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Article

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Energy Reports

Provided in Cooperation with:

Elsevier

Suggested Citation: Wang, Jianliang; Bentley, Yongmei (2020) : Modelling world natural gas production, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, pp. 1363-1372, <https://doi.org/10.1016/j.egy.2020.05.018>

This Version is available at:

<https://hdl.handle.net/10419/244126>

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Research paper

Modelling world natural gas production

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ARTICLE INFO

Article history:

Received 15 March 2020

Received in revised form 11 May 2020

Accepted 20 May 2020

Available online xxxx

Keywords:

Natural gas production

Ultimately recoverable resource

Multi-cycle modelling

ABSTRACT

As the cleanest fossil fuel in terms of carbon dioxide (CO₂) emissions, natural gas demand is expected to increase rapidly in future due to its important role in the transition of the world energy system. In this case, understanding potential limits to future production of the world's natural gas resources becomes increasingly important. This paper uses a modified multi-cycle generalized Weng model to forecast the long-term production of natural gas by region, and also globally. Both conventional and unconventional gas production are considered. Our results show that world natural gas production is likely to peak in the range 3.7 to 6.1 trillion cubic meters per year (tcm/y) between 2019 and 2060 depending on assumptions made on the size of the global ultimately recoverable resource (URR) of natural gas. A comparison of this paper's forecasts with those from the scientific literature and from major energy institutes shows that the projection in this paper's 'high scenario' can be seen as a likely upper-bound on future global natural gas production. To turn this upper-bound projection into reality, great efforts will be needed from the gas industry to discover more conventional and unconventional gas resources, and to make these recoverable.

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1. Introduction

1.1. Background of the study

As the cleanest fossil fuel in terms of carbon dioxide emissions, natural gas plays an important role in the world energy transition from a high-carbon to a low-carbon system (Zou et al., 2016; Wang et al., 2018b). Therefore, it is reasonable to expect that natural gas demand will increase rapidly in the future. According to the World Energy Outlook 2018 released by International Energy Agency (IEA, 2018), world natural gas demand will increase from 3.75 trillion cubic meters per year (tcm/y) in 2017 to 5.40 tcm/y in 2040 in the 'New Policies' Scenario. This corresponds to an average annual growth rate for natural gas demand over the next 23 years of 1.6%, which is significantly higher than that for oil (0.4%) and coal (0.1%) (IEA, 2018). Faced by this rapid increase in demand, an important question is: Can the world natural gas production in future meet this increasing demand? To answer this question, a quantitative analysis of the world long-term natural gas production is necessary.

Current studies on natural gas production are mainly from two sources: one is from major energy institutes, including the

International Energy Agency (IEA), the U.S. Energy Information Administration (EIA), the Organization of the Petroleum Exporting Countries (OPEC), the British Petroleum (BP) and DNV GL. Readers can find the respective production forecasts from the above institutes' annual publications, specifically, the World Energy Outlooks (WEOs) by IEA (2018), International Energy Outlooks (IEOs) by EIA (2018), World Oil Outlooks (WOOs) by OPEC (2018), Energy Outlooks (EOs) by BP (2019), and Energy Transition Outlooks (ETOs) by DNV GL (2018). Furthermore, the results from these publications are all for long-term periods, and include not only production from conventional gas resources, but also those from unconventional gas resources. However, all the predictions by these institutes on gas production, except for that by DNV GL (2018), would seem to be essentially demand-driven analyses, i.e. they assume that the world's gas resources are sufficient to be extracted at the flow rates required to meet forecast demand (Wang et al., 2017). These predictions thus risk giving insufficient consideration of the potential constraints due to the depletion of the fossil resource. Therefore, a supply-side analysis, i.e. one that considers the potential constraints set by the quantity of non-renewable resource estimated as recoverable, is suggested by many scholars to help the world better understand the possible production growth rates of these resources (Ward et al., 2012; Höök and Tang, 2013; Wang et al., 2017).

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1.2. Focus of the study

The other main source of studies on future natural gas production is the peer-reviewed scientific literature. By reviewing academic papers published after the year 2000, we find that natural gas production has been modelled by many studies, and covering both conventional and unconventional gas resources. For example, Söderbergh et al. (2009) analysed the long-term production of natural gas resources in Norway. Lin and Wang (2012) and Wang et al. (2013b) predicted the long-term production of China's conventional natural gas resources. Patzek et al. (2013) predicted the long-term production of Barnett shale gas resources in US. Salmachi and Yarmohammadtooski (2015) analysed the production for the coalbed methane wells. Wang et al. (2016) forecast the long-term production growth of China's unconventional gas resources. Wang et al. (2018a) forecast the short-term (monthly) production of US shale gas resources. Most of these studies, except the study by Wang et al. (2018a), are from a supply side perspective having considered the amount of resources. However, the main problem with the majority of such studies is that they focus only on the natural gas production of specific regions rather than that of the whole world. If we search for studies of natural gas production for the whole world, we find only 13 studies analysing the world long-term natural gas production quantitatively. In this paper, we examine these studies from three perspectives: the forecast models used, the modelling structure applied, and the inclusion or exclusion of unconventional gas resources.

The first perspective is the forecast models used. There are three main models used in literature, i.e. the Hubbert model (e.g. Laherrere, 2002), the linear growth model (e.g. Brecha, 2008), and the Geologic Resources Supply–Demand Model (GeRS–DeMo) (e.g. Mohr et al., 2015). Of these models, the Hubbert model is the most widely used, which was used by 8 out of the 13 studies analysed (i.e. Al-Fattah and Startzman, 2000; Laherrere, 2002; Imam et al., 2004; Zerta et al., 2008; Nel and Cooper, 2009; Valero and Valero, 2010, 2011; Maggio and Cacciola, 2012). Actually, this is not just the case for natural gas production forecasts. In the area of modelling the long-term production of oil and coal, the Hubbert model is the best known and most widely used model (e.g. Nashawi et al., 2010; Wang et al., 2011; Saraiva et al., 2014). However, the Hubbert model assumes that the production curve is symmetric, i.e. the production will peak at a point when 50% of ultimately recoverable resource (URR) has been exploited, which is usually not met in reality (Bardi, 2005; Wang et al., 2011). For example, Brandt (2007) investigated the production curves of 67 regions and found that the real production curves are often asymmetric and often positively skewed, i.e. when the production peak before 50% of the URR was exploited, and it was found that the increase in rate of production before peak was higher than the decline rate of production after peak. Other studies (e.g. Wang et al., 2011; Wang, 2014) also indicate that the positively skewed curve model presents a better fit for historical production data. Therefore, a positively skewed curve model is selected in this paper to understand the scope for future production of natural gas.

The second perspective is the modelling structure applied in literature. Among the 13 studies analysed, 9 forecast the world natural gas production by using top-down analysis (i.e. Laherrere, 2002; Imam et al., 2004; Brecha, 2008; Zerta et al., 2008; Kharecha and Hansen, 2008; Nel and Cooper, 2009; Valero and Valero, 2010, 2011; Maggio and Cacciola, 2012); and only 4 studies used bottom-up analysis (i.e. Al-Fattah and Startzman, 2000; Mohr and Evans, 2007, 2011; Mohr et al., 2015). In modelling the world natural gas production, bottom-up analysis often refers to country-by-country or region-by-region analysis and subsequent

aggregation to the global level (although the term can also apply to field-by-field and also project-by-project analysis). Comparing with top-down analysis, bottom-up analysis by country or region provides more information, since it can provide not only the likely pathway for the future world natural gas production, but also the production behaviours for different countries or regions, and how they affect the world total gas production curve. Therefore, to better understand the future production of natural gas resources, we suggest that bottom-up analysis, at least by region, be used.

The third perspective is whether unconventional gas resources are included or excluded in the analysis. Only 3 of the post year-2000 studies we surveyed considered unconventional natural gas resources in their modelling (i.e. Mohr and Evans, 2007, 2011; Mohr et al., 2015), while the other studies considered only the conventional gas resources (e.g. Imam et al., 2004; Brecha, 2008; Zerta et al., 2008). It is recognized that the extraction of unconventional gas resources has significantly accelerated after the US shale revolution, and many studies suggest that the unconventional gas resources achieve large-scale development in the future (IEA, 2018; Medlock, 2012; IEA, 2011). Therefore, it is important to include the unconventional natural gas resources in modelling the future long-term production of the world natural gas.

The aim of this paper is, therefore, to analyse the long-term production of natural gas resources from the supply side as follows: by using a modified positively skewed curve model, by including both conventional and unconventional gas resources in the analysis, and by dividing the world into seven regions, i.e. Europe, Commonwealth of Independent States (CIS), Africa, Middle East, Asia Pacific, North America and Latin America.

1.3. Novelty of the study

Fig. 1 compares the main points of the differences of this study from existing studies. The individual contribution of each of these points may not be seen as very significant as they can also be seen in other studies (e.g. bottom-up analysis is used in world phosphate rock production forecast by Walan et al. (2014); unconventional gas is included in Wang et al. (2016) in forecasting China's gas production; and a generalized Weng model is used in modelling China's conventional natural gas production by Wang et al. (2013b)). However, the combined use of these points in a single study to forecast global natural gas production is novel. Furthermore, this paper has also made a modification to the original Weng mode by introducing the F-test to determine the number of cycles. Therefore we see this paper as an original contribution to the topic area.

The structure of the remainder of this paper is as follows: Section 2 describes the method and the data used; Section 3 discusses the main results, and the impacts; and Section 4 draws the conclusions of this study.

2. Methodology and data

2.1. Models for forecasting production of non-renewable energy resources

Natural gas is a non-renewable energy resource. For non-renewable resources such as this, a very likely pathway for their long-term production is to increase and reach the production peak first, then decline inevitably due to the depletion of resources (Wang et al., 2017), which means that the long-term production curve of these resources is usually bell-shaped. Furthermore, this bell-shaped production behaviour has been observed in the regions studied by Nashawi et al. (2010), Saraiva et al. (2014), and Höök et al. (2010). The improvement in technology and economic conditions will lead higher production in

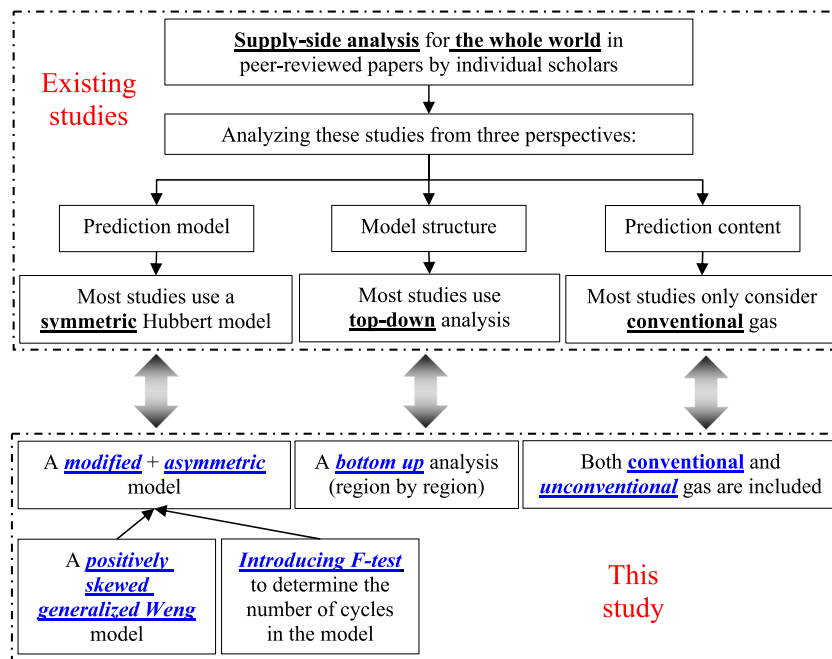


Fig. 1. The differences of this study from existing studies.

more fields and therefore increasing reserves. However, the main contribution of such additional reserves is to delay the date of the production peak, and/or lower the decline rate after peak, but cannot prevent the production peak completely (Bentley, 2002; Sorrell et al., 2010). As a result, ‘bell-shaped’ curve fitting models have long been the most widely-used models for forecasting long-term production pathways of non-renewable energy resources (Cavallo, 2004; Rehrl and Friedrich, 2006; Wang and Feng, 2016), although some other models can also be used, such as system dynamic models (e.g. Tang et al., 2010; Kiani and Pourfakhraei, 2010), economic models (e.g. Fisher, 1964) and hybrid econometric models (e.g. Moroney and Berg, 1999). Each type of models has its own pros and cons, but in this paper we adopt a bell-shaped model in light of its strong empirical and theoretical underpinnings, suitability for supply-side analysis, and relatively low requirement on input data.

2.2. Selection of the base model for this study – Weng model

Bell-shaped curve-fitting models can in turn be divided into three categories, i.e. symmetrical curve models, positively-skewed curve models and negatively-skewed curve models (Wang and Feng, 2016). Currently, symmetrical curve models (the well-known Hubbert model is one example) are the most widely used in the literature (Al-Fattah and Startzman, 2000; Laherrere, 2002; Imam et al., 2004; Zerta et al., 2008; Nel and Cooper, 2009; Valero and Valero, 2010, 2011; Maggio and Cacciola, 2012). However, due to the problematic assumption of symmetrical curve shape versus actual observation on post-peak regions, positively-skewed curve models are recommended and used here to forecast long-term natural gas production. A review of literature indicate that the generalized Weng model is the most widely used positively-skewed curve model.

In 1984, the Weng model was first proposed to forecast the production rates of oil and gas in China (Weng, 1984). Later, Chen (1996) developed a theoretical derivation of the Weng model, and proposed the generalized Weng model. The model has since been used by a number of researchers for modelling the production of fossil resources. For example, Feng et al. (2007, 2010) used the generalized Weng model to forecast China’s oil

production and world natural gas production. The model was then used by Wang et al. (2011) in modelling world conventional oil production. Wang et al. (2011) also compared the forecast performance of generalized Weng model with the Hubbert model and the result showed that the generalized Weng model had a better fit to historical production data. The model was then used to model both China’s conventional gas production (Wang et al., 2013b) and unconventional gas production (Lv et al., 2012). All these studies show that the generalized Weng model has a better prediction ability than any other models of its type. For this reason, the generalized Weng model is chosen as the bell-shaped curve-fitting model to be used in this paper.

According to Wang et al. (2011) and Wang and Feng (2016), the basic equation of the single-cycle generalized Weng model is as follows:

$$q(t) = URR \frac{1}{c^{b+1} \Gamma(b+1)} t^b \exp\left(-\frac{t}{c}\right) \quad (1)$$

where $q(t)$ is the annual production at time t , URR is ultimately recoverable resources, and b and c are parameters. $\Gamma(b+1)$ is the gamma function, when b is positive, $\Gamma(b+1) = b!$.

To solve Eq. (1), historical production data and URR data need to be provided. A nonlinear least-squares numerical computation technique is used to determine the value of parameters b and c as follows: (1) assuming guessed values of b and c , and getting the forecast production; (2) obtaining the optimum values of b and c by minimizing the differences between the forecast production and actual historical production by adjusting the guessed values of b and c ; and (3) getting the final forecast results by inputting the optimum values of b and c . The root-mean-square error (RMSE) is a widely used index to evaluate the differences between the forecast production and historical actual production. Lower RMSE means lower differences. The basic equation for calculating RMSE is (Wang et al., 2011):

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (q_{act} - q_{for})^2}{n}} \quad (2)$$

where n is the number of data points (for example, if the historical data is from 2000–2018, then $n = 19$), q_{act} is actual gas

production, and q_{for} is estimated gas production. The calculation process can be achieved easily using available software. In this paper, the Solver Microsoft Excel add-in program is used to get the optimum values of the parameters.

2.3. Modification of Weng model

In reality, for many reasons such as discovery of new fields, application of new development techniques or disruption from political issues, historical oil or gas production curves often have more than one production cycle (e.g. UK oil production) (Nashawi et al., 2010; Wang et al., 2011). To capture this effect, the multi-cycle generalized Weng model was proposed, having the equation as follows (Feng et al., 2010; Wang et al., 2011, 2013b):

$$q(t) = \sum_{i=1}^k q(t)_i = \sum_{i=1}^k \left[URR \frac{1}{c^{b+1} \Gamma(b+1)} t^b \exp\left(-\frac{t}{c}\right) \right]_i \quad (3)$$

where k is the total number of production cycles.

In multi-cycle modelling, the number of production cycles can affect the forecast results significantly. Generally, adding more production cycles may improve the goodness-of-fit and result in a lower RMSE (Anderson and Conder, 2011). However, too many production cycles could also lead to over-fitting and result in a situation where random noise is described instead of the underlying behaviour (Höök et al., 2011), which leads to poor forecasting (Höök et al., 2011; Wang and Feng, 2016). Furthermore, more production cycles also mean higher calculation effort. For this reason, it is important to determine the number of production cycles to use. Current multi-cycle modelling usually chooses the number of production cycles according to the researchers' subjective view or qualitative analyses of historical production data (see examples in Al-Fattah and Startzman, 2000; Imam et al., 2004), which can make the results highly uncertain since different researchers may use different number of cycles even though the same historical production curve is used. Therefore, establishing a quantitative method to determine the number of production cycles is required (Wang and Feng, 2016). This problem is solved by modifying the traditional multi-cycle generalized Weng model, specifically, by introducing an F-test method to determine the number of production cycles. In this F-test method, an additional production cycle is added only if the root-mean-square error (RMSE) is improved significantly. The improvement of RMSE is represented by using a proposed F-value, and the significance is judged by comparing the proposed F-value and the standard F-value at the given significance level.

The proposed F-value is shown as follows:

$$F_{value} = \frac{RMSE_{bef}^2}{RMSE_{aft}^2} \frac{n - m_{aft} - 1}{n - m_{bef} - 1} \quad (4)$$

where $RMSE_{bef}$ and $RMSE_{aft}$ are the values of RMSE before and after an additional production cycle is added, respectively, and usually, $RMSE_{bef} > RMSE_{aft}$; m_{bef} and m_{aft} are the number of free parameters before and after an additional production cycle is added, respectively, and usually, $m_{bef} < m_{aft}$; n has the same meaning as shown in Eq. (2). The standard F-value at a given significance level is given as $F_{\alpha}(n - m_{bef} - 1, n - m_{aft} - 1)$. Therefore, an additional production cycle should only be added when:

$$F_{value} > F_{\alpha}(n - m_{bef} - 1, n - m_{aft} - 1) \quad (5)$$

where α denotes the significance level, and in this paper, $\alpha = 0.1$.

2.4. Production data and URR scenarios

Based on the description of Section 2.3, it can be seen that historical production and the ultimately recoverable resource (URR) are the two key input data for the modelling. Historical production can be collected directly from the production data of 1950–1969 (Mohr et al., 2015) and from the production data of 1970–2017 (BP, 2018) as shown in Fig. 2.

The URR is the total volume of an energy resource which might ultimately be produced commercially (IEA, 2008). Unlike with historical production, the URR value needs to be estimated. To estimate the value of a URR, it is necessary to understand the definitions of resources and reserves first. In this paper, the definitions of the Federal Institute for Geosciences and Natural Resources of Germany (Bundesanstalt für Geowissenschaften und Rohstoffe) (BGR, 2017) is used since their assessment results for natural resources have been widely used by many major institutes in the world, such as the Intergovernmental Panel on Climate Change (IPCC, 2000), the International Institute for Applied Systems Analysis (Johansson et al., 2012), the IEA (2018) and the World Energy Council (WEC, 2013). Therefore, the volume of natural resources in BGR estimates can be seen as an influential view from industry.

BGR (2017) defines reserves and resources as follows:

- Reserves refer to “proven volumes of energy resources economically exploitable at today's prices and using today's technology”.
- Resources refer to “proven amounts of energy resources which cannot currently be exploited for technical and/or economic reasons, as well as unproven but geologically possible energy resources which may be exploitable in future”.

By reviewing the current literature, two main methods are used to estimate the value of a URR. The first is to estimate the URR by summing the cumulative production and reserves (e.g. Nel and Cooper, 2009; Wang et al., 2013a). However, according to the definition of reserves as used by the BGR, a URR estimated in this way includes only the recoverable volume from already discovered deposits, and at current technical and economic levels. Hence, it excludes the potential recoverable volumes from both discovered and undiscovered deposits due to the future improvements in technical and economic conditions, and thus yields a rather low estimate of URR. Therefore, a second method is proposed to estimate a higher URR, by summing cumulative production, reserves and the resources (see, for example, Maggio and Cacciola, 2012; IEA, 2012; BGR, 2017). However, this second way of estimation may result in a rather high URR since the achievement of assumed technical and economic improvement is itself uncertain, and also affected by other factors such as fluctuations in price.

Moreover, it is recognized that a URR estimate is often not a static value, and can change over time. Therefore, to consider the uncertainties of URR estimates, in this paper a scenario analysis is carried out to reflect these two methods of URR estimation. In our ‘low scenario’, the URR is estimated by the first method while the second method is used to estimate the URR in our ‘high scenario’. Such scenario analysis has been used in many studies (e.g. Mohr et al., 2015; Wang et al., 2015, 2016). We judge that there is a high probability that the actual gas URRs will fall in the range between the low and high scenarios given in this paper.

The data we use for cumulative production, reserves and resources of natural gas are those from BGR (2017). These include not only values for conventional gas, but also for unconventional gas (i.e. tight gas, shale gas and coal bed methane, CBM). Gas hydrates are not included in this paper since they seem still far from large-scale commercial development in this century. For this

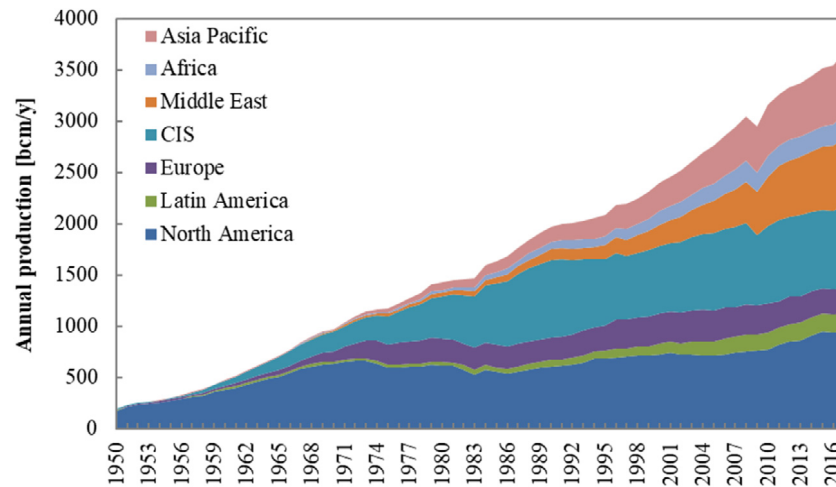


Fig. 2. Historical production of world natural gas resources by region.

reason, many other studies also exclude gas hydrates in their analysis (e.g. Mohr and Evans, 2011; Wang and Feng, 2016; IEA, 2018).

Based on the above definitions, the URR estimates for the two different scenarios can then be estimated, and are shown in Table 1.

3. Results and discussion

3.1. Results

Based on the data analyses from the previous section, the results of the world natural gas production by regions and categories are presented in Fig. 3 while the detailed results for each region are shown in Appendix.

As can be seen in Fig. 3, in the 'low scenario', we calculate that world natural gas production will peak at 3.7 tcm/y in 2019 (see Fig. 3A). There are two reasons for this relatively early peak in world gas production. Firstly, the assumed remaining recoverable volume of conventional gas in the low scenario is not very great (as shown in Table 1, the reserves of conventional gas are 189.5 tcm, which is only 1.6 times higher than cumulative production). Secondly, the production contribution of unconventional gas resources is marginal (see Fig. 3C). Furthermore, by focusing on the production of each region, we can see that Middle East and CIS are the two major contributors for gas production in this scenario since they have higher volumes of remaining resources compared to other regions.

In the 'high scenario', the world natural gas production keeps increasing over the next several decades, until 2060 when a peak production of 6.1 tcm/y is reached (see Fig. 3B). This is a very different picture of production growth compared to the low scenario. There are two main reasons for this. One is that more conventional resources become recoverable in this scenario (see Table 1, 323.4 tcm of gas resources are added to the URR estimate), and the other is that a significant volume of unconventional gas resources is included in this URR (see Table 1, where 319.7 tcm of unconventional gas resources are added to the URR). In this case, both conventional and unconventional gas production achieve rapid increases in future (see Fig. 3D). In addition, it can be seen that the Middle East, CIS, North America and Asia Pacific are the four regions which hold dominate positions in future world natural gas production, although the reasons for this are different. As can be seen in Table 1, the first two regions (i.e. the Middle East and CIS) have significant conventional resources, while the other two regions (i.e. North

America and Asia Pacific) have significant unconventional gas resources.

Based on the description in Section 2.4, the URR estimate in the high scenario not only considers the current recoverable quantities from discovered resources, but also those potential recoverable quantities from both discovered resources and undiscovered resources. This is one of the reasons why production in the high scenario is significantly higher than that in the low scenario. However, it should be noted that bringing those potential recoverable quantities into actual production relies on two prerequisites. One is the improvement of technical and economic conditions, which reflects many uncertainties, and the other is the continued exploration for the recoverable, which needs large investment. Therefore, a large effort is needed by the world gas industry to achieve the production levels shown in the high scenario.

3.2. Discussion

3.2.1. Comparison with existing peer-reviewed literature

A comparison of the results of this paper with those in the existing academic literature is shown in Figs. 4 and 5, with data presented in Table 2.

Fig. 4 indicates the projections of conventional gas production in the academic literature (10 of 13 studies belong to this type of projection) and their average value as well as our results (which include unconventional gas), while Fig. 5 presents those production projections in the academic literature that include both conventional and unconventional gas resources (3 of 13 studies belong to this type of projection) and their average value. From Figs. 4 and 5, it can be seen that the results of this paper fall within the range of values found in the literature. Furthermore, the result in our low scenario is similar to the average value of the other conventional gas projections (see Fig. 4). The reasons for this are: (1) in our low scenario, nearly all the recoverable quantities of gas resources are of conventional gas, and (2) the URRs in these conventional gas projections range from 232–435 tcm, with an average value of 304 tcm, which is similar to the URR value in our low scenario (see Table 2).

In addition, the forecast production curve in our high scenario is higher than most of current projections, and of the average value of those conventional plus unconventional gas projections except for that of "Mohr et al. (2015)-High" (see Fig. 5).

The reason is that URR in the high scenario of Mohr et al. (2015) includes substantial volumes of gas hydrate, since a purpose of the Mohr et al. (2015) study was to investigate if the CO₂

Table 1
Estimated natural gas URR values by region, under two different scenarios.

Region	CP① [Tcm]	Reserves[Tcm]		Resources[Tcm]		URR[Tcm]	
		Cv.*②	Unconv.③	Cv. ④	Unconv.⑤	Low scenario**	High scenario***
Europe	12.8	3.2		5.4	13.9	16.0	35.4
CIS	31.3	63.2	0.04	130.9	48.2	94.6	273.7
Africa	4.6	14.4		35.5	44.2	18.9	98.7
Middle East	9.4	79.4		42.3	13.8	88.8	144.9
Asia Pacific	10.7	15.9	1.66	46.9	84.8	28.3	159.9
North America	43.8	5.8	5.38	39.3	73.5	55.0	167.8
Latin America	4.3	7.6		23.1	41.3	11.9	76.3
Total	116.9	189.5	7.08	323.4	319.7	313.5	956.6

Note:
 (1) CP: Cumulative production; Cv.: Conventional gas; Unconv.: Unconventional gas; Cv.*: includes the 'tight gas' reserves.
 (2) Data for CP, Reserves (Cv. and Unconv.) and Resources (Cv. and Unconv.) are from BGR (2017).
 (3) **URR = ①+②+③; ***URR = ①+②+③+④+⑤.

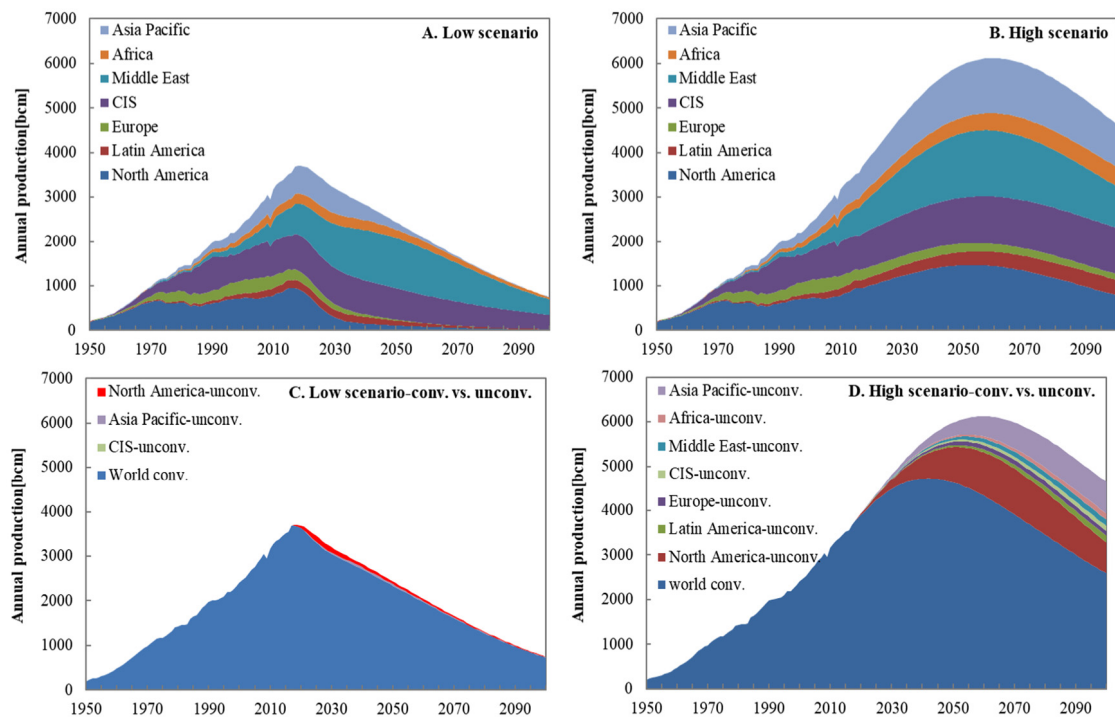


Fig. 3. World natural gas production by region and category.

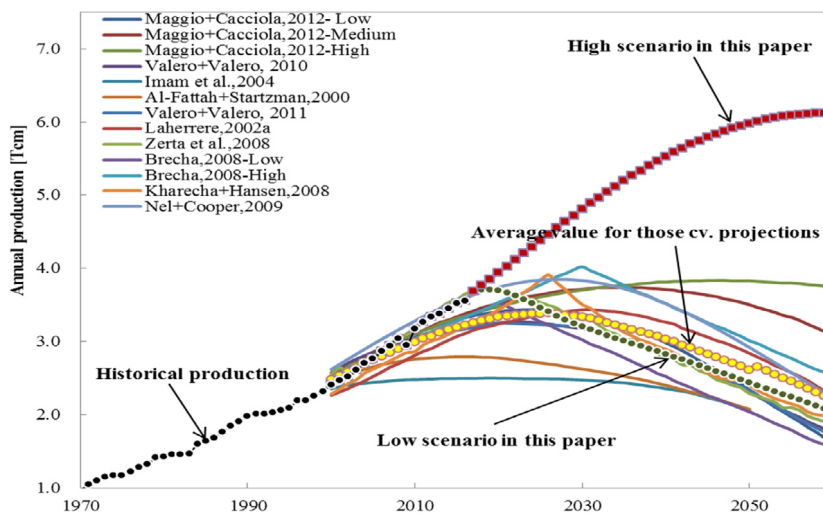


Fig. 4. Comparison of our results with conventional gas projections in the literature.

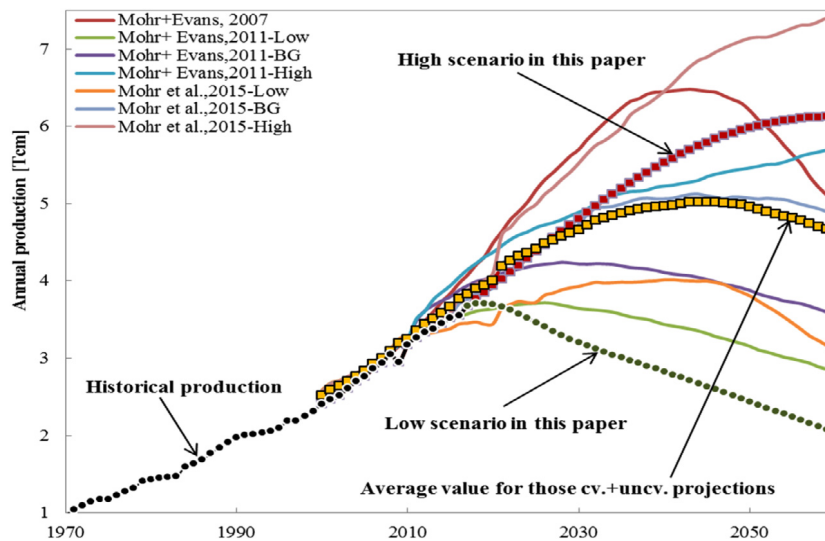


Fig. 5. Comparison of our results with conventional and unconventional gas projections in literature.

emission scenarios in IPCC reports are plausible even if considering emissions from extremely large unconventional resources. Therefore, our projection in the high scenario could be seen as a likely upper-bound of future global natural gas production.

Table 2 shows some other information, such as the methods and analysis structure of the studies cited. Most of this information has already been mentioned in the introduction section of this paper, and therefore is not discussed further here.

3.2.2. Comparison with recent gas forecasts from major institutes

In addition to the studies in peer-reviewed academic journals, a number of influential international institutes also present their views on future natural gas production in their annual publications, including the IEA, EIA, BP and OPEC. These forecasts include not only conventional gas, but also unconventional gas, and where these forecasts are widely used by industry and policy makers. Fig. 6 compares the results of this paper with the projections from the latest publications of these institutes.

As can be seen in Fig. 6, except for the results from DNV GL (2018), all other projections show a clear growth in future production due to the improvement of economic and technical conditions and the development of unconventional gas resources. Furthermore, this growth pathway in production from the institutes is largely consistent with the results shown in our high scenario, but significantly higher than that in our low scenario results.

This comparison shows that nearly all forecasts agree that it is nearly impossible to achieve a continued growth in gas production by relying only on conventional gas resources. Thus, to achieve a significant growth pathway as shown in the forecasts of the major institutes or this paper's high scenario, large investment and significant technical progress need to be given to the supply side of natural gas industry.

3.2.3. The impacts of biogas and synthetic natural gas on future gas production

The sources for gas production analysed in this paper are those for natural gas. However, to tackle the increasingly severe issue of climate change, some other low-carbon energy sources have developed rapidly in recent decades. The first important type of these low-carbon energy sources is biogas. This is produced by anaerobic fermentation of different forms of organic matter, and can be used in various ways, such as generating electricity, producing heat and powering transport (Scarlat et al., 2018). Most

biogas production occurs in Europe, though other regions are also increasingly deploying the technology. Global biogas production increased from 7.8 bcm/yr in 2000 to 41.8 bcm/yr in 2018 (in methane equivalent), with an annual average increase rate of 9.8% (WBA, 2019; IEA, 2020). According to World Bioenergy Association (WBA, 2019) and International Energy Agency (IEA, 2020), biogas production is expected to keep increasing in future. In the 'Stated Policies' Scenario of the World Energy Outlook published by the IEA, biogas production is forecast as about 175 bcm/yr by 2040 (IEA, 2020). A second important type of low-carbon energy resource is coal-based synthetic natural gas (SNG), also called coal-to-gas (CTG). Currently, major SNG plants are mainly located in China (Yang and Jackson, 2013; Minchener, 2013). Since 2013, China's SNG industry has entered a period of rapid growth with a significant number of new SNG projects being proposed (Wang et al., 2019). According to the China's official plan, total SNG capacity could reach about 40 bcm/yr (Yang and Jackson, 2013), which is a large increase compared to the current level.

Based on the above analysis, annual gas production in 2040 from biogas and SNG combined could reach about 220 bcm/yr or more. But in this paper, we forecast production of natural gas in 2040 to be much larger, at 2830 bcm/yr in the low scenario and 5530 bcm/yr in the high scenario. Therefore, while the development of biogas and SNG is expected to increase, their production is not likely to affect the conclusions of our paper significantly.

4. Conclusions

Two main conclusions of this study can be summarized as follows:

First, a modified multi-cycle generalized Weng model has been used with low and high estimates for the world's ultimately recoverable resource (URR) of natural gas to forecast the two possible paths for world natural gas production out to 2100. The URR assumptions are based on BGR estimates published in 2017 and reflect both conventional and unconventional gas. The results show that in our high scenario, the world gas production can continue to increase significantly to reach a peak production at around 6.1 tcm/y in 2060, while in the low scenario world gas production will peak as early as 2019, at a production rate of 3.7 tcm/y. The difference in the assumptions of the two URR values are the main reason for the significant difference between these two projections. The actual gas production will almost surely be

Table 2
Comparison of published forecasts with the results in this paper.

Studies	URR[Tcm]	Model	Peak Prod.[Tcm]	PeakYear	Resources Category	Analysisstructure
Al-Fattah and Startzman (2000)	285	Multi-cycleHubbert	2.8	2014–2017	Cv.	Bottom-up*
Laherrere (2002)	354	Multi-cycleHubbert	3.4	2031	Cv.	Top-down
Imam et al. (2004)	261	Multi-cycleHubbert	2.5	2019	Cv.	Top-down
Mohr and Evans (2007)	526	Multi-period Production	6.5	2043	Cv.+uncv.	Bottom-up*
Zerta et al. (2008)	n.a.	Single-Hubbert	3.7	2018	Cv.	Top-down
Brecha (2008)	232–306	Linear Growth	3.5–4	2020–2030	Cv.	Top-down
Kharecha and Hansen (2008)	n.a.	Linear Growth	3.9	2026	Cv.	Top-down
Nel and Cooper (2009)	324	Single Logistic	3.8	2027	Cv.	Top-down
Valero and Valero (2010)	278	Single-cycle Hubbert	3.3	2023	Cv.	Top-down
Valero and Valero (2011)	265	Single-cycle Hubbert	3.3	2020	Cv.	Top-down
Mohr and Evans (2011)	402–790	GeRS–DeMo	3.7–5.8	2026–2065	Cv.+uncv.	Bottom-up**
Maggio and Cacciola (2012)	269–435	Multi-cycleHubbert	3.4–3.8	2024–2047	Cv.	Top-down
Mohr et al. (2015)	374–1256	GeRS–DeMo	4.1–7.7	2041–2068	Cv.+uncv.	Bottom-up**
This paper	313–957	Modified multi-cycle generalized Weng	3.7–6.1	2019–2060	Cv.+uncv.	Bottom-up*

Note: Peak Prod.: Peak Production; GeRS–DeMo: Geologic Resources Supply–Demand Model; Cv.: Conventional; Uncv.: Unconventional; n.a.: not available; Bottom-up*: region-by-region analysis; Bottom-up**: country-by-country analysis.

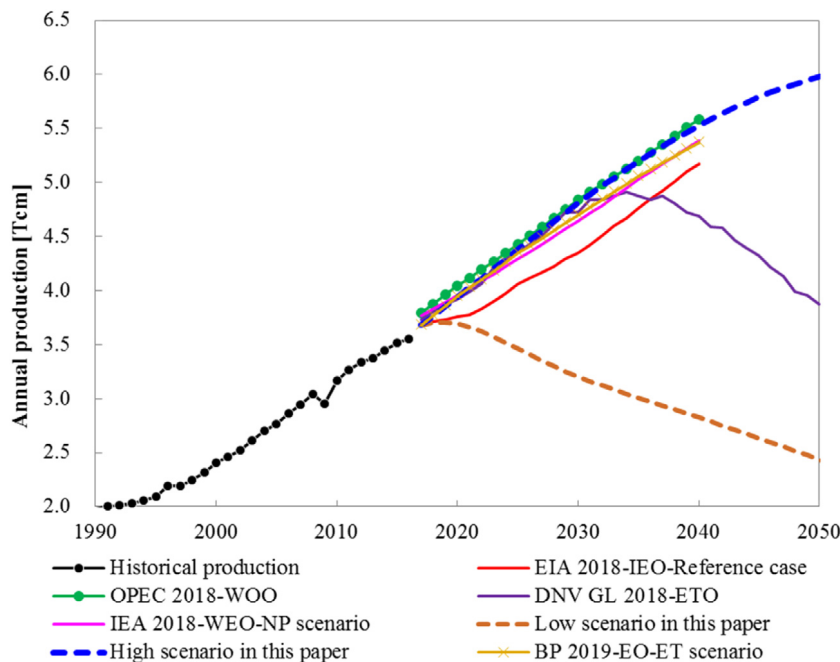


Fig. 6. Comparison of the results in this paper with those of other institutes. Notes: NP scenario–New Policies scenario; ET scenario–Evolving transition scenario. Source: IEA (2018), EIA (2018), OPEC (2018), BP (2019), DNV GL (2018).

higher than the low scenario projection, but also lower than the projection in the high scenario.

Second, by comparing the world gas production projections of this paper set by the size of estimated gas resources with other similar resource-based projections in the literature published since 2000, the results show that our low forecast is similar to the projections based only on conventional gas, while our high forecast is higher than most current forecast results even when both conventional and unconventional gas resources are considered. We conclude therefore that the forecast results in our high scenario should be seen as a realistic likely upper-bound of future world natural gas production. By comparing our projections with those from the major energy institutes, we find that the latter's projections roughly follow our upper-bound projection. Given that the world is looking for a significant production increase in natural gas to help the transition to a low-carbon world, our results suggest that the ability to make this upper-bound projection a reality is far from certain. Moreover, it is clear from our lower-bound scenario that significant increases in global gas production will require a great deal of effort from the world's gas

industry to discover more conventional and unconventional gas resources, and to make these recoverable.

CRediT authorship contribution statement

Wang Jianliang: Conceptualization, Data curation, Methodology, Software, Writing - original draft. **Bentley Yongmei:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research has been supported by the National Natural Science Foundation of China (Grant Nos. 71874201, 71503264, 71673297 and 71874202) and the Humanities and Social Sciences Youth Foundation of the Ministry of Education of China (Grant No.

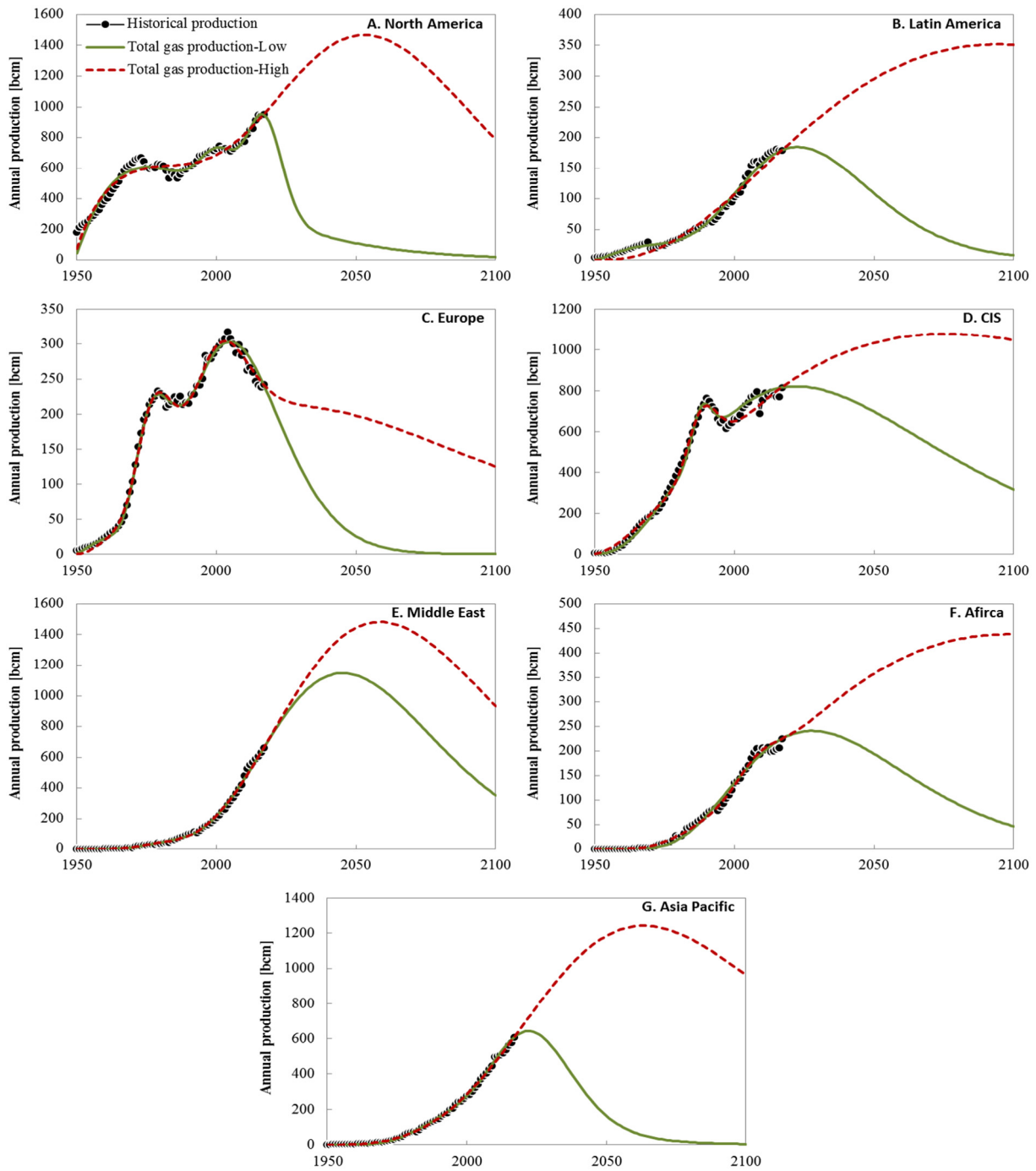


Fig. A.1. Projected future natural gas production in different regions. Note: Historical production is assumed to be conventional gas.

19YJCZH106). We also received helpful comments from Dr Roger Bentley, an expert from Petroleum Analysis Centre, Ireland, and anonymous reviewers.

Appendix

Detailed forecast results for each region are shown in Fig. A.1.

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