovery
South America	**11**	**2**	**5**	
World	**872**	**2494**	**5178**	

[a] All of Southern African URR was assumed to be in South Africa.
[b] All of Australia and New Zealand URR was assumed to be in Australia.
[c] All of Western Europe URR was assumed to be in the UK.
[d] Assumed Campbell and Heaps (2009) estimate with 25% recovery.
[e] Produced and proved reserves from Benneche (2007) probable to speculative resources from Curtis (2009).
[f] All of South America and Mexico's URR were assumed to be in Mexico.

Table A.7
Shale gas resources in EJ for the world by region.

Region	Rogner (1997)	Cramer et al. (2009)
Sub-Saharan Africa	294	289
Australia[a]	2478	2429
North Asia[b]	3780	3704
South East Asia[c]	336	330
Eastern Europe	42	41
Western Europe	546	534
FSU	672	660
Middle East and North Africa	2730	2677
North America	4116	4034
South America[d]	2268	2225
World	**17,262**	**16,923**

[a] Australia and Japan; Japan believed to have little resources.
[b] Vietnam to Mongolia.
[c] Burma to PNG.
[d] Includes Mexico.

No literature estimate could be found that indicated that conventional natural gas production could peak around 2065, despite the static and dynamic Case 3 scenarios highlight that this is probable if the URR estimate from the well respected BGR institute is correct.

The demand assumed here is for the world, which requires large deposits of natural gas do not become stranded. It is possible that future bottlenecks may occur if adequate LNG shipping terminal and natural gas pipelines are not built. In particular, infrastructure such as the Turkey to Austria pipeline is necessary to ensure that Middle East natural gas production continues to grow and to provide Europe with a secure source of natural gas should Russia and Former Soviet Union countries continue to have disagreements over the price of natural gas.

The North American market is an important gas region due to the current shale boom, and will be discussed. The shale gas production in North America is projected to underpin most of the future growth to North American gas production. Canada is currently dependent on natural gas to exploit its natural bitumen resources.[4] It is projected that natural gas production will peak sometime between 2010 and 2064, at 27.1–44.8 EJ/y with the Case 2 projections indicating a peak in 2018 and 2023 at 31 and 34 EJ/J respectively. It is unlikely that South America will be able to export much natural gas, so it is important that Canada and USA users and governments manage the long term use of natural gas.

6. Conclusion

The ultimately recoverable resources for conventional and unconventional natural gas for each country were determined. The URR was determined to be 10,700–18,300 EJ for conventional sources and 4250–11,000 EJ for unconventional sources (coalbed methane, tight and shale gas). The conventional natural gas resources are dominated by Iran, Qatar, FSU and USA with considerable contributions from other nations. A demand–production model (Mohr, 2010) was used to create six natural gas projections, static projections have no production and demand interactions and dynamic projections have interactions.

[4] In the long term it would make sense to gasify mined natural bitumen to create a synthetic gas to extract the larger in situ resources.

Table A.8
Shale gas recoverable resources for North America EJ (Mohr and Evans, 2010).

Field	Theal (2009)		FERC (2010)		Dawson (2010)		Henning (2010)	Skipper (2010)	Kuuskra and Stevens (2009)[c]
	U^a	R^b	2006	2008	Low	High			
USA									
Marcellus	58	213	36	275			275	273	210
Haynesville	77	205	36	264			265	263	138
Fayetteville	36	58	27	44			44	45	56
Barnett	33	53	65	102			46	46	62
Woodford	14	26	13	18			12	16	34
Antrim			14	21			21		
Southwest Wyoming			36	56					
Deep Bossier	7	27							
New Albany							20		
Other								525	
Total	225	582	226	779	0	0	683	1168	499
Canada									
Montney	24	77			158	315			116
Muskwa	24	69			79	179			137
Horn River									
Utica	4	40			7	44			
Maritimes					12	51			
Cordova					32	71			
W.C.S.B.[d]					4	15			
Total	52	186			291	675		263–1050	252

[a] Unrisked.
[b] Risked.
[c] Kuuskraa and Stevens, URR values.
[d] Western Canada Sedimentary Basin.

Table A.9
Assumed shale gas URR estimates for North America EJ (Mohr and Evans, 2010).

Country	Basin	Low	BG	High
Canada	Montney	24	116	315
Canada	Muskwa/Horn River	24	137	179
Canada	Utica	4	40	44
Canada	Maritimes	12	51	51
Canada	Cordova	32	71	71
Canada	W.C.S.B.	4	15	15
USA	Marcellus	59	210	273
USA	Haynesville	77	138	263
USA	Fayetteville	36	56	58
USA	Barnett	38	62	107
USA	Woodford	14	34	34
USA	Other USA	104	124	525
North America		**425**	**1052**	**1934**

Table A.10
Shale gas URR in EJ for the rest of the world based on Rogner (1997) and a 15% recovery.

Country	Low	BG	High	Comments
Morocco	205	205	205	50% of Middle East and North Africa
Zaire	44	44	44	All Sub- Saharan Africa
Africa	**249**	**249**	**249**	
Australia	372	372	372	Assumed no resources in Japan
China	567	567	567	All of North Asia
Thailand	50	50	50	All of South East Asia
Asia	**989**	**989**	**989**	
Italy	82	82	82	All of Western Europe
Poland	6	6	6	All of Eastern Europe
Europe	**88**	**88**	**88**	
FSU	**101**	**101**	**101**	All of FSU
Jordan	205	205	205	50% of Middle East and North Africa
Middle East	**205**	**205**	**205**	
Brazil	340	340	340	Assumed all of South America
South America	**340**	**340**	**340**	
Rest of World	**1972**	**1972**	**1972**	
World	**2397**	**3024**	**3906**	By combining with Table A.9

Table A.11
Tight gas reserves by region (http://www.total.com/static/en/medias/topic1026/tight-gas-reservoirs_2007.pdf).

Region	Percentage (%)
USA+Canada	45
FSU	12
Middle East	7
China+Australia	33
Other	3

Table A.12
Tight gas in place in EJ for the world by regions (Mohr, 2010).

Region	Rogner (1997)	Cramer et al. (2009)
Sub-Saharan Africa	840	815
Australia[a]	756	741
North Asia[b]	378	371
South East Asia[c]	588	593
Subcontinent[d]	210	222
Eastern Europe	84	74
Western Europe	378	371
FSU	966	964
Middle East and North Africa	882	852
North America	1470	1446
South America[e]	1386	1371
World	**7938**	**7821**

[a] Australia and Japan; Japan believed to have negligible resources.
[b] Vietnam to Mongolia.
[c] Burma to PNG.
[d] Afghanistan to Bangladesh.
[e] Includes Mexico.

The projections by Laherrère (2007), Campbell and Heaps (2009) and Zhang et al. (2010) are broadly confirmed by Cases 1 and 2, however, no literature estimates are as optimistic as the Case 3 projections.

Table A.13
Tight gas URR in EJ (Mohr, 2010).

Region	Low	BG	Comments Case 1 and 2	High	Comments High
Algeria	7	19	1/3 Other (http://www.total.com/static/en/medias/topic1026/tight-gas-reservoirs_2007.pdf)	43	1/3 of ME and NA Cramer et al. (2009)[a]
Egypt				43	1/3 of ME and NA Cramer et al. (2009)[a]
Nigeria				122	Southern Africa Cramer et al. (2009)
Africa	**7**	**19**		**208**	
Australia	82	204	1/3 China/Australia[b]	111	Pacific (OECD) Cramer et al. (2009)
China	163	408	2/3 China/Australia[b]	56	North Asia Cramer et al. (2009)
India				33	Subcontinent Cramer et al. (2009)
Indonesia	7	19	1/3 Other (http://www.total.com/static/en/medias/topic1026/tight-gas-reservoirs_2007.pdf)	89	South Asia Cramer et al. (2009)
Asia	**252**	**631**		**289**	
Germany				14	1/4 of Western Europe (Cramer et al., 2009)
France				14	1/4 of Western Europe (Cramer et al., 2009)
Netherlands				14	1/4 of Western Europe (Cramer et al., 2009)
UK				14	1/4 of Western Europe (Cramer et al., 2009)
Europe				**56**	
FSU	**89**	**222**	http://www.total.com/static/en/medias/topic1026/tight-gas-reservoirs_2007.pdf	**156**	FSU + Eastern Europe (Cramer et al., 2009)
Saudi Arabia	52	130	Middle East(http://www.total.com/static/en/medias/topic1026/tight-gas-reservoirs_2007.pdf)	43	1/3 of ME and NA (Cramer et al., 2009)[a]
Middle East	**52**	**130**		**43**	
Canada	145 (Mohr and Evans, 2010)	210 (Mohr and Evans, 2010)		326	Mohr and Evans (2010)
USA	431 (Mohr and Evans, 2010)	489 (Mohr and Evans, 2010)		658	Mohr and Evans (2010)
North America	**576**	**699**		**984**	
Argentina	7	19	1/3 Other (http://www.total.com/static/en/medias/topic1026/tight-gas-reservoirs_2007.pdf)	69	1/3 of South America Cramer et al. (2009)
Mexico				69	1/3 of South America (Cramer et al., 2009)
Venezuela				69	1/3 of South America (Cramer et al., 2009)
South America	**7**	**19**		**207**	
World	**983**	**1720**		**1943**	

[a] Middle East and North Africa.
[b] http://www.total.com/static/en/medias/topic1026/tight-gas-reservoirs_2007.pdf indicates most tight gas resides in Russia/China and North America, hence the bias towards China split.

Appendix A. URR Calculations

This section contains the tables of URR information. (see Tables A.1–A.13).

Appendix B. Dynamic demand

The dynamic demand is the same as the static demand except that $\tilde{D}(t)$ is modified as described:

$$\tilde{D}(t) = \begin{cases} \tilde{D}(t-1)(1-0.15G(t)); & \text{if } \tilde{D}(t-1) > 62 \ \& \ \mathrm{D}(t) > 62 \\ [62-\tilde{D}(t-1)0.15G(t)]; & \text{if } \tilde{D}(t-1) \leq 62 \ \& \ \mathrm{D}(t) > 62 \\ \tilde{D}(t-1)[e^{0.02502}-0.15G(t)]; & \text{if } \breve{D}(t) \leq 62 \end{cases} \tag{B.1}$$

with

$$\breve{D}(t) = \tilde{D}(t-1)(e^{0.02502}-0.15G(t)) \tag{B.2}$$

$G(t)$ is the fractional difference between supply and demand defined as:

$$G(t) = \frac{D(t-1)-P(t-1)}{P(t-1)} \tag{B.3}$$

where $P(t-1)$ is the world's production of natural gas in the year $t-1$.

Appendix C. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2011.04.066.

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