Energy Policy 48 (2012) 820–828

Contents lists available at SciVerse ScienceDirect

Energy Policy

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

Exploring crude oil production and export capacity of the OPEC Middle East countries

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HIGHLIGHTS

- ► We simulate the future scenario of crude oil export and production using ACEGES.
- ► The simulated results are analyzed using the GAMLSS framework.
- ► The peak points of oil export and production will come early in this century.
- ► The OPCE Middle East will produce most of the world crude oil in the near future.
- ► These countries will continuously be the key players in the crude oil markets.

ARTICLE INFO

Article history:
Received 6 April 2012
Accepted 14 June 2012
Available online 4 July 2012

Keywords:
Crude oil export
OPEC Middle East
ACEGES

ABSTRACT

As the world economy highly depends on crude oil, it is important to understand the dynamics of crude oil production and export capacity of major oil-exporting countries. Since crude oil resources are predominately located in the OPEC Middle East, these countries are expected to have significant leverage in the world crude oil markets by taking into account a range of uncertainties. In this study, we develop a scenario for crude oil export and production using the ACEGES model considering uncertainties in the resource limits, demand growth, production growth, and peak/decline point. The results indicate that the country-specific peak of both crude oil export and production comes in the early this century in the OPEC Middle East countries. On the other hand, they occupy most of the world export and production before and after the peak points. Consequently, these countries are expected to be the key group in the world crude oil markets. We also find that the gap between the world crude oil demand and production broadens over time, meaning that the acceleration of the development of ultra-deep-water oil, oil sands, and extra-heavy oil will be required if the world continuous to heavily rely on oil products.

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1. Introduction

Crude oil consumption, particularly the relatively inexpensive conventional oil, is linked closely to the wealth of industrialized countries as well as the dramatic economic expansion of emerging economies. Many of the fast growing economies have relatively few crude oil resources of their own while most of the remaining crude oil resources are geographically concentrated in a few countries around the world. By way of an example, Table 1 shows the gap between demand centers and production centers as well as the geographic concentration of the crude oil resources.

Because of the critical importance of crude oil to modern economic activity, it is important to try to estimate plausible trajectories of future country-specific crude oil production and export capacities while accounting for below and above ground uncertainties that might limit the export capacity of the major world crude oil players. For example, Hallock et al. (2004) and Voudouris et al. (2011) argue that the world is going to be increasingly dependent on fewer and fewer crude oil exporters located mostly in the Middle East and nearby regions.

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http://dx.doi.org/10.1016/j.enpol.2012.06.027

Here we explore the export capacity of the OPEC (Organization of the Petroleum Exporting Countries) member countries in the Middle East, namely Saudi Arabia, Iran, Iraq, Kuwait, United Arab Emirates (UAE), and Qatar. These countries are critically important crude oil producers and exporters, because these countries occupy about one third of the world crude oil production (and more than 90% of the Middle East) in 2010 (EIA, 2011) and IEA (2010) places the onus of increased oil supplies on the six major national oil companies in these countries (Stevens, 2012). Besides, five of these countries are in the five highest crude oil reserves countries as shown in Table 1 and Qatar is in the 12th (25.4 billion bbl). Collectively, the six countries analyzed here hold more than 60% of the world crude oil proved reserves and 99% of the proved reserves in the Middle East (BGR, 2009).

In addition to the high geographic concentration of crude oil reserves, the OPEC Middle East countries produce and export crude oil to the rest of the world. Fig. 1 shows that these countries play important roles as the sources of fueling the world economy for several decades. The OPEC Middle East provided around 40% of the world net export in this period with Saudi Arabia a dominant player by far. Stevens (2012) argues that the main Gulf Cooperation Council exporters (i.e. Saudi Arabia, Kuwait, and UAE) have sufficient capacity to cover the loss of exports from all the other Arab exporting countries. As shown in Fig. 2, the OPEC Middle East countries are consistently producing more crude oil compared with their domestic demand for crude oil. It is important to note that some other countries such as Russia, Canada, and Venezuela are also important oil producers and potentially influential crude oil exporters. However, we focus on the six OPEC Middle East countries as we consider that these countries will be the key players in the world crude oil export markets at least until ultra-deep-water oil, oil sands, and extra-heavy oil enhance their market shares and extraction rates.

Based on these circumstances, it is anticipated that these six OPEC Middle East countries are likely to play an increasingly dominant role in the world oil export markets as we move forward and their behavior and plausible export capacity will have a significant impact in the world oil markets.

Although there are several studies using a variety of modeling approaches (economic, physical, and statistical) to explore the future production of crude oil based on the concept of representative agent (e.g. Al-Jarri and Startzman, 1997; Bartlett, 2000; Campbell, 1997; Campbell and Heapes, 2008; Caithamer, 2008; Deffeyes, 2002; Duncan and Youngquist, 1999; Hallock et al., 2004; Kaufmann, 1991; Laherrere, 2006; Mohr and Evans, 2007, 2008, 2009; Nashawi et al., 2010; Wells, 2005; Wood et al. 2003), there are few studies analyzing the export capacity of crude oil and no studies doing that for all of individual countries. This is because they focus on assessing the future production of crude oil and little consider the demand. Hallock et al. (2004) is one comprehensive study evaluating production, demand, and export of the 47 major oil-producing counties based on the representative agent modeling.

In this study, we use the ACEGES (Agent-based Computational Economics of the Global Energy System) model (first proposed by Voudouris, 2011 and demonstrated by Voudouris et al., 2011) to explore the future (until 2050) export and production potential of crude oil of the six OPEC Middle East countries by explicitly modeling the crude oil demand and supply for 216 countries. Crude oil in this study primarily includes crude oil and lease condensate as defined by Energy Information Administration (EIA) (see also Section 2.2 below). As discussed by Voudouris et al. (2011), the key advantage of the ACEGES model is the high

Table 1
GDP and crude oil reserves in the top 10 GDP and crude oil reserves countries in 2009.

Top 10 GDP countries	GDP (trillion$)	Reserves (billion bbl)	Top 10 reserves countries	Reserves (billion bbl)	GDP (trillion$)
United States	14.05	28.4	Saudi Arabia	262.4	0.37
Japan	5.03	0.04	Iran	137.0	0.33
China	4.99	14.8	Iraq	115.0	0.07
Germany	3.30	0.3	Kuwait	104.0	0.11
France	2.62	0.1	UAE	97.8	0.27
United Kingdom	2.17	5.7	Russia	76.7	1.22
Italy	2.11	0.9	Libya	44.3	0.06
Brazil	1.59	18.0	Venezuela	41.2	0.33
Spain	1.46	0.1	Kazakhstan	39.8	0.12
India	1.38	5.8	Nigeria	37.2	0.17

*Data sources: World Bank (2012) for GDP; BGR (2009) for crude oil reserves.

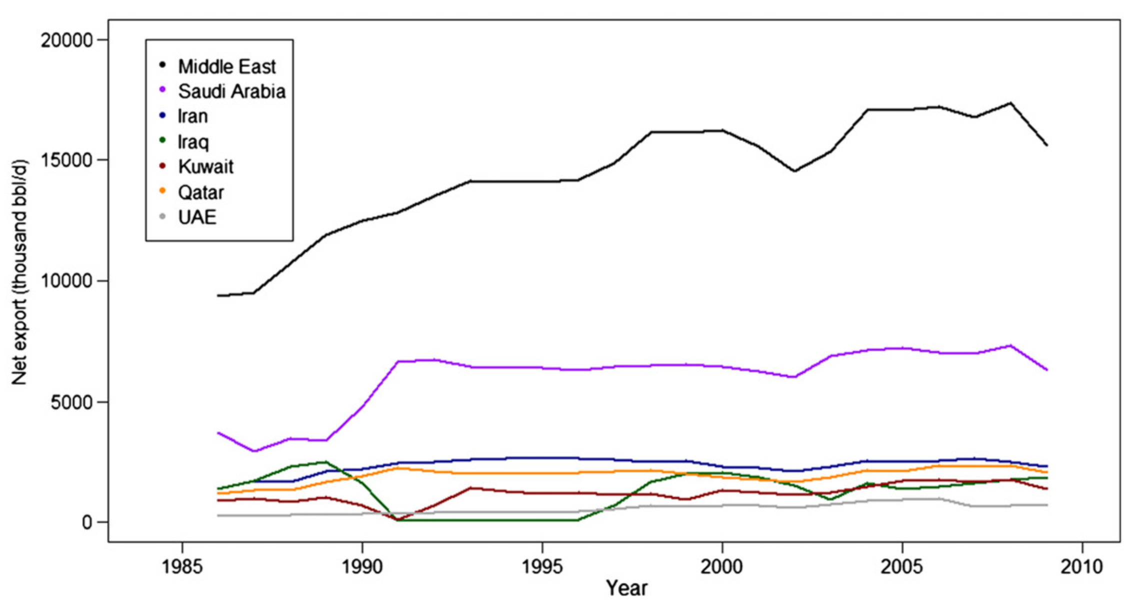

Fig. 1. Net export (export minus import) of crude oil for the period 1986–2009 (Data source: EIA, 2011).

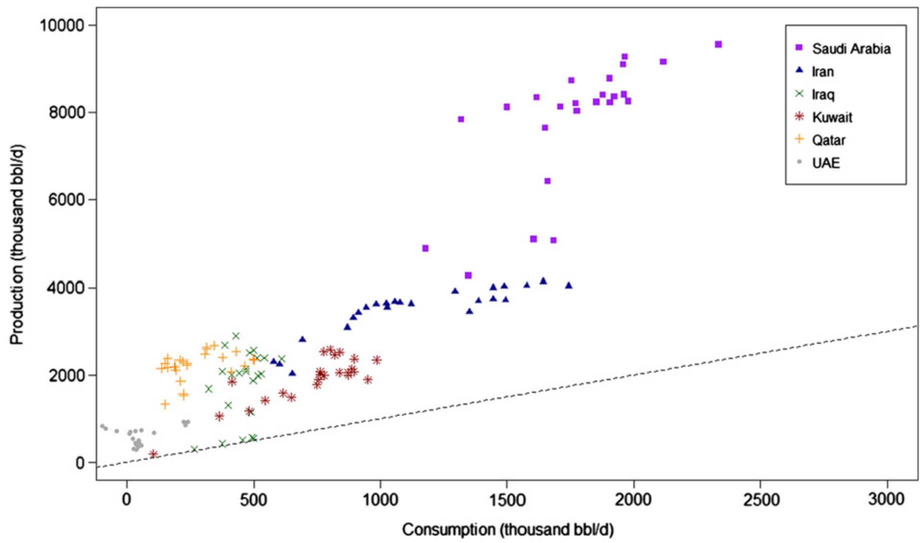

Fig. 2. Production versus consumption for the period 1986–2009. The dashed line indicates the balance between production and consumption . *Data source*: EIA, 2011.

degree of heterogeneity that can be incorporated in the scenarios in order to quantify the uncertainties within each scenario (in addition to the wide range of uncertainties that can be explored by developing fundamentally different scenarios—internally coherent and plausible narratives about the future).

Section 2 outlines the ACEGES model, particularly the decision rule of the agents (countries). Because the ACEGES model is a realistically-rendered agent-based model, it also discusses how the model is initialized with observational data and how heterogeneity is introduced in the model. This section also discusses the GAMLSS (Generalized Additive Models for Location, Scale and Shape) framework developed by Rigby and Stasinopoulos (2005) as a method of analyzing and summarizing the simulated scenarios. Section 3 presents the results of the analysis. Section 4 concludes this study.

2. Methods

2.1. ACEGES model

The ACEGES model is an agent-based model (ABM) for exploratory energy policy. ABM is a novel and flexible modeling framework for the computational study of socio-economic and natural processes (Epstein, 2007; Tesfatsion, 2006). ABM conceptualizes, in this instance, the world crude oil markets as a complex adaptive system of interacting agents (countries) who do not necessarily possess perfect rationality and information. ABMs require detailed specifications of structural conditions (e.g. crude oil originally in place before any extraction), institutional arrangements (e.g. long-term trade agreements), and behavioral dispositions (e.g. decision rules of crude oil production). The latter is fundamentally important in order to develop plausible scenarios. The conceptual framework for the ACEGES model is discussed by Voudouris (2011) while a mathematical description of the decision rule for crude oil production is given by Voudouris et al. (2011).

Once the ACEGES model has been initialized with observational data (see Section 2.2 below), we run a large number of simulations in order to explore the uncertainty space of the selected scenario. The results of the ACEGES-based scenarios are analyzed using the GAMLSS framework discussed below in Section 2.4. This means that the ACEGES-based scenarios for crude oil production and export capacity are analyzed within a highly flexible regression framework so that we can quantify the variability within each scenario by means of smoothed centile curves against year that collectively define the conditional probability density function for crude oil production or crude oil export capacity given each year.

2.2. Model initialization and data

The ACEGES model is initialized with the observational data. This requires setting a base year, which in this study is 2001. In other words, each of the 216 countries in the ACEGES model is initialized with the real-world data as of 2001 while the first simulated year is 2002. Although it is possible to initialize the model with the base year other than 2001, we selected 2001 to compare the country-specific results with the global results reported by Voudouris et al. (2011).

The ACEGES model is initialized with the following data for each country:

(i) The domestic demand of crude oil in 2001 (following Hallock et al., 2004 and Voudouris et al., 2011, the domestic demand is an adjusted demand for total petroleum liquids—an averaged proportion of the demand for liquefied petroleum gas from EIA, 2011. The averaged proportion represents the part of the liquefied petroleum gas consumption covered by the natural gas plant liquids production rather than crude oil).
(ii) The projected growth rates of oil demand using the three scenarios (i.e. Current Policies Scenario, New Policies Scenario, and 450 Scenario) of IEA (2010).
(iii) The volume of producible crude oil originally present before any extraction (i.e. EUR, the total of cumulative production, proved reserves, estimates of undiscovered reserves, and possible reserves growth) from (a) Campbell and Heapes (2008): data available for 62 countries with global EUR of 1.9 trillion barrels; (b) EUR 5%-probability of USGS (2002): data available for 52 countries with global EUR of 3 trillion bbl (excluding reserves growth); (c) BGR, 2009: data available for 132 countries with global EUR of 419 Gt (3.1trillion bbl) (d) CIA (2010): data available for 93 countries with global EUR of 2.4 trillion bbl. Note that CIA (2010) provides estimates of the proved reserves of crude oil at the beginning of 2009. Therefore, EUR of CIA (2010) is the sum of (1) the cumulative production for all the countries up to

2008 using the data sources discussed in (v) below and (2) the proved reserves. Also note that it does not include undiscovered oil. The main advantage of this is the construction of EUR for 93 countries. This is important because by modeling more of the countries of the world, and having both production and demand for them, the model has a more accurate picture of the net demand for imports, which is what is being apportioned among the pre-peak net producers.

(iv) The annual crude oil production for 2001 (crude oil including lease condensate) from EIA (2011). Because of the use of crude oil, we are really testing whether the EUR estimates, in the form of crude oil, generate results consistent with the empirical data.

(v) The cumulative production at the start of 2001. The cumulative production (1859–2001) is based on (a) API (1971) before 1964; (b) DeGolyer and MacNaughton (2006) from 1964 to 1994; (c) EIA (2011) from 1994 to 2001. The production data is adjusted following Voudouris et al. (2011) to fit to the definition of EIA (2011), which includes crude oil and lease condensate.

(vi) The estimates of crude oil remaining at the start of 2001, which is (iii)–(v).

(vii) The maximum allowable projected growth rates of oil production. This defines the constrained oil production from t to $t+1$. We use the values between 0.05 and 0.15, which are defined based on literature review and our own calculations (Voudouris et al., 2011).

(viii) The assumed peak/decline point (e.g. 0.5 of EUR). We use the values between 0.35 and 0.65 of EUR, which are defined based on literature review and our own calculations for post-peak countries (Voudouris et al., 2011).

Because the crude oil production and demand data by EIA (2011) contain quantities not included in the estimates of EUR by BGR, 2009, Campbell and Heapes (2008), and USGS (2002), we corrected for this by multiplying historical demand and production data by a country-specific ratio. Our approximations of the correction ratios are estimated following a modification of the approach outlined by Hallock et al. (2004) (see also Section 2.2 of Voudouris et al., 2011). Clearly, because of the different timing assumptions, these country-specific ratios are approximations of the true unknown country-specific ratios. Therefore, the results reported here should be interpreted as approximations of crude oil production and export capacity.

In this study, we do not aim to estimate EUR of crude oil (e.g. Caithamer, 2008; Campbell and Heapes, 2008; Nashawi et al., 2010; USGS, 2002). Rather, we focus on exploring plausible pathways of crude oil export capacity and production given a broad range of EUR (and also the other parameters shown above) estimates reported in literature.

2.3. Collective View Scenario

We developed a scenario by probabilistically sampling the uncertainty parameter-space to analyze crude oil production and export capacity. The uncertainty space is defined by (i) a range of EUR estimates, (ii) variations in the proportion of EUR extracted at the decline point, (iii) the annual demand growth for oil, and (iv) potential limits to the abilities of countries to increase annual production. In particular, the ACEGES model uses a Monte Carlo process to sample the uncertainty space while each scenario needs a number of simulation runs, say 1000 simulations, to explore the full uncertainty space of the scenario. The Monte Carlo process of the ACEGES model is based on historically driven uniform distributions for the peak/decline point, production growth, and EUR estimates. The uniform distribution for the demand growth is based on IEA (2010), which also includes 'forces in the pipeline' such as policies that will be implemented. Each of the four uniform distributions is country specific. By using the uniform distribution, we put an equal weight between the minimum and maximum such as the demand growth for oil based on the scenarios presented in IEA (2010). The latter implies that our scenario assumes that the future in terms of the demand for oil will be a combination of the Current Policies Scenario, New Policies Scenario, and 450 Scenario of IEA (2010). Therefore, we name our scenario as the "Collective View Scenario."

A number of caveats are in order, given the range of uncertainties in existing estimates of EUR, upstream investments for production growth rates, and socio-economic policies affecting oil demand growth. Here we did not consider non-cheap or unconventional oil such as extra-heavy oil, oil sands, and ultra-deep-water oil. While the world does contain large amounts of 'non-chap' oil resources that can substitute for 'cheap' crude oil, the substantially higher capital and production costs, requirements for natural gas for upgrading, and the environmental impacts associated with extracting these resources make their potential contribution to the world oil mix unclear (George, 1998; Hallock et al., 2004). Because we use estimates of EUR, we also implicitly assume that 'reserves growth' and 'to be discovered oil' will become 'known' and economically recoverable at some point in time. This clearly also assumes that the price levels to reclassify 'to be discovered oil' and 'reserves growth' into 'known oil' will not retard demand significantly. For the demand growth rates, we assume that the demand growth rates for oil given in IEA (2010) already include the manifestation of possible future advances so that the estimates of EUR become available on time for extraction. Because these demand growth rates are based on specific oil price projections, oil prices are only indirectly represented in the current implementation of the ACEGES model. This approach is consistent with the other studies in the literature such as Hallock et al. (2004).

Although we report here the export capacity and production of the OPEC Middle East countries based on the Collective View Scenario, we evaluated 216 countries in order to assess the net world demand that needs to be met. From this net world demand, we then estimated the 'call on the OPEC' based on Eq. (5) in Voudouris et al. (2011).

In this study, we run the model from 2001 to 2050.

2.4. GAMLSS framework

GAMLSS statistical models are semi-parametric regression type models. They are parametric in that they require a parametric distribution assumption for the response variable, and 'semi' in the sense that the modeling of the parameters of the distribution, as functions of explanatory variables, may involve non-parametric smoothing functions.

In GAMLSS, the exponential family distribution assumption for the response variable (Y), such as oil production or oil export capacity, is relaxed and replaced by a general distribution family, including highly skew and/or kurtotic continuous and discrete distributions. The systematic part of the model is expanded to allow modeling not only of the mean (or location) but other parameters of the distribution of Y as, linear and/or non-linear, parametric and/or smooth non-parametric functions of explanatory variables. Hence, GAMLSS is especially suited to modeling a response variable which does not follow an exponential family distribution (e.g. leptokurtic or platykurtic and/or positively or negatively skew response variable) or which exhibit heterogeneity (e.g. where the scale or shape of the distribution of the response variable changes with explanatory variable(s)).

A GAMLSS model can be defined as $M=\{D, G, T, \Lambda\}$ where D specifies the distribution of the response variable Y, G specifies the set of link functions, T specifies the predictor terms (e.g. year), and Λ specifies the smoothing hyper-parameters. The distribution D can have up to four parameters, μ, σ, ν, and τ, representing respectively the location, scale, and two shape parameters to allow for skewness and kurtosis in the distribution.

The GAMLSS model is defined by

$$\begin{aligned} g_1(\mu) &= \eta_1 = X_1\beta_1 + \sum_{j=1}^{J_1} h_{j1}(x_{j1}) \\ g_2(\sigma) &= \eta_2 = X_2\beta_2 + \sum_{j=1}^{J_2} h_{j2}(x_{j2}) \\ g_3(\nu) &= \eta_3 = X_3\beta_3 + \sum_{j=1}^{J_3} h_{j3}(x_{j3}) \\ g_4(\tau) &= \eta_4 = X_4\beta_4 + \sum_{j=1}^{J_4} h_{j4}(x_{j4}) \end{aligned} \quad (1)$$

where each h_{jk} function is a smooth non-parametric function of an explanatory variable x_{jk}.

Specifically, the GAMLSS model in Eq. (1) allows the user to model each distribution parameter as a linear function of explanatory variables and/or as semi-parametric functions such as penalized beta (regression) splines introduced by Eilers and Marx (1996).

When a single explanatory variable is used, the model (Eq. (1)) becomes

$$\begin{aligned} g_1(\mu) &= \eta_1 = h_1(x) \\ g_2(\sigma) &= \eta_2 = h_2(x) \\ g_3(\nu) &= \eta_3 = h_3(x) \\ g_4(\tau) &= \eta_4 = h_4(x) \end{aligned} \quad (2)$$

In the GAMLSS model (Eq. (1)), applied to a continuous response random variable, the conditional distribution of the quantile residuals $U_i = F_{Y_0}(Y_i|x_i)$, given all the values of the explanatory variable(s) x_i for observation i, is the same uniform distribution (over the range 0–1) for all i, i.e. $U_i \sim U(0,1)$. The corresponding normalized quantile residuals $R_i = \Phi^{-1}[U_i]$ have a standard normal $N(0,1)$ distribution. The subscript 0 in Y_0 indicates that this is the original GAMLSS model (Eq. (1)).

Here we use a flexible extension to the GAMLSS model, by assuming that U_i have the same non-uniform distribution for all i, with probability density function (pdf) $f_U(u)$ and cumulative distribution function (cdf) $F_U(u)$. The approach is known as calibration (e.g. Efron and Tibshirani, 1994). Calibration applied to the GAMLSS model is described below. The calibration approach used here has the advantage that it makes the sample percentage below every centile curve equal to its desired centile percentage.

Hence, we fit the common distribution to the observed quantile residuals u_i for $i = 1,2,\ldots,n$. This is done by estimating the common cdf $F_U(u)$ using its empirical cdf. For simplicity of presentation ignoring the subscript i and the conditioning on x_i, then $U = F_{Y_0}(Y)$. Now, let random variable $V = F_U(U)$, then it can be proved that $V \sim U(0,1)$ (i.e. a uniform distribution over the range 0–1). Therefore, $V = F_U[F_{Y_0}(Y)]$ and $Y = F_{Y_0}^{-1}[F_U^{-1}(V)]$, where F^{-1} indicates the inverse cdf.

Hence, the true pdf of Y is given by $f_Y(y) = f_U[F_{Y_0}(y)]f_{Y_0}(y)$ and the true cdf of Y is $F_Y(y) = p(Y \le y) = p(U \le u) = p(V \le \nu) = \nu$ since $V \sim U(0,1)$, where $\nu = F_U[F_{Y_0}(y)]$.

Hence, a centile value y for Y corresponding to probability ν is given by $y = F_{Y_0}^{-1}[F_U^{-1}(\nu)]$ or $y = F_{Y_0}^{-1}[u]$ where $u = F_U^{-1}[\nu]$. Here ν is the output (or desired) centile probability for Y and u is the input centile probability for Y_0 put into $y = F_{Y_0}^{-1}[u]$ in the original GAMLSS model to achieve the desired probability ν for Y.

Now, the estimated centiles for Y with desired probability ν are given by $y = \hat{F}_{Y_0}^{-1}[\hat{u}]$ where $\hat{u} = \hat{F}_{Y_0}^{-1}[\nu]$ using the inverse cdf of the fitted original GAMLSS model and the inverse of the empirical cdf of u respectively.

The use of centiles enables us to provide probabilistic statements about the future production and export capacity of the selected countries given the ACEGES-based Collective View Scenario. Following Voudouris et al. (2011), the Collective View Scenario is presented using centile curves rather than single lines. However, in order to avoid using centile curves from different distributions (because different countries might need different distributions to capture their production and export capacity over time), here we fix the distribution that summarizes the ACEGES-based scenario by employing the calibration methodology as discussed above.

3. Results

Here we show the results of the analysis on a country basis focusing on the six OPEC Middle East countries because of the significance and influence of these countries on the world crude oil markets. Before observing the export capacity of the six countries, we first show the trajectories of crude oil production.

3.1. Crude oil production for the OPEC Middle East countries

The centile curves for crude oil production for each country were estimated by the fitting GAMLSS model (Eq. (2)) using the SHASH (Sinh-Arcsinh) distribution (Jones and Pewsey, 2009) for crude oil production (with separate calibration for each country). The data used for the fitting was the simulated crude oil production (Y) against time (X), obtained from the ACEGES model. The SHASH distribution was selected based on the worm plot (Van Buuren and Fredriks, 2001), detrended Owen's plot (Owen, 1995), and Akaike information criterion. In addition, the maximum oil production and peak year for all simulations (separately for each country) were saved and the median and 99% interval for maximum oil production and year were calculated.

Fig. 3 shows crude oil production for Saudi Arabia. The curves are the smoothed centile curves for crude oil production against year, while the dots are the simulated crude oil production from the ACEGES model. Saudi Arabia has the largest crude oil reserves in the world (see Table 1 above), thus it will basically remain the significant crude oil producing country. In addition, its energy

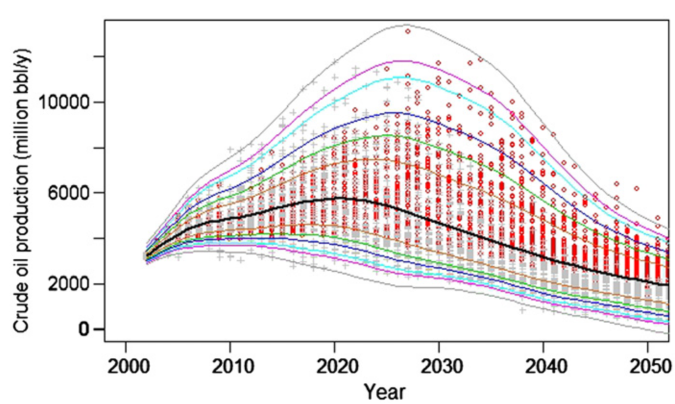

Fig. 3. Probabilistic trajectories of crude oil production for Saudi Arabia. Centile curves of 0.1, 0.5, 1, 5, 10, 20, 50, 80, 90, 95, 99, 99.5, and 99.9%. The red-circle dots indicate crude oil production that corresponds to above average EUR estimates while the gray-plus symbols correspond to below average EUR estimates (same for Figs. 4–9). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

policy is moderate compared to the other OPEC countries and it has remaining power for additional supply of crude oil (Stevens, 2012). Consequently, there is no doubt that it will continue to be a key player in the world crude oil markets.

The result shows that the annual production will increase from 2931 million bbl/y in 2001. The central 50% centile projection is shown by the black curve (same for the other figures below), and the peak will be approximately 5800 million bbl/y in around 2020. This means that the production of Saudi Arabia will reach around one fifth of the world production, which is approximately 30,000 million bbl/y for the 50% centile case (Voudouris et. al., 2011).

The maximum crude oil production and peak year for Saudi Arabia were obtained from all the simulations giving medians 7100 million bbl/y and year 2020 with 99% intervals (3400, 12,300) million bbl/y and year (2006, 2038), respectively. Note that the median of the maximum (i.e. peak) oil production is different from the oil production peak of the median curve. Similarly, the median of the peak year is different from the peak year of the median curve.

In general, the higher production curves (upper production frontiers) would be realized when higher estimates of EUR, higher maximum allowable production growth rate, and higher peak/decline point are combined. On the other hand, when lower estimates of EUR, lower maximum allowable production growth rate, and lower peak/decline point are combined, then lower production curves (lower production frontiers) are likely to be realized. It is important to note that the relationship between higher estimates of EUR and upper production frontiers is not particularly strong because the other key three uncertainties also affect the production profile. Having said that a reasonable degree of correlation is visually observed in Fig. 3 where the simulated crude oil production corresponding to above average EUR estimate are represented by the red-circle dots.

The production profiles of the other countries are shown in Figs. 4–8. Similar to Fig. 3, the curves are the smoothed centile curves against year estimated using the SHASH distribution of the GAMLSS framework (with calibration for each country) based on the Collective View Scenario. The annual crude oil production of Iran, Iraq, Kuwait, UAE, and Qatar is also expected to increase from their 2001 level, namely 1359 million bbl/y, 872 million bbl/y, 729 million bbl/y, 805 million bbl/y, and 261 million bbl/y, respectively. The figures show that the peak production for the 50% centile curve will be approximately 4000 million bbl/y in around 2029 for Iran, 3400 million bbl/y in around 2033 for Iraq, 1100 million bbl/y in around 2015 for Kuwait, 1800 million bbl/y in around 2022 for UAE, and 440 million bbl/y in around 2018 for Qatar.

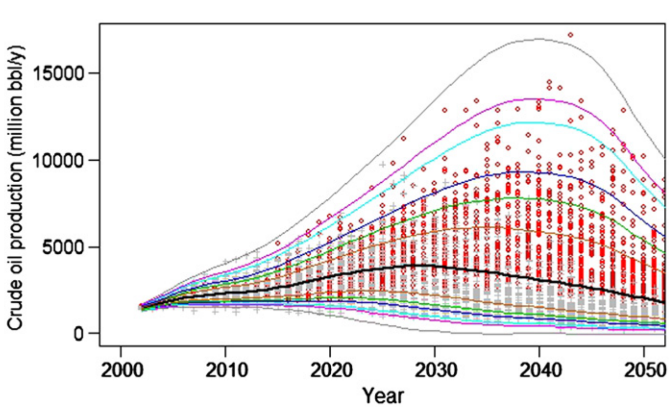

Fig. 4. Probabilistic trajectories of crude oil production for Iran. Centile curves of 0.1, 0.5, 1, 5, 10, 20, 50, 80, 90, 95, 99, 99.5, and 99.9%.

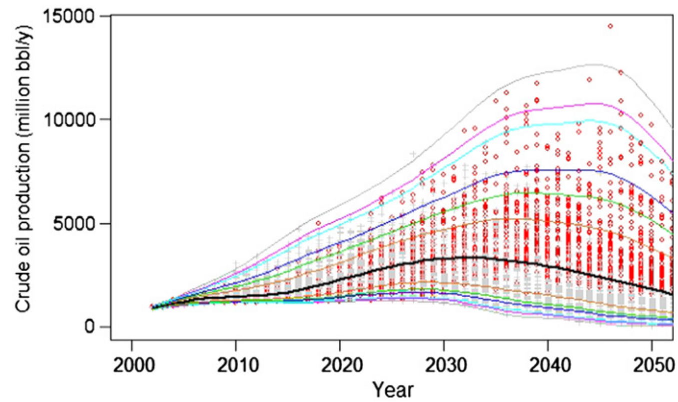

Fig. 5. Probabilistic trajectories of crude oil production for Iraq. Centile curves of 0.1, 0.5, 1, 5, 10, 20, 50, 80, 90, 95, 99, 99.5, and 99.9%.

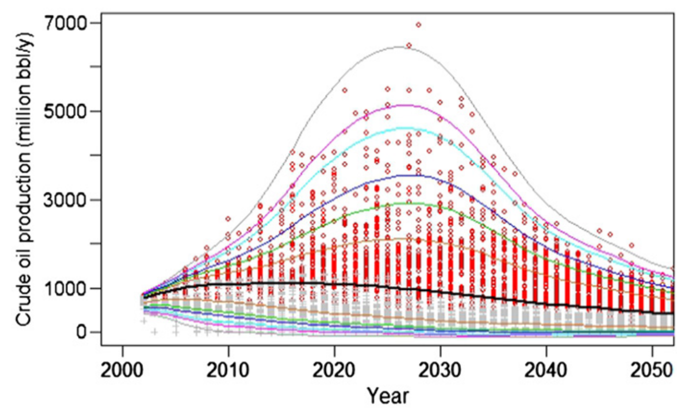

Fig. 6. Probabilistic trajectories of crude oil production for Kuwait. Centile curves of 0.1, 0.5, 1, 5, 10, 20, 50, 80, 90, 95, 99, 99.5, and 99.9%.

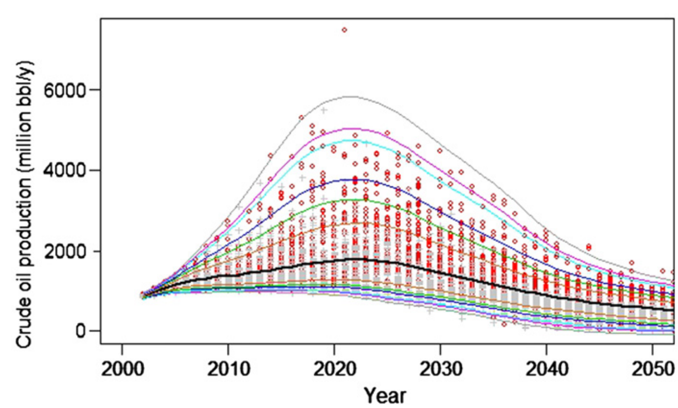

Fig. 7. Probabilistic trajectories of crude oil production for UAE. Centile curves of 0.1, 0.5, 1, 5, 10, 20, 50, 80, 90, 95, 99, 99.5, and 99.9%.

The maximum crude oil production and peak year for each country were obtained from all its simulations giving medians 5600 million bbl/y and year 2026 with 99% intervals (1500, 14,900) million bbl/y and year (2004, 2050) respectively for Iran, 5200 million bbl/y and year 2030 with 99% intervals (1800, 12,500) million bbl/y and year (2012, 2050) for Iraq, 1200 million bbl/y and year 2015 with 99% intervals (400, 6000) million bbl/y and year (2002, 2041) for Kuwait, 2100 million bbl/y and year 2021 with 99% intervals (1000, 5700) million bbl/y and year (2008, 2038) for UAE, and 530 million bbl/y and year 2017 with 99% intervals (260, 980) million bbl/y and year (2002, 2038) for Qatar.

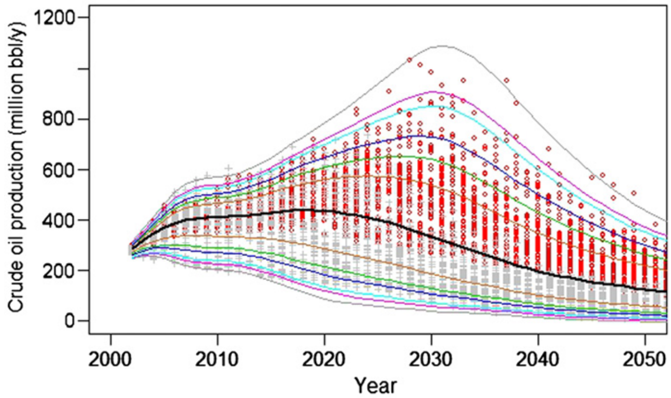

Fig. 8. Probabilistic trajectories of crude oil production for Qatar. Centile curves of 0.1, 0.5, 1, 5, 10, 20, 50, 80, 90, 95, 99, 99.5, and 99.9%.

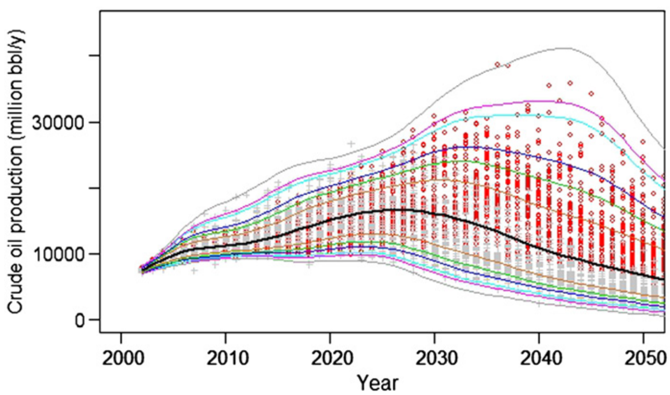

Fig. 9. Probabilistic trajectories of total crude oil production for OPEC Middle East countries. Centile curves of 0.1, 0.5, 1, 5, 10, 20, 50, 80, 90, 95, 99, 99.5, and 99.9%.

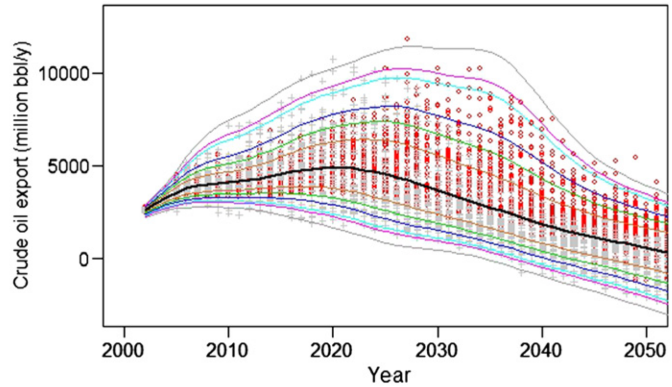

Fig. 10. Export capacity of crude oil for Saudi Arabia. Centile curves of 0.1, 0.5, 1, 5, 10, 20, 50, 80, 90, 95, 99, 99.5, and 99.9%. The red-circle dots indicate the export capacity for crude oil for above average EUR estimates, while the gray-plus symbols indicate the export capacity for below average EUR estimates (same for Figs. 11–16). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

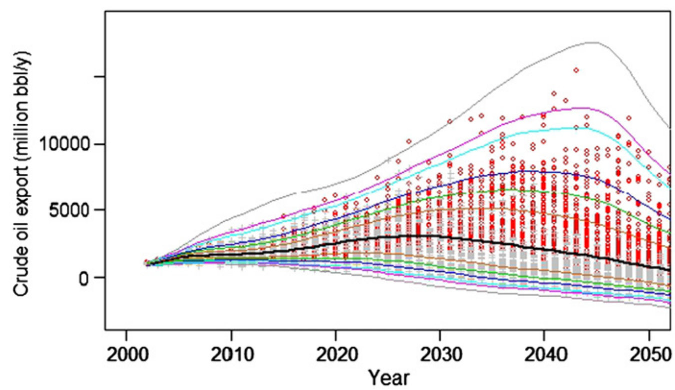

Fig. 11. Export capacity of crude oil for Iran. Centile curves of 0.1, 0.5, 1, 5, 10, 20, 50, 80, 90, 95, 99, 99.5, and 99.9%.

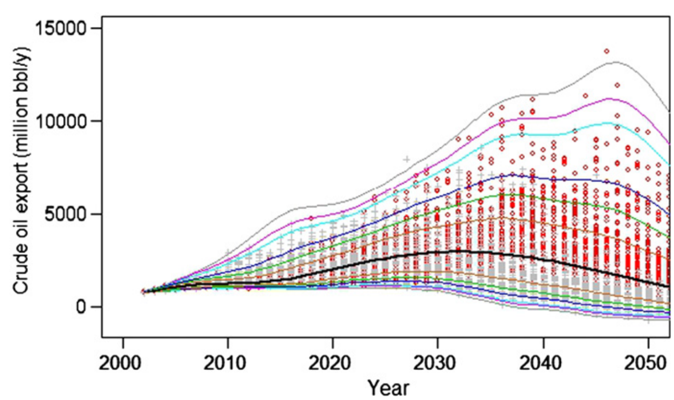

Fig. 12. Export capacity of crude oil for Iraq. Centile curves of 0.1, 0.5, 1, 5, 10, 20, 50, 80, 90, 95, 99, 99.5, and 99.9%.

In addition, Iran and Iraq have a potential to increase their crude oil production higher than Saudi Arabia in the middle of this century. This is because Iran and Iraq hold the second and third largest crude oil reserves in the world following Saudi Arabia while their present production level is much smaller than Saudi Arabia.

Totally, crude oil production of the six OPEC Middle East countries (Fig. 9) can reach its peak of approximately 16,700 million bbl/y in around 2026 for the 50% centile curve, which is about 60% of the world production. The maximum crude oil production and peak year for the six countries were obtained from all the simulations giving medians 18,900 million bbl/y and year 2027 with 99% intervals (10,300, 34,100) million bbl/y and year (2012, 2050), respectively.

3.2. *Crude oil export capacity for the OPEC Middle East countries*

Because of the relatively high potential for crude oil production increases of the six OPEC Middle East countries as describe above, their export capacity of crude oil also increases (Figs. 10–15) despite the corresponding increase of their domestic demand for crude oil. The curves are the smoothed centile curves estimated using the SHASH distribution (with calibration for each country) of the GAMLSS framework selected based on the ACEGES-based scenarios while the dots are the simulated crude oil export potential.

Saudi Arabia has the largest export capacity based on the 50% centile curve. As the figure indicates, its export capacity can be in the range of 1.1–4.6 times from the present level at the peak point. For the 50% centile curve, it can reach approximately 5000 million bbl/y in around 2021.

Similar tendencies are seen in the export capacity of the other OPEC Middle East countries. Iran has the second largest export capacity based on the 50% centile curve. Its export capacity can be in the range of 1.1–18 times from the present level at the peak point (approximately 3200 million bbl/y in around 2028 for the 50% centile curve). The third largest country is Iraq. Its export capacity can be in the range of 1.3–18 times from the present

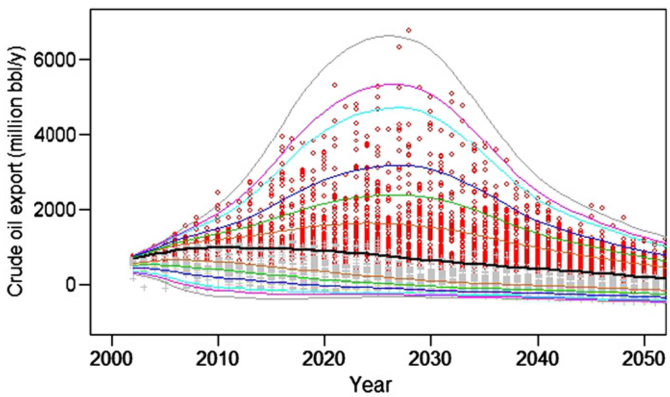

Fig. 13. Export capacity of crude oil for Kuwait. Centile curves of 0.1, 0.5, 1, 5, 10, 20, 50, 80, 90, 95, 99, 99.5, and 99.9%.

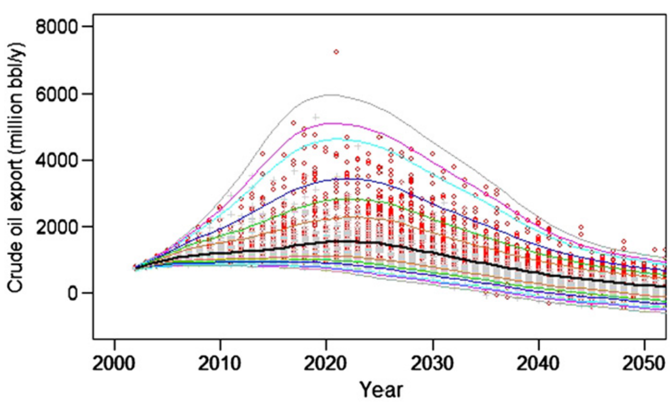

Fig. 14. Export capacity of crude oil for UAE. Centile curves of 0.1, 0.5, 1, 5, 10, 20, 50, 80, 90, 95, 99, 99.5, and 99.9%.

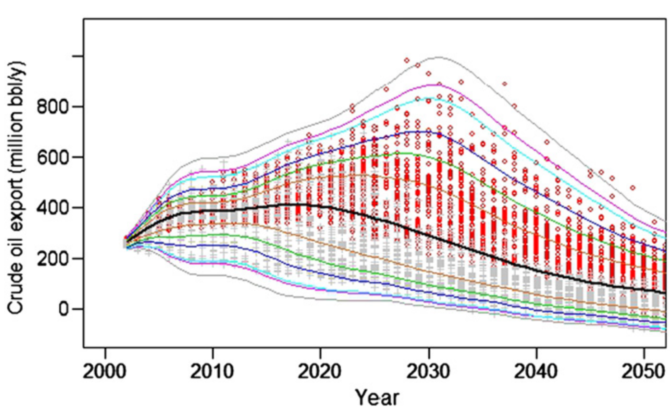

Fig. 15. Export capacity of crude oil for Qatar. Centile curves of 0.1, 0.5, 1, 5, 10, 20, 50, 80, 90, 95, 99, 99.5, and 99.9%.

level at the peak point (approximately 3100 million bbl/y in around 2032 for the 50% centile curve).

The export capacity of the other countries is that the peak point based on the 50% centile curve is approximately 1000 million bbl/y in around 2010 for Kuwait, 1600 million bbl/y in around 2022 for UAE, and 420 million bbl/y in around 2018 for Qatar.

The maximum export capacity and peak year for each country were obtained from all the simulations giving medians 6300 million bbl/y and year 2020 with 99% intervals (2800, 10,900) million bbl/y and year (2006, 2038) respectively for Saudi Arabia, 4900 million bbl/y and year 2026 with 99% intervals (950, 13,800) million bbl/y and year (2004, 2050) for Iran, 4900 million bbl/y and year 2030 with 99% intervals (1600, 12,000) million bbl/y and year (2012, 2050) for Iraq, 1100 million bbl/y and year 2014 with 99% intervals (300, 5900) million bbl/y and year (2002, 2041) for Kuwait, 2000 million bbl/y and year 2021 with 99% intervals (900, 5500) million bbl/y and year (2005, 2038) for UAE, and 500 million bbl/y and year 2017 with 99% intervals (240, 940) million bbl/y and year (2002, 2038) for Qatar.

The collective export capacity of crude oil for the six OPEC Middle East countries (Fig. 16) can reach its peak of approximately 14,400 million bbl/y in around 2026 based on the 50% centile curve. The maximum export capacity and peak year for the six countries were obtained from all the simulations giving medians 16,600 million bbl/y and year 2026 with 99% intervals (8500, 31,300) million bbl/y and year (2011, 2050), respectively.

For the lower centile curves (lower frontier of export capacity), there is a possibility that the six OPEC Middle East countries would not be net exporters of crude oil from around 2035 onwards. This can happen when the combination of the scenario is higher annual oil demand growth, lower annual production growth, and lower EUR estimates. Furthermore, even though these six countries can increase the amount of crude oil production and export capacity, the world can be short of crude oil with high probability in early this century (Fig. 17). This is happening when emerging economies increase their oil demand and heavily rely on crude oil for transportation and electricity generation.

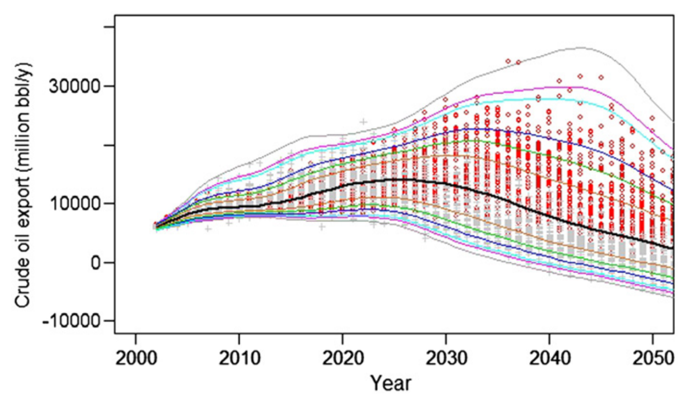

Fig. 16. Export capacity of crude oil for the total of the six countries. Centile curves of 0.1, 0.5, 1, 5, 10, 20, 50, 80, 90, 95, 99, 99.5, and 99.9%.

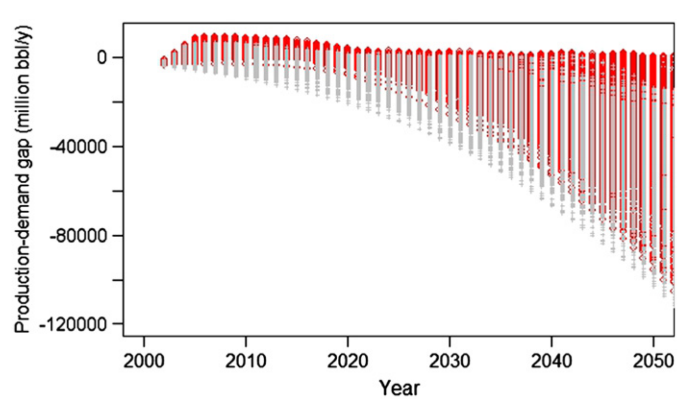

Fig. 17. Gap between production and demand of crude oil in the world. The red-circle dots indicate the gap for above average EUR estimates, while the gray-plus symbols indicate the gap for below average EUR estimates. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In this case, we will likely observe a sharp price rise and fall in demand. The crisis might necessitate a higher penetration of extra-heavy oil, ultra-deep-water oil, and oil sands, and/or a shift to other energy sources such as natural gas and renewables.

In summary, the peak of country-specific crude oil production and export capacity is likely to come within the first half of this century for the OPEC Middle East countries, the tendencies of which are similar to the global peak as indicated in Voudouris et al. (2011) which may be caused by the behavior of these countries. The OPEC Middle East countries will continue to be a dominant group in the world crude oil markets for the foreseeable future.

4. Concluding remarks

We recognize that it is nearly impossible to predict the exact future evolution of country-specific crude oil export capacity. However, we consider it is realistic to provide plausible scenarios based on the information available today. The information used in designing scenarios should be based on the history and current forces in the pipeline. Such scenarios should not be based on wishful thinking, but alternative options should be explored by means of controlled computational experiments.

It was demonstrated that the ACEGES model offers a new and novel way for exploring plausible futures of the country-specific dynamics for crude oil production and export capacity. We have also applied a statistical technique, the GAMLSS framework, as a way of analyzing and summarizing the ACEGES-based scenario.

The ACEGES model can simulate a large number of combinations of scenarios by adjusting any of the most important and uncertain driving forces of the scenarios. We here presented results of crude oil production and export of the six OPEC Middle East countries, which had so far played significant roles and were expected to keep playing significant roles in the world crude oil markets. These simulated results were analyzed using the GAMLSS framework by selecting the SHASH distribution (with calibration for each country). Given the Collective View Scenario, the results indicate that the peak year of crude oil production of the OPEC Middle East countries might happen between 2018 and 2033 for the 50% centile curve. The peak year of the export capacity of crude oil of these countries might happen between 2010 and 2032 for the 50% centile curve. Furthermore, we cannot reject the claim that the OPEC Middle East countries will necessarily manage to avoid a gap between world crude oil demand and supply. An oil crash would put additional pressure on developing extra-heavy oil, ultra-deep-water oil, and oil sands.

In our view, all of the trajectories are plausible portrayals of the future of crude oil production and export given the combinations of the uncertainties. Therefore, we provide the range of the future situations considering possible uncertainties rather than a point forecast.

Our purpose of a series of studies using the ACEGES model is to provide a computational model that can be used as a research and planning method for long-term energy planning and investment processes by policy makers and industries. Therefore, we should consider not only crude oil but also expensive oil resources in the model for the future study.

Disclaimer

The views expressed in this article are those of the authors and do not necessarily represent those of Deutsche Bank SpA and ABM Analytics Ltd.

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