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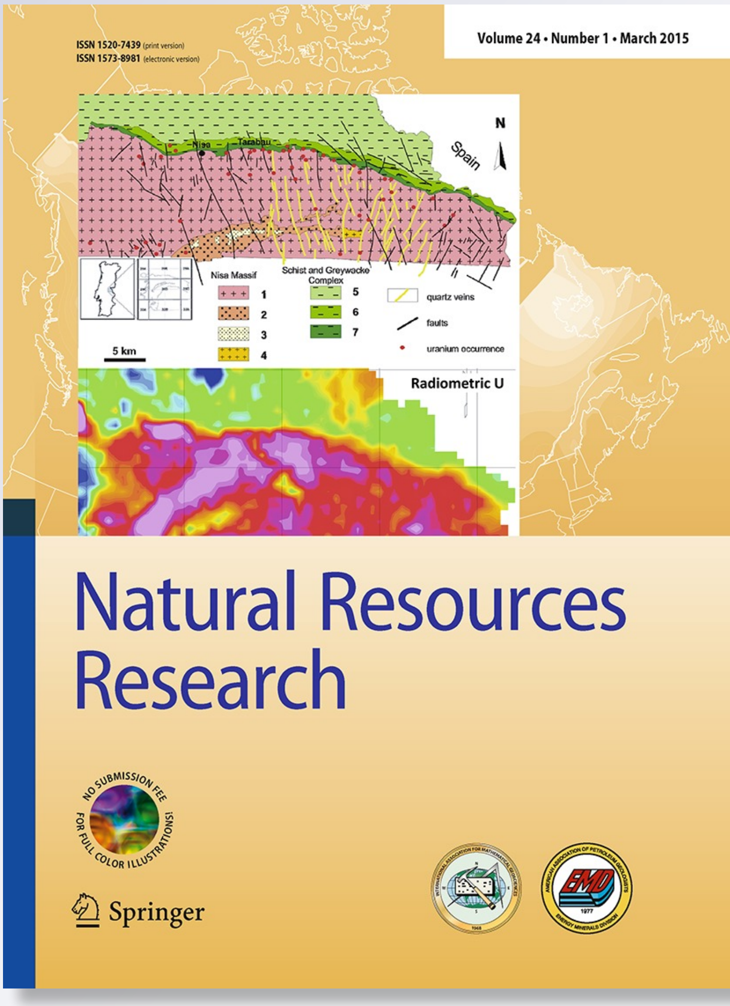

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Potential Impact of Unconventional Oil Resources on Major Oil-Producing Countries: Scenario Analysis with the ACEGES Model

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The role of unconventional oil is increasing in global energy markets. Although conventional oil is being depleted, unconventional oil might manage or eliminate supply constraints in meeting the demand for oil without large positive step changes in the prices. In this study, we use the ACEGES model, which is agent-based, to explore the potential impact of unconventional oil on the evolution of the oil markets, focusing on four important oil-producing countries. We also use quantile sheets to summarize the simulation results. Given the estimated potential of conventional and unconventional resources, the results suggest that the production profiles will change tremendously. Although countries rich in conventional oil, such as Saudi Arabia and Iran, will still occupy the global oil markets for approximately the first half of this century, oil production in countries with rich unconventional resources, such as Canada and Venezuela, will be higher in production than Saudi Arabia and Iran from 2050 to 2060. This change in production means that the market power in the global oil markets will shift from Middle Eastern countries to Canada and Venezuela in this century.

KEY WORDS: Unconventional oil, Resource depletion, Uncertainties, Scenario analysis, ACEGES.

INTRODUCTION

Secure, sustainable, and competitive energy is fundamentally important to individual countries' economy, industry, and citizens, and producing it is a core goal of their policy. To achieve this goal, policymakers need adequate instruments to act within their borders and to promote their interests in relation to other countries.

Energy, particularly oil and natural gas, is a global business. This means that countries face growing competition for fossil fuel resources, including competition from emerging countries and the energy producers themselves. The growth in population and the rising standards of living could push up global energy demand. Such a rise in demand is increasing global prices, bringing energy impoverishment to many and wreaking havoc on countries where fossil fuel subsidies prevail.

Fossil fuels are widely used around the world to fuel economic activities. The global oil and natural gas markets are likely to undergo a dramatic change over the next few decades. Recently, the role of unconventional energy resources, such as oil sands and extra-heavy oil (for oil), and shale gas and coal bed methane (for natural gas), has increased in the global energy markets. Although we now face the scarcity of conventional fossil fuel resources, such unconventional energy resources might manage or eliminate supply constraints in meeting the demand

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for oil and natural gas without large positive step changes in the price of energy resources.

Many modeling approaches for forecasting oil production can be classified into two types: top-down models, which forecast aggregate production through some form of extrapolation of aggregate variables (e.g., curve-fitting, system dynamic simulations, and macroeconometric models); and bottom-up models, which represent the supply chain of the upstream oil industry and forecast aggregate production as the sum of production from smaller units [e.g., scenarios in the World Energy Outlook of the International Energy Agency (IEA) and the Annual Energy Outlook of the US Energy Information Administration (EIA)] (Jakobsson et al. 2014).[4] The impact of top-down models on decision-making is insignificant, whereas bottom-up models are continuously used by energy companies, energy consultancy firms, banks, and public institutions to guide investments and policymaking (Jakobsson et al. 2014).

Many studies, however, using different types of top-down models (e.g., variants of the Hubbert model, the generalized Bass model, the depletion rate model, the demand-production interaction model, and a combination of some approaches) are seen as analyzing the outlook for oil production, e.g., the Hubbert approach (Caithamer 2008; Nashawi et al. 2010); the depletion rate approach (Campbell and Heapes 2008; Hallock et al. 2004); the Bass model (Guseo 2011); growth model (Höök et al. 2011); the demand–supply interaction (Mohr 2010); a combination of the Hubbert and Bass models (Mohr and Evans 2010a); and other mathematical models (Mohr and Evans 2007, 2008, 2009). (See also Höök (2014) for more about studies on depletion rate modeling.) These studies are based on the general family of nonlinear (parametric) regression models. In such studies, forward-looking outlooks for global oil production, including unconventional energy resources, have not been explored with the same level of intensity compared with those that did not include them, despite their growing importance in fueling socio-economic activities as described previously (Guseo 2011; Mohr and Evans 2010b). In addition, the studies have different levels of inclusion of unconventional resources. Guseo (2011), for example, treats the estimated ultimate recoverable resources (EUR) of conventional (cheap) and unconventional (heavy) oil separately in the two-wave model and estimates the aggregated oil production. In this study, unconventional oil is not separated by type. Mohr and Evans (2010b), on the other hand, simply analyze the production of unconventional oil, but they separately model natural bitumen, extra-heavy oil, and shale oil.

Although curve-fitting models are the major methods as mentioned previously, bottom-up models play an important role in forecasting future oil production (Jakobsson et al. 2012, 2014). For example, Jakobsson et al. (2012) develop a bottom-up optimization model combining economic and geologic concepts, in which oil producers maximize the net present value over the field's entire production horizon. Jakobsson et al. (2014) review nine bottom-up models, which are well- or field-based models.

In this study, we use an agent-based model (ABM), the ACEGES (Agent-based Computational Economics of the Global Energy System) model[5] [first proposed by Voudouris (2011), and applied by Matsumoto et al. (2012, 2014b) and Voudouris et al. (2011, 2014)]. The ACEGES model is a bottom-up type model we use to explore the potential impact of unconventional oil resources on the future evolution of the oil markets, focusing on several important oil-producing countries. Because oil is not a homogeneous resource, we face different classification systems adopted by the EIA, the IEA, Oil and Gas Journal, World Oil Magazine, BP, and the World Oil and Gas Review, to name a few (Guseo 2011). Unconventional oil often includes natural gas liquids (NGL), heavy oils, such as tar sands and oil shales, as well as deep-water oils, and polar oils (Guseo 2011). In this analysis, we treat extra-heavy oil and oil sands as unconventional oil (see also "Model Initialization and Data" section).

Matsumoto et al. (2014b) analyze the impact of unconventional oil resources globally and find that unconventional oil can increase peak production by about 1.3 times and delay the peak year by about 60 years. However, it is important to clarify which countries will play a significant role in such

[4] Brandt (2010) also reviews several types of modeling approaches for analyzing future oil production, including top-down and bottom-up models.

[5] Nonlinear diffusion of innovation models is a common counterpart of agent-based frameworks under a mean-field approximation [see Guseo and Guidolin (2008, 2009, 2010, 2011, 2014) and Guseo and Mortarino (2012)].

effects, and how and when the global market power will change. As discussed by Voudouris et al. (2011), the key advantage of the ACEGES model is that a high degree of heterogeneity is easily incorporated in the scenarios, while the macroscopic phenomena (i.e., global oil markets in this study) emerge from the bottom up rather than being predefined by the Walrasian Auctioneer[6] with specific statistical and mathematical properties. Therefore, key uncertainties (e.g., the EUR, demand and production growth, and the state of depletion at the peak) are country specific and can be explored with (a) parametric and/or non-parametric distributions based on historical observations and/or (b) subjectively defined by users based on personal experience and ''forces in the pipeline'' (e.g., upstream investment policies that have been announced but not yet implemented).

The ACEGES-based scenario narrative is constructed from key information extracted from simulated outputs. In this study, we apply the quantile sheets (Schnabel and Paul 2013) to summarize simulation results and we propose a method for developing continuous scenarios of the global oil markets that consider unconventional oil resources using the ACEGES model. Scenarios are coherent and credible alternative stories about the future, based on the identified driving forces. Following DuMoulin and Eyre (1979), a scenario is a planning technique (a) to examine future plausibility and (b) to learn plausible forms energy crises may take in the future.

The rest of the paper is constructed as follows. In ''Methods'' section, we outline the ACEGES model, particularly the decision rule of the agents (countries). Because the ACEGES model is a realistically rendered ABM, we also discuss how the model is initialized with observational data and how heterogeneity is introduced in the scenarios. In ''Results and Discussions'' section, we present the results of the scenario, focusing on the selected major oil-producing countries. The narratives of the scenario are summarized with the estimated time-varying quantiles. In ''Concluding Remarks'' section, we conclude this study.

[6] The Walrasian Auctioneer aggregates the demands and supplies submitted by agents wishing to trade their assets in a market and then announces the first potential trading price (Bauwens and Giot 2001).

METHODS

The ACEGES Model

The ACEGES model is an ABM for exploratory energy policy. The ABM is a relatively new, flexible modeling framework for the computational study of socioeconomic and natural processes (Epstein 2007; Tesfatsion 2006). The ABM paradigm conceptualizes, in this instance, the global oil markets as a complex, adaptive system of interacting agents (countries) that do not necessarily possess perfect rationality and information. In Figures 2 and 4 in Voudouris et al. (2011), the ACEGES-based simulation shows a good trajectory of historical production. The median of simulation results is in line with the history on the global level (see also, Fig. 1 in Voudouris and Di Maio (2010) for the world oil production and Fig. 13 in it for the selected countries).[7] Although the current model framework follows the specifications of Matsumoto et al. (2012) and Voudouris et al. (2011), it is enhanced by incorporating unconventional oil resources.

Until recently, the contribution of unconventional oil in supplying the economy was very limited (Campbell and Laherrére 1998; Guseo 2011); consequently, the rate of exploiting unconventional oil resources might differ from that of conventional oil resources. However, reduction in cost caused by technology and regulatory changes is expected to happen for developing unconventional oil resources in the near future, as we have experienced in shale gas production in United States, since oil remains one of the most important energy sources for the society. For example, production of oil sands in Canada is gradually increasing (CAPP 2013). Since the ACEGES model develops long-term scenarios for this century, about 100 years, we assume that the rate of exploitation of unconventional oil resources is same as that of conventional oil resources.[8]

The ACEGES model is based on the framework proposed by Voudouris (2011). The mathematical description of the oil production of the

[7] It is not clearly stated in Voudouris et al. (2011), and only figures are shown.

[8] Note that it does not mean that the rate of exploiting the resources is stable, but it can depend on the amount of the remaining resources, and on technological, economic, political, and/or geological conditions.

ACEGES model, the key idea of which is based on Hallock et al. (2004), is expressed as follows [the following explanation is from Voudouris et al. (2011). See also Voudouris and Di Maio (2010)]:

$$p_{a_t} = p_{a_{t-1}} + g_{a_t} \times d_{a_{t-1}} \times wd_{a_t} \quad (1)$$

$$p_{a_t} = p_{a_{t-1}} + g_{a_t} \times d_{a_{t-1}} \quad (2)$$

$$p_{a_t} = p_{a_{t-1}} - (p_{a_{t-1}} \times (p_{a_{t-1}}/y_{a_{t-1}})) \quad (3)$$

$$wd_{a_t} = (nwd_{t-1}/nppnp_{t-1}) \times (p_{a_{t-1}}/mp_{t-1})) \quad (4)$$

where t is time; a is country; p_{a_t} is annual oil production of a_t; g_{a_t} is oil demand growth of a_t; d_{a_t} is oil demand of a_t; y_{a_t} is oil yet to be produced by a_t at the beginning of t; wd_{a_t} is amount of demand to be satisfied by a_t if it is a net producing country; nwd_t is net world demand at t; $nppnp_t$ is total number of pre-peak net producers at t; mp_t is mean production from the pre-peak net producers at t.

Following Campbell (1996), Eq. (1) represents the production decision of the swing countries. This decision is based on the assumption that (a) the swing countries will continue to produce oil to fulfill the net unfulfilled global demand for oil and (b) the swing countries will not produce oil at their maximum capacity, unless it is necessary. Therefore, they will choose to produce the minimum between their production capacity and Eq. (1). This is, effectively, an approximation of the consumers' logic, an approach first developed by Royal Dutch Shell (Jefferson and Voudouris 2011).

Equation (2) is adjusted (as needed) based on the maximum allowable (country specific) production growth from time t to $t + 1$. This model specification is important, for example, in cases where a country (e.g., a pre-peak producer) has enough reserves but cannot meet its domestic demand for oil because of below- and/or above-ground constraints, or because it is uneconomical to further stimulate capacity growth (as it can be less expensive to import oil, until the "organic" growth in the production capacity from t to $t + 1$ meets the domestic demand). Equation (3) shows the production decision of post-peak producers, and Eq. (4) is net unfulfilled global demand fulfilled by a_t.

Figure 1 displays the decision rule for oil production of the agents in the ACEGES model. Since the ACEGES model represents 216 countries, the behavior rule shown in Figure 1 is country specific. In the current implementation of the ACEGES model, countries only consuming but not producing oil have the following attributes: oil demand d_{a_t} and oil demand growth g_{a_t}. Furthermore, these countries have a single operation representing their individual demand for oil.

The key idea is that an agent's oil production tends to peak when approximately the peak/decline point of the EUR has been extracted (Hallock et al. 2004).[9] In particular, if $p_{a_t} = 0$, then the agent always exits with production = 0. If $p_{a_t} > 0$, the agent checks if it is a pre-peak producer, i.e., if the cumulative production is less than the "EUR×peak/decline point." If this is true, then the agent checks if it is a pre-peak net producer—it can cover its domestic demand. If it is a pre-peak net producer, then Eq. (1) is selected. If the agent is not a pre-peak net producer, then Eq. (2) is selected. If the cumulative production is larger than the "EUR×peak/decline point," then Eq. (3) is selected. It assumes $p_{a_t}/\, y_{a_t} = p_{a_{t-1}}/\, y_{a_{t-1}}$ which corresponds to the reserve-to-production ratio (R/P) being constant post-peak for each agent a. Equation (1) uses wd_{a_t}, given by Eq. (4). Effectively, Eq. (4), which is a re-parameterization of the equation used by Hallock et al. (2004), assumes that agents with larger $p_{a_{t-1}}$ would have the capacity to produce additional oil and be able to increase production to meet net world demand. Reynolds and Baek (2012) discuss that a tight oil supply can cause increases in the oil price, using an autoregressive distributed lag (ARDL) bound testing with the Hubbert curve. Since the ACEGES model, however, uses the IEA (2012) for the projected demand growth rates that are based on specific oil price projections (see section "Model Initialization and Data"), it is assumed that the price information is already included in the demand growth, although only in an indirect way [see section "Scenario" and Matsumoto et al. (2012)]. Therefore, it can be said that oil producers can benefit by producing wd_{a_t}, if they have sufficient capacity for the production [Eq. (1)].

Pre-peak net producers are countries with a large amount of resources (compared with their cumulative production) and production greater than the countries' domestic demand (e.g., OPEC countries). By definition, the number of pre-peak net producers decreases with time. They are the key players in the global oil markets.

The ACEGES model can also be used for thought experiments by interactively adjusting the model's most important and uncertain parameters

[9] See also the depletion analysis by Höök (2014), which shows that peak of production is usually less than 50 % of the EUR.

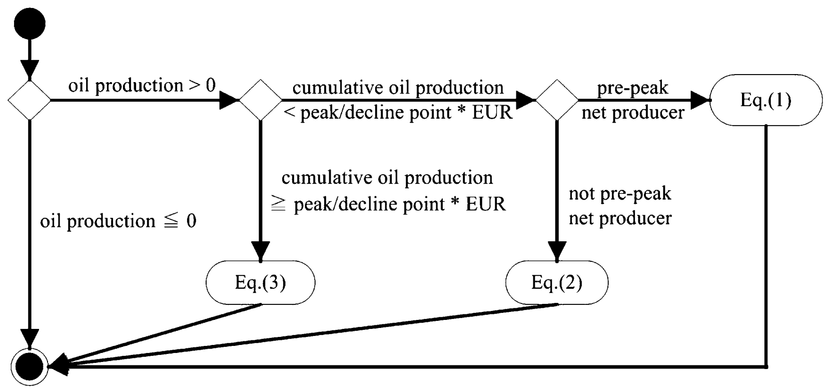

Figure 1. Simplified behavioral rule for production [created based on Voudouris et al. (2011)].

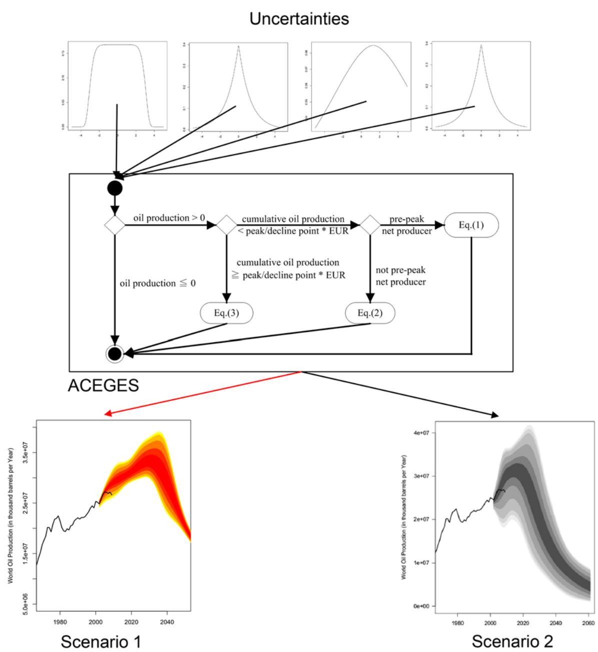

Figure 2. Scheme of ACEGES-based scenarios [created based on Voudouris et al. (2014)].

(see section "Scenario"). For example, Fig. 2 shows that key uncertainties are not necessarily restricted to a limited set of values but are defined by highly flexible probability distributions. Using the simulation engine of the ACEGES model, country-specific distributions are used to explore the full uncertainty space of scenarios by running many simulations.

As discussed by Jefferson and Voudouris (2011), the ACEGES model supports the development of scenarios with computational experiments to portray plausible futures. The key advantage of the ACEGES model is the explicit modeling of 216 countries and a high degree of complexity that can be introduced to explore the uncertainties of global oil market outlooks.

Model Initialization and Data

There are two categories of oil resources: conventional and unconventional. Conventional resources are extracted from oil fields. In contrast, unconventional resources are those produced in places where conventional resources are not produced (EIA 2014) and include oil sands and extra-heavy oil. Recently, US shale gas production has boomed as an unconventional natural gas resource. For oil, Orinoco extra-heavy oil in Venezuela and the oil sands in Canada are especially important commercial unconventional resources. This study treats oil sands and extra-heavy oil as described above.

The ACEGES model requires a base year to be set, which in this study is 2008. This means that each of the 216 countries handled in the ACEGES model is initialized with real-world data as of 2008. As explained below, the ACEGES model requires historical data for the analysis. In such a case, however, historical cumulative data rather than historical trends are used in the model.

The ACEGES model is initialized with the following data for each country, depending on the requirements of the scenario:

(i) The annual domestic demand of oil in the base year (EIA 2012).
(ii) The projected growth rates for oil demand using the three scenarios of the IEA (2012)

(i.e., the Current Policies Scenario, the New Policies Scenario, and the 450 Scenario).

(iii) The volume of producible conventional oil that exists before any is extracted (i.e., the EUR, the total cumulative production, proved reserves, estimates of undiscovered reserves, and possible reserves growth) from (a) Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), data available for 132 countries (BGR 2011) and (b) the sum of the cumulative production [see (v) below] and the latest proved reserves (EIA 2012) for countries not included in BGR (2011), i.e., remaining 84 countries. The EUR estimated with the second method do not include undiscovered oil. However, this process is essential for considering the production aspect of as many countries as possible in the model. That is to say, 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 by modeling more countries in the world and having production and demand for countries. Having said that, this estimate should not be used alone, because it is potentially a large underestimation of the actual EUR. The EUR in the four selected countries (see section "Results and Discussions"), when unconventional oil is not included, are 466 Gb (Giga barrels) in Saudi Arabia, 269 Gb in Iran, 66 Gb in Canada, and 168 Gb in Venezuela. When such oil is included, the corresponding figures are 466 Gb in Saudi Arabia, 269 Gb in Iran, 865 Gb in Canada, and 769 Gb in Venezuela. Because of the issue of the definition of conventional and unconventional oil (Guseo 2011) and because we use BGR (2011) for unconventional oil resources [see (vii) below], we use only the EUR based on BGR (2011) in this study.

(iv) The annual production of oil in the base year (EIA 2012).

(v) The cumulative production of oil at the beginning of the base year. Although the starting point differs by country because of the data available, the cumulative production (1859–2008) is based on (a) the American Petroleum Institute (1971) before 1964; (b) DeGolyer and MacNaughton (2006) from 1964 to 1994; and (c) EIA (2012) from 1994 and onward. The oil production data are adjusted following Voudouris et al. (2011) to fit the EIA definition (EIA 2012), which includes crude oil and lease condensate.

(vi) The estimates of oil remaining at the beginning of the base year [(iii)–(v)].

(vii) The estimate of unconventional oil (oil sands and extra-heavy oil) reserves and resources (BGR 2011).

(viii) The maximum allowable projected growth rates for oil production. This constrains the growth of oil production from t to $t + 1$. This is defined based on a literature review and our own calculations of a recent trend of unconventional oil production (CAPP 2013; Höök et al. 2012; Voudouris 2011). In the analysis, the values between 1 and 8 % (median = 4.5 %) are used. Note that since it is the "maximum allowable" growth, it does not necessarily attain the rate.

(ix) Assumed peak/decline point of oil production (e.g., 50 % of the EUR). This is defined based on a literature review and our own calculations for post-peak countries (Voudouris 2011). In the analysis, the values between 35 and 65 % (median = 50 %) are used.

In this study, we focus on exploring plausible pathways for producing oil in major oil-producing countries with and without unconventional resources, given the broad range of uncertainty of the parameters shown previously. If unconventional oil resources are included in the analysis, the aggregated production of conventional and unconventional oil is obtained, since the EUR of the two are aggregated in the model.

Scenario

We developed a scenario by stochastically sampling the uncertainty space of key driving forces to analyze oil production. In the model, the uncertainty space is defined by (a) a range of the EUR estimates; (b) variations in the proportion of the EUR extracted at the peak/decline point; (c) the annual growth in demand for oil; and (d) potential limits on the ability of countries to increase annual oil production. In particular, the ACEGES model uses a Monte Carlo process to sample the uncertainty space while each scenario needs numerous simulation runs, for example, 10,000 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 the EUR estimates. The uniform distribution for the demand growth is based on the IEA (2012), which includes ''forces in the pipeline,'' such as policies that will be implemented and expected changes in energy prices. Each of the four uniform distributions is country specific. By using uniform distribution, we put an equal weight on the values between the minimum and maximum, such as the growth in demand for oil based on the scenarios presented by the IEA (2012). This implies that our scenario assumes that the future, in terms of oil demand, will be a combination of the Current Policies Scenario, the New Policies Scenario, and the 450 Scenario.

In this study, we focus on analyzing the impact of unconventional oil resources on future global oil markets. To directly compare the future profiles if unconventional resources are included and not included, the definition of the resources should be consistent; that is, we use an identical data source for the resources (i.e., the EUR). Thus, we do not use the Monte Carlo process for the EUR and instead fix them to BGR (2011). This is one of the wide ranges of plausible scenarios that can be developed by the ACEGES model.

Caveats are in order, given the EUR estimates, upstream investment for production growth rates, and socioeconomic policies that affect oil demand growth. We investigate unconventional oil, such as extra-heavy oil and oil sands. Although unconventional resources are not currently common energy resources in the global oil markets, the role of unconventional resources is increasing as conventional resources are being depleted. As mentioned previously, oil sands production in Canada has been increasing over time, particularly in this century (CAPP 2013).

In addition, because we use the EUR estimates, we also implicitly assume that ''reserves growth'' and ''to be discovered'' oil will become ''known'' and economically recoverable at some point. Fantazzini et al. (2011) point out that in the short term to the medium term, the available oil supply is, essentially, fixed and obtaining the oil remaining in currently producing reservoirs requires additional equipment and technology that come at a high price in capital. Lutz et al. (2012) indicate that oil production is price inelastic in the medium run, and production expansion is limited because of time and capital consuming the necessary investments. In the long run, however, since oil production is less price inelastic, increasing production by increasing capital should be considered (Lutz et al. 2012). Tverberg (2012) points to the link between oil supply limits and a financial crisis and discusses that oil prices may never reach a high-enough level to stimulate extraction that requires very expensive extraction techniques. However, since this study considers the long term, about 100 years, production cost will have to account for the cost-reducing effects of improved technology, which requires investment (Aguilera 2014). High oil prices should lead to increased investment in oil projects (e.g., exploration and reserves growth), and over the long term, the eventual result would be increased production and cost reductions because of technological improvement (Aguilera 2014). As a result, the cost curves of oil supply developed, for example, by Aguilera (2014), Aguilera et al. (2009), and Remme et al. (2007) show that oil production, including both conventional and unconventional oil, is feasible. Production costs would not be as high as they are now, nor would they be at a historical high.

The previous assumption also implies that the price levels to reclassify ''to be discovered'' oil and ''reserves growth'' into ''known'' oil will not slow down oil demand significantly. This is also supported by the price inelasticity of oil demand (Lutz et al. 2012).[10] Moreover, the cost curves of oil supply explained previously (Aguilera 2014; Aguilera et al. 2009; Remme et al. 2007) indicate the possibility.

For the demand growth rates, since scenarios in the IEA (2012) are used, the rates for oil given by the IEA (2012) include the manifestation of possible future advances so that the EUR estimates become available in time for extraction. Therefore, future energy and environmental policies as well as economic growth (i.e., some sort of economic and social policies) have already been involved in them. These policies include, for example, national energy plans, early retirement of nuclear power plants, fuel economy targets in the transportation sector, and

[10] On the other hand, Tverberg (2012) discusses that the high oil price reduces oil demand and may cause a recession.

climate-change measures (IEA 2012). Furthermore, because these demand growth rates are based on specific oil price projections (IEA 2012), oil prices are indirectly represented in the current implementation of the ACEGES model. This approach is consistent with other studies in the literature (Hallock et al. 2004).

In this study, we run the model from the base year (2008) to 2100. When a large number of simulations are implemented, the results are summarized by country using the quantile sheets (Schnabel and Paul 2013). By using the ACEGES model with quantiles, we suggest a move from the multi-pathway scenarios, a key innovation from 1971 when Shell's Group Planning shifted away from single-line forecasting (Jefferson 2012; Jefferson and Voudouris 2011), to continuous scenarios as a way of emphasizing the key features of oil production over time.

RESULTS AND DISCUSSIONS

In this section, we discuss the results for major oil-producing countries. For conventional oil, Saudi Arabia and Iran are the two largest oil-producing and oil-exporting countries today and in the future (Matsumoto et al. 2012). For unconventional oil, Canada and Venezuela will be the key countries, since Canada has a large amount of oil sands (602 Gb of resources and 198 Gb of reserves—89.7 % of global oil sands), and Venezuela has a large amount of extra-heavy oil (445 Gb of resources and 156 Gb of reserves—99.7 % of global extra-heavy oil), as explained in the previous section (BGR 2011). Therefore, we show the production profiles of these four countries.

Figures 3–6 show probabilistic forecasts for oil production in these countries. In each figure, sub-figure (a) shows the production without unconventional oil resources, and sub-figure (b) shows production with unconventional oil resources.

Figures 3 and 4 indicate that the oil production density decreases rapidly as the production moves toward the peak—when unconventional oil is a factor or when it is not—in the countries with a large amount of conventional resources. In addition, the density increases in the post-peak period and then reaches a relative equilibrium. A similar tendency is observed in Venezuela, when unconventional resources are not included (Fig. 6a). However, as Figures 5b and 6b indicate, the oil production density continues by around 2040–2050 and then

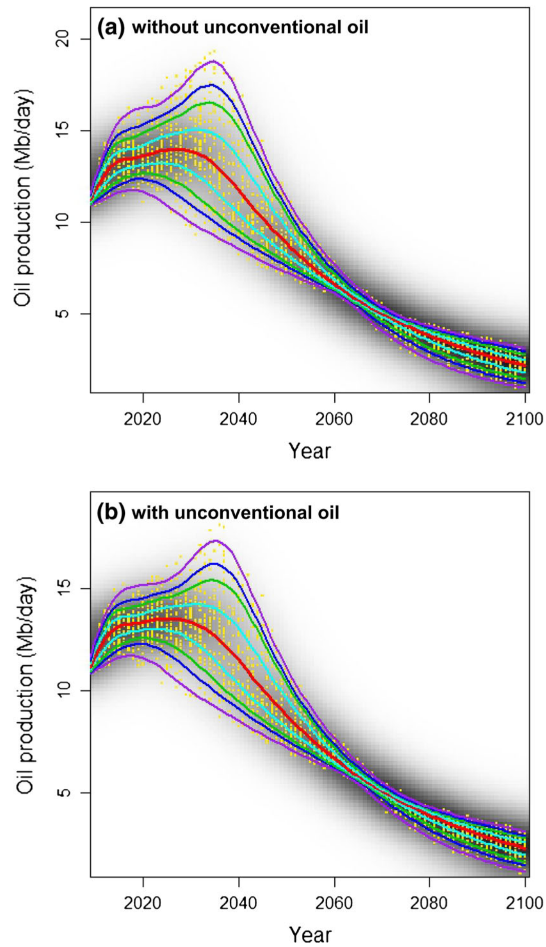

Figure 3. Probabilistic forecasts for oil production in Saudi Arabia. *Yellow dots* are simulated results, and density is shown with a *gray scale*. Quantile curves are 1, 5, 10, 25, 50, 75, 90, 95, and 99 % (from the *bottom line*). Sub-figure **a** is the production when unconventional oil is not considered; sub-figure **b** is the production when unconventional oil is considered. These explanations are same for the following figures.

decreases in the countries with rich unconventional oil resources, even during the post-peak period when unconventional resources are included. Clearly, the degree of density differs according to whether unconventional resources are included.

The curves in the figures show the time-varying, smoothed quantiles for oil production in the four selected countries estimated with the quantile sheets (Schnabel and Paul 2013), while the dots are the simulated oil production from the ACEGES model. The data used for the fitting were simulated oil production (Y) against year (X), obtained from the ACEGES-based simulations. In addition, the maximum oil production and the peak year for all

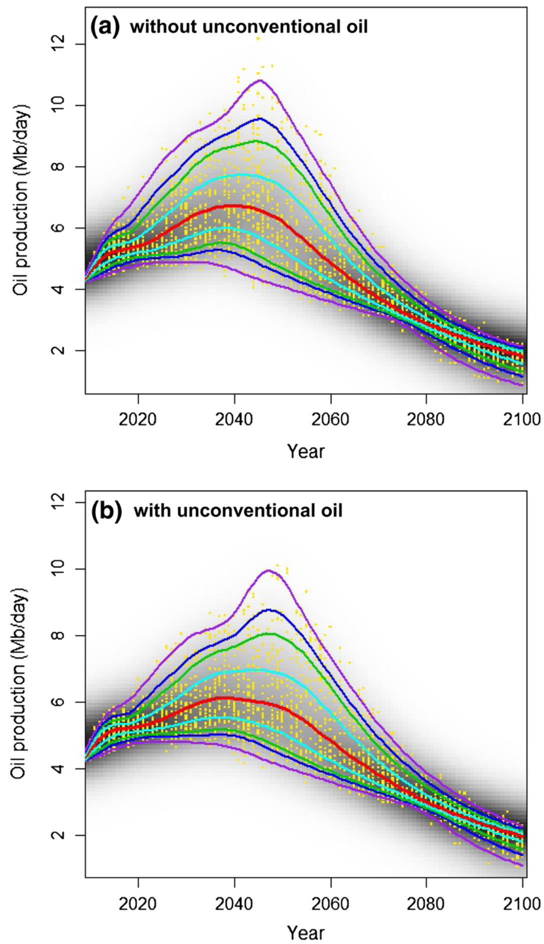

Figure 4. Probabilistic forecasts for oil production in Iran.

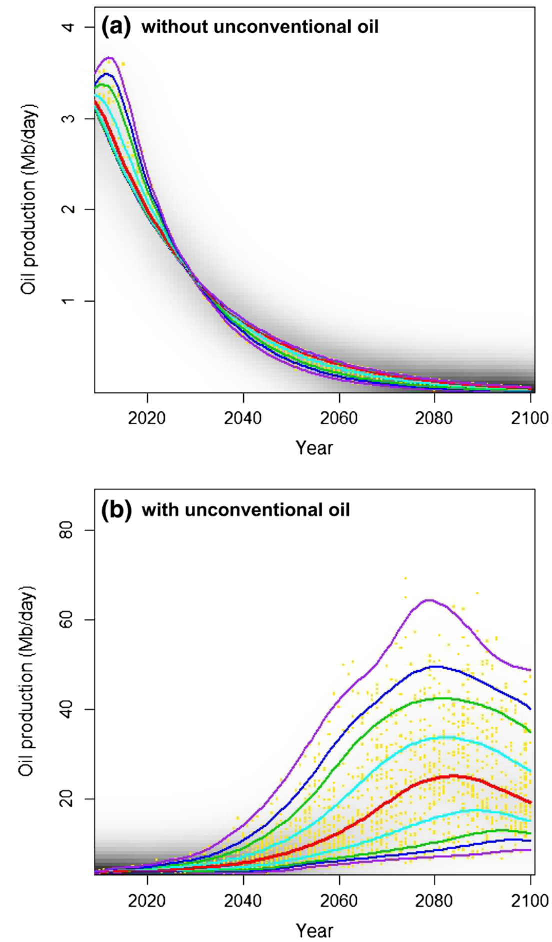

Figure 5. Probabilistic forecasts for oil production in Canada.

simulations were saved, and the median and 99 % interval for maximum oil production and year were calculated. The median quantile, $q_{0.5}$, is indicated by the solid red line in each figure (the central curve). The median production states that given the scenario, there is a 50 % probability that the actual oil production will be above or below the line. The results show that the annual production will increase from the base year levels in the four countries. In Saudi Arabia, the peak of the median case will be approximately 15.2 Mb/day (million barrels per day) in around 2027, when unconventional resources are not included in the model, while the peak will be 14.6 Mb/day in around 2029, when unconventional resources are included. The production of Saudi Arabia estimated by the ACEGES model is higher than the highest production (12.3 Mb/day) in the New Policies Scenario in the IEA (2012). However, the production is continuously increasing (i.e., not in the peak) within the years' IEA (2012) estimates. In addition, Nashawi et al. (2010) indicate higher peak oil production than the IEA (2012) (around 14.0 Mb/day). Furthermore, comparing global oil production forecasts in the New Policies Scenario (96.9 Mb/day, which is the highest one until 2035) with peak global oil production, for example, in Hallock et al. (2004) (both their survey and analysis) and the survey by Mohr (2010),[11] the New Policies Scenario shows lower production. This comparison implies that the projections in this study are in the range of estimates in previous studies, although our estimates are at a high level in the literature.

[11] For example, the survey by Hallock et al. (2004) shows 22.0–77.8 Gb/year (60.3–213.2 Mb/day) and that in Mohr (2010) shows 143–372 EJ/year (68.4–177.9 Mb/day). These studies do not show production by country.

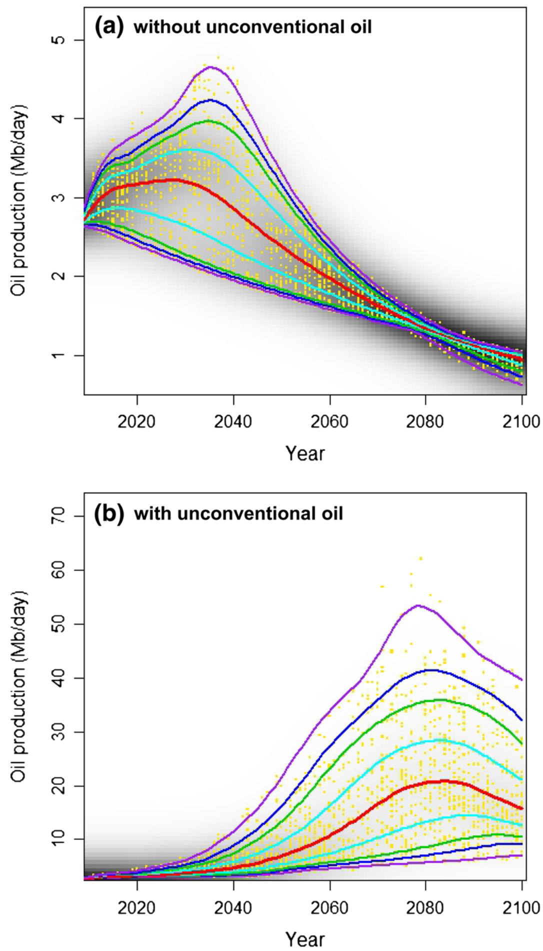

Figure 6. Probabilistic forecasts for oil production in Venezuela.

Similarly, the peaks of the median case will be roughly 7.7 Mb/day in circa 2038 in Iran, 3.1 Mb/day in 2010 in Canada, and 3.6 Mb/day in 2023 in Venezuela, when unconventional resources are excluded. The peaks will be roughly 6.9 Mb/day in circa 2040 in Iran, 35.6 Mb/day in 2090 in Canada, and 28.9 Mb/day in 2088 in Venezuela, when unconventional resources are included in the model.

The important observations are the shifts in peak production when unconventional resources are included. For the countries with rich conventional oil, peak production will decrease because part of the net unfulfilled global oil demand will also be produced by the countries with rich unconventional oil (see below). Because of this decrease in peak production (and overall annual production levels), the speed of oil depletion will be slower, and the peak years will shift a few years later, or a production level similar to that of peak production will continue for a longer time as a result.

For the countries with rich unconventional oil, however, peak production will increase tremendously (11 times higher in Canada and 8 times higher in Venezuela) because of the amount of unconventional resources, including reserves as described previously. These resources (and reserves) are about twice as large as Saudi Arabia's conventional oil resources (and reserves); Saudi Arabia is the world's richest conventional oil country (337 Gb). Because of this very large amount of unconventional oil, the peak years will shift to the latter half of this century in these countries (80 years into the future in Canada and 65 years into the future in Venezuela). Consequently, the oil production of Canada and Venezuela will occupy more than 20 % of the global oil production in the latter half of this century (from around 2060 to 2070), if sufficient unconventional oil resources are extracted [see Fig. 5 of Matsumoto et al. (2014b) for global oil production with unconventional oil resources]. Another important observation is that unconventional resources will smooth the post-peak production phase as shown in the figures. It is in line with BGR (2008), stating that "after peak oil, the nonconventional oil production will rather modify the decline in oil supply than close the gap between demand and supply."

The upper quantile, $q_{0.99}$, states that there is only 1 % probability that actual oil production will be above the upper quantile production. Thus, the upper quantile production might be considered a stochastic production frontier. Similarly, the lower quantile, $q_{0.01}$, states that there is only 1 % probability that the actual oil production will be below the lower quantile production. Thus, the lower quantile production might be interpreted as the floor of production.

The maximum oil production and the peak year obtained from all simulations between 1 and 99 % are (11.5, 19.6) Mb/day and year (2015, 2041) in Saudi Arabia, (5.0, 11.4) Mb/day and year (2021, 2056) in Iran, (3.1, 3.8) Mb/day and year (2009, 2012) in Canada, and (2.6, 4.9) Mb/day and year (2009, 2041) in Venezuela, when unconventional resources are not included. Similarly, the 98 % intervals are (11.5, 18.0) Mb/day and year (2015, 2041) in Saudi Arabia, (5.0, 10.5) Mb/day and year (2021, 2059) in Iran, (8.3, 74.4) Mb/day and year (2060, 2100) in Canada, and (6.8, 61.6) Mb/day and year (2059, 2100) in Venezuela, when unconventional resources are included. These tendencies are similar to those seen in the median case. Note that in the case of the upper quantile, the production in Canada and Venezuela does not attain its peaks until 2100.

Time-varying quantiles provide a comprehensive description of the distribution of production, and how it changes over time. Thus, time-varying quantiles characterize oil market dynamics and a country's production. From these figures, the shape of production profiles is completely different, whether unconventional resources are included or not in countries with rich unconventional resources. In general, higher production curves (upper production frontiers) are likely when a higher maximum allowable production growth rate and a higher peak/decline point are combined. When a lower maximum allowable production growth rate and a lower peak/decline point are combined, lower production curves are likely.

De Castro et al. (2009) show that to avoid an economic recession, the growth of unconventional oil production needs to be over 10 % annually.[12] Such a high growth rate is not observed in this study (see Figs. 5b, 6b, and Matsumoto et al. (2014b) for the global situation). De Castro et al. (2009) recognize that 10 % growth is not realistic. However, increases in global oil demand by which an economy grows can be fulfilled without such a high growth rate of unconventional oil production, at least until around 2040–2050 in the median case (Matsumoto et al. 2014b). In addition, more sophisticated economic analyses, such as those using computable general equilibrium models, often show that without such a high growth rate in oil production (and demand) or even with a negative growth rate, economic growth is feasible because of the substitution effect among oil, other energy, and other economic factors [e.g., Masui et al. (2011) and Matsumoto et al. (2014a) show results on a global level; Okagawa et al. (2012) show results for some countries].

CONCLUDING REMARKS

Uncertainties exist concerning future oil production that simply cannot be modeled effectively over the long term by any method (Brandt 2010; Hallock et al. 2014). In that case, a more robust planning tool could be created by encompassing the future with a range of forecasts generated by a range of parameter settings encompassing the different estimates (Hallock et al. 2014). This study presented continuous scenarios considering uncertainties rather than multi-pathway scenarios or single-line forecasting. To make the forecast of future oil production useful for considering energy policies and strategies, it will be important to consider uncertainties and to provide information with probability because of the existence of various uncertainties in the future. Policymakers formulate a policy or strategy for the future based on the most likely scenario. However, even if it is the most likely one, the scenario is not necessarily realized for certain. Thus, policymakers also need to take into account a possible range of scenarios for risk management. Particularly, it is essential to prepare if the amount of available oil is lower than expected. In that case, policymakers need to take measures to control the demand and/or to replace oil with other energy sources. In addition, they may also need to prepare for an increase in prices caused by a tight supply. Such measures are especially important for oil-importing countries, which will suffer economically first.

This study showed the ACEGES model offered a novel method for exploring the plausible futures of the dynamics of global oil markets and oil production. The ACEGES model explicitly models 216 countries, although we focused on analyzing the four selected countries in this paper, which made it possible to consider oil production and the demands of each country and to develop global oil markets from the bottom up. The estimated oil production according to the ACEGES model showed a certain level consistent with history (Voudouris et al. 2011). The number of related studies analyzing many countries is limited, but comparing the results of this study with such country-level analyses (Nashawi et al. 2010; IEA 2012), the oil production of Iran, Canada, and Venezuela in this study was in a reasonable range. The oil production in Saudi Arabia, however, was higher than that in these studies. However, when the global oil production in these studies and other studies (see the previous section) was looked at, our results for Saudi Arabia indicated possible values. This study developed continuous scenarios of the global oil markets and, in doing so, considered probability, which was essential to do, since great uncertainty exists in the future. In developing the scenarios, the study used the Monte Carlo process to sample the uncertainty space by

[12] De Castro et al. (2009) assume that the variation of GDP depends on the variation in oil demand.

country and implemented numerous simulation runs to explore the full uncertainty space of the scenario. Such scenario development is effective to examine their future plausibility and to learn of the plausible forms that energy crises may take in the future (DuMoulin and Eyre 1979). It is important to note that the information used in designing scenarios should be based on history and the current forces in the pipeline. Scenarios should not be based on wishful thinking, but alternative opinions should be explored with controlled computational experiments (Matsumoto et al. 2012). We also used time-varying quantiles as a way of analyzing and visualizing various aspects of the time-varying distribution of oil production in probability terms.

The ACEGES model can simulate a very large number of scenarios by adjusting any of the most important and uncertain driving forces of the scenarios. In this study, we presented the potential impact of unconventional energy resources on future global oil markets, particularly focusing on the four major oil-producing countries.

Given the estimated potential of conventional and unconventional resources obtained from BGR (2011) and the parameters with uncertainty, the scenario suggests that the production profiles will change tremendously if unconventional resources are included. Saudi Arabia and Iran, the most important oil-producing countries today, will still occupy the global oil markets for approximately the first half of this century, when unconventional resources are included. However, Canadian oil production will be higher than that of these two countries beginning in 2050–2060, and Venezuela will follow Canada in the latter half of this century. This means that the market power in the global oil markets will shift from the Middle Eastern countries to Canada and Venezuela during this century, provided that investment in unconventional oil is implemented, regulatory and environmental regimes allow the development, and competition through flexible and developed markets is promoted (Aguilera 2014; Brandt 2008, 2009; Cleveland and O'Connor 2011).

In this study, future oil production with and without unconventional oil resources was analyzed by aggregating the EUR of conventional and unconventional oil. Since this study is a country-level analysis (but not well- or field-level analysis) and countries with rich conventional oil and those with rich unconventional oil are different, it is considered that the influence of our approach is not large. However, to estimate production by type (not only between conventional and unconventional resources but also among unconventional resources), modeling oil resources by type will be necessary. Therefore, we will improve our model to be able to separately model different types of resources for our future study. To do so, we will also need to include the relationship among the supply, the demand, and the amount of resources and the prices/costs of the resources in the model, since the prices/costs are one of the determinants in selecting the type of energy resources to use.

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