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A study on the future of unconventional oil development under different oil price scenarios: A system dynamics approach

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HIGHLIGHTS

- Variables and loops affecting oil production are formulated mathematically.
- Shares of conventional and unconventional oil in the global oil market is analyzed.
- Oil production rate under different oil price scenarios up to 2025 is simulated.
- Unconventional oil would obtain a considerable share in market in the short-term.
- A late peak for the conventional oil resources would occur.

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ABSTRACT

Fluctuations in the oil global market has been a critical topic for the world economy so that analyzing and forecasting the conventional oil production rate has been examined by many researchers thoroughly. However, the dynamics of the market has not been studied systematically with regard to the new emerging competitors, namely unconventional oil. In this paper, the future trend of conventional and unconventional oil production and capacity expansion rates are analyzed using system dynamics approach. To do so, a supply-side modeling approach is utilized while main effective loops are modeled mathematically as follows: technological learning and progress, long and short-term profitability of oil capacity expansion and production, and oil proved reserve limitations. The proposed model is used to analyze conventional and unconventional oil production shares, up to 2025, under different oil price scenarios. The results show that conventional oil production rate ranges from 79.995 to 87.044 MB/day, which is 75–80 percent of total oil production rate, while unconventional oil production rate ranges from 19.615 to 28.584 MB/day. Simulation results reveal that unconventional oil can gain a considerable market share in the short run, although conventional oil will remain as the major source for the market in the long run.

1. Introduction

The global oil market has observed variations in market players' strategies since the first energy cricis. The main evolutions are on the demand side, where it has been trying to reduce the dependency on imported oil after 1970s. The most important strategies are: renewable energy development (Lund, 2007; Lund and Mathiesen, 2009), utilization of oil substitutes (Aleklett, 2008; Henriques and Sadorsky, 2008; Samii and Teekasap, 2010), controlling energy intensity and promoting efficiencies (Energy Outlook 2030, 2013; Geller et al., 2006; Liddle, 2012; Matheny, 2010), supporting financial market to increase market power and oil price control (Foster, 1996; Silvério and Szklo, 2012).

A recently emerging strategy, influencing the structure of the market's supply side, is to increase the rate of exploitation of unconventional oil resources. Specifically, the first three countries with major unconventional oil resources are the USA, Russia, and China (Kuuskraa et al., 2013) and it is discussed that the era of cheap oil in the world finished (Owen et al., 2010) and production from unconventional oil resources gradually becomes more economical.

The most important factor which affects unconventional oil development is the oil price dynamics, which directly affects the profitability of unconventional oil production and capacity expansion rate. An increase in the oil price will result in an increase in the oil production rate in the short run and a raise in the

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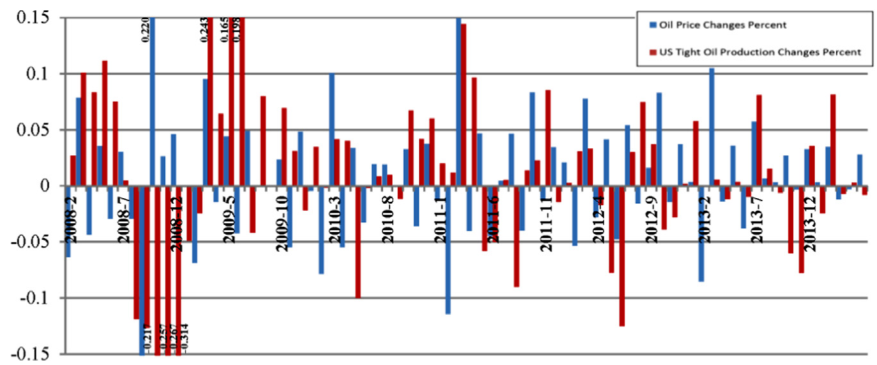

Fig. 1. Annual changes in the oil price and US tight oil production (percents) �(Ratner and Tiemann, 2014).

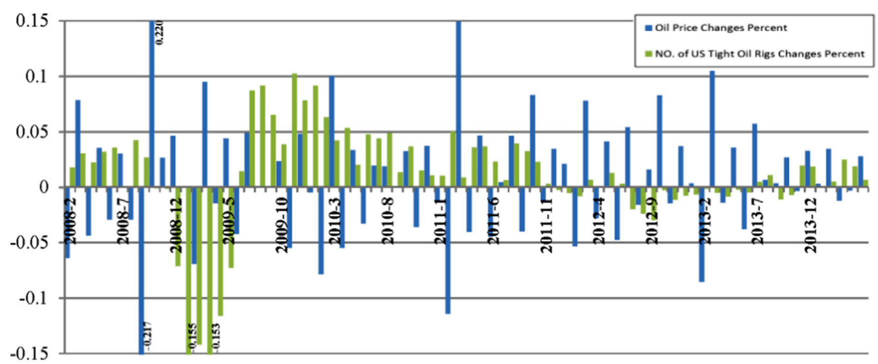

Fig. 2. Annual changes in the oil price and number of US tight oil active rigs (percents) (Ratner and Tiemann, 2014).

Table 1
Granger causality test results for changes in the oil price and changes in US tight oil production.

Lags	Cause var.	Affected Var.	*P*-value
1	ΔPrice	ΔProduction	0.721
2			0.7171
3			0.0312 (✓)
4			0.0128 (✓)
5			0.0231 (✓)
6			0.126
7			0.128
8			0.2058
9			0.0201 (✓)
10			0.0122 (✓)
11			0.1607
12			0.2024
13			0.0349 (✓)
14			0.0799
15			0.0975
16			0.1775
17			0.3993
18			0.0878
19			0.1827
20			0.1722

Table 2
Granger causality test results for changes in the oil price and changes in the number of US tight oil active rigs.

lags	Cause Var.	Affected Var.	*P*-value
1	ΔPrice	ΔRig NO.	0.2319
2			0.0583
3			0.1147
4			0.1229
5			0.0924
6			0.1091
7			0.0073 (✓)
8			0.0018 (✓)
9			0.0050 (✓)
10			0.0080 (✓)
11			0.0313 (✓)
12			0.0868
13			0.0703
14			0.0143 (✓)
15			0.0346 (✓)
16			0.0052 (✓)
17			0.0093 (✓)
18			0.262
19			0.5406
20			0.624

production capacity expansion in the long run, which are caused by investments in technological progress (i.e. increases in recovery factor). Figs. 1 and 2 depict the annual changes in oil price[1] along with those in the US tight oil production rate and the number of active production rigs, respectively. Moreover, Tables 1 and 2 summarize the results of several Granger causality tests, between changes in the oil price versus those in the US tight oil production rate and the number of active production rigs, respectively. A Granger causality test evaluates statistical causality between two variables with various time lags (TSAY, 2005). It reveals that increases in the oil price will result in more tight oil production with a 3–5 month lag in the USA. Furthermore, it will result in more active rigs with a 7–11 month lag and more oil production with a 9–10 month lag. Since unconventional oil production has still a minor share in the global oil market, a significant statistical causal relationship from its production to price could not be found yet.

The analysis and estimation of the world oil production rate has been seriously considered by many researchers. Using a logistic equation, Hubbert introduced his method for prediction of oil production. For the USA, he predicted that it peaks between 1965 and 1970 (Hubbert, 1982, 1956). Since then, researchers have tried

[1] Here, OPEC's reference basket price (in 1993 US $) is considered as the oil price basis.

Table 3
Review of researches about unconventional oil development.

Row	Author(s)	Main methodology	Main Result
1	Salameh (2003)	Data analysis and experiment	• Unconventional oil will be hard pressed to meet 4% of the global oil-demand in 2020
2	Greene et al. (2006)	Economic equilibrium	• Peaking of non-Middle Eastern conventional oil production is likely sometime between 2010 and 2030 • Transition from conventional to unconventional oil will begin before 2030
3	Maggio and Cacciola (2009)	Hubbert theory	• Global oil production from unconventional oil will be approximately 12% in 2030 and 20% in 2050
4	De Castro et al. (2009)	System dynamics modeling	• The peak oil decline requires more than 10% of sustained growth of non-conventional oil production over at least the next two decades
5	Mohr and Evans (2010)	Difference equations	• Unconventional oil production is anticipated to peak between 49 and 88Mb/d in 2076–2084
6	Matsumoto and Voudouris (2015)	Scenario analysis and probabilistic forecasts (ACEGES Model)	• Countries rich in conventional oil, will still occupy the global oil markets for approximately the first half of this century, oil production in countries with rich unconventional resources, will be higher in production than Saudi Arabia and Iran from 2050 to 2060
7	Mohr et al. (2015)	Difference equations	• Growth in unconventional oil is anticipated to be insufficient to offset conventional oil declines • After 2100 unconventional oil resources being exhausted

to calculate the Hubbert Peak for the world petroleum production in different countries (Kiani et al., 2009; Nashawi et al., 2010; Reynolds, 2014; Reynolds and Kolodziej, 2008). However, Cavallo (2004) discussed that not only does resource limitation affect oil production rate and Hubbert peak, but also technological, political, and economic constraints have their own effects and Hubbert prediction of the resource limitation (Q_{max}) represents the most easily accessible production based constraint.

In this regard, System Dynamics[2] methodology has been frequently used by different researchers all over the world (Kiani et al., 2010) in order to facilitate inclusion of different factors (i.e. economic, technological, geological, environmental, etc.) that affect current and future trends of oil production rate and investments in oil industry infrastructure in both national and international levels (Bassi, 2006; Bodger and May, 1992; Bodger et al., 1989; Budzik and Naill, 1976; Chi et al., 2009; Choucri et al., 1990; Chowdhury and Sahu, 1992; Davidsen et al., 1990; Hosseini et al., 2014; Sterman et al., 1988; Tao and Mingyu, 2007).

Investigation into the dynamics of competition between two technologies or products in a market has a considerable long record and has been presented in various case studies (Sterman, 2000). Despite a plentiful literature in modeling conventional oil production and capacity expansion, there exist few challenges to model the recent development of unconventional and conventional oil production dynamics altogether. A research in 2003, neglecting structural modeling of the global oil market and merely analyzing related statistics, argued that the global oil production will probably peak between 2004 and 2005 and the world oil demand will overtake oil supply in 2008–2010. This gap stimulates the development of unconventional oil up to 4% of the total oil production in 2020, which will fill the gap in conjunction with renewable energy development (like wind, solar, and hydrogen) up to 2025 (Salameh, 2003).

The USGS[3] evaluations of oil resources all over the world (USGS, 2000) are discussed with an optimistic view that the peak of non-Middle Eastern conventional oil production is likely sometime between 2010 and 2030 and world conventional oil production will slow substantially after 2020 (if it does not decline) and the transition from conventional to unconventional oil will begin before 2030 (Greene et al., 2006).

Another research investigated the effect of unconventional oil on the world peak oil and concluded that the production peak of conventional oil ranges between 80.27 and 87.95 MB/day, and occurs between 2009 and 2021; and the unconventional oil production rate will increase to 12% of the world total oil production in 2020, and then to about 20% by 2050 (Maggio and Cacciola, 2009).

A further research used system dynamics concisely to analyze the development of unconventional oil versus conventional one. In its succinct model, technological, geological, and economic factors affecting unconventional oil development are briefly considered. The authors concluded that a strong requirement of unconventional oil production is necessary in order to maintain the economic growth of the world's economy and to prevent economic recession; a 10% yearly increase in unconventional oil production capacity is essential (De Castro et al., 2009).

Mohr and Evans (2010) formulated difference equations to forecast unconventional oil development in the long-term and showed that in pessimistic, the best guess, and optimistic scenarios, the global unconventional oil production peak occurs between 2076 and 2084 with a production rate between 49 MB/day and 88 MB/day.

Using a scenario analysis approach and probabilistic forecast, it is concluded that countries which are rich in conventional oil, such as Saudi Arabia and Iran, will still occupy the global oil market for approximately the first half of this century; however, for the second half, unconventional oil producers will take the power in the global market (Matsumoto and Voudouris, 2015).

In another research, considering unconventional oil development in North America (Canada and the USA), Venezuela, and the Former Soviet Union (FSU), it is shown that the lack of conventional oil will not be retrieved by unconventional oil because the development of unconventional oil will result in a less increase in conventional oil production and postpones its peak to 2100 (Mohr et al., 2015).

Table 3 summarizes aforementioned researches briefly.

The present paper, is an effort to model different mechanisms of oil production and capacity expansion rate in both conventional and unconventional oil regarding their interconnections and important factors such as the long-term oil production capacity expansion profitability, oil production and capacity expansion costs, learning phenomenon, oil production technology (recovery factor), and limitations on both the conventional and unconventional global resources. Moreover, based on the recent analyses and forecasts about the global oil and energy market (Annual Energy Outlook 2015, 2014; World Oil Outlook, 2014; Energy Outlook 2030, 2013), different and distinct scenarios of the oil price are formulated, simulated, and compared, in order to conclude a more realistic forecast about the future trend of conventional and

[2] Detailed descriptions for System Dynamics and its methodological steps, applications, and case studies are discussed by Sterman (2000).
[3] US Geological Survey

unconventional oil production rates. To do so, system dynamics modeling methodology is utilized to overcome complexities in modeling such an issue and to compare its results under different scenarios. However, this research mainly focuses on policy-related issues and looks for economic mechanisms, rather than modeling the dynamics of technological shemes, such as probable variations in learning speed which may happen due to some technological leaps in the field.

The rest of this paper is organized as follows. In the next section, a brief explanation with regard to the research methodology and process is given and the suitability of the system dynamics methodology is discussed for investigating the problem. Section three clarifies the conceptual framework of the study in which relationships among main variables of the model are described in the form of causal loop diagrams. Section four gives details about mathematical expression of the model, where main equations and utilized parameter values are mentioned. In the first part of section five, the model's validity is examined briefly, which is assessed through dimensional consistency, behavior at extreme conditions, and the behavior reproduction test. In the second part of section five, simulation results for the conventional and unconventional oil production rates in the world are discussed under different low, medium, and high oil price scenarios. The last section contains the conclusion.

2. Research methodology

In this work, system dynamics approach is used as the main methodology. The reasons to choose such a complicated method for modeling can be summarized as the following:

- The issue occurs during a long-term interval and has long-term consequences. This activates slow dynamics in the system, which trigers feedback effects.
- Different kinds of variables (i.e. economic, technological, and geological) influence the system behavior with interconnected relationships.
- There are various nonlinear relations among the system's variables and the feedback loops.

These characteristics of the complex system in the oil market hinder most of other methodologies, such as econometrics, to comprehend the system behavior well. System dynamics, as a powerful tool for system thinking, is an approach which is used to investigate, analyze, and forecast a system's behavior and to overcome the complexities in problems. It focuses on developing both qualitative and quantitative models of complex situations and then experiments and studies the behavior of the models over time. Furthermore, it emphasizes on the importance of understanding the structure of a given system, the consequences of structure on the behavior of the actors (through nonlinear feedback causal relationships), and processes which operate in order to define the characteristics of that system (Forrester, 1961; Sterman, 2000).

The model proposed in this paper tries to help practitioners (i.e. researchers, policy-makers, investors, governments, etc.) understand the dynamics of the main variables involved in the world's oil industry which leads to conventional and unconventional oil production share of the total oil consumption. Moreover, it contributes to an analysis of possible oil price scenarios in order to make the best evaluation of the future world oil production rate.

Fig. 3 represents main steps of this study based on system dynamics methodology. At the first step, the related literature is reviewed in order to determine main effective variables in the development of conventional and unconventional oil production and the relationships among them. Next, the main problem is articulated and main effective variables are selected to conduct the study. In the third step, a conceptual framework is formulated in which the main balancing and reinforcing loops and mechanisms affecting conventional and unconventional oil production and capacity expansion is clarified through causal loop diagrams (CLD). By the next step, gathering time series data of the system's variables from 1993 to 2013, a mathematical model is developed to simulate the current and future trends of conventional and unconventional oil production and capacity expansion. Before the system is simulated, the validation of the model is tested in step five. In this step, dimensional consistency of the model and its true behavior at extreme conditions are assessed. Moreover, a behavior reproduction test is utilized, both qualitatively and quantitatively, where normality of the residuals is examined. Finally, future trends of both conventional and unconventional oil production are simulated and analyzed under three oil price scenarios, which are defined based on the international oil and energy outlooks and forecasts in low, medium, and high oil prices.

3. Conceptual framework of unconventional and conventional oil production

The model developed by this research considers four main structures for both conventional and unconventional oil as follows:

i. The effect of learning phenomenon on cost reduction of oil production and capacity expansion,
ii. The effect of oil price as well as capital and operational expenses dynamics on long-term profitability of production capacity expansion,
iii. The relationship between short-term profitability of oil production and oil production rate with regard to physical constraints on the proved reserves,

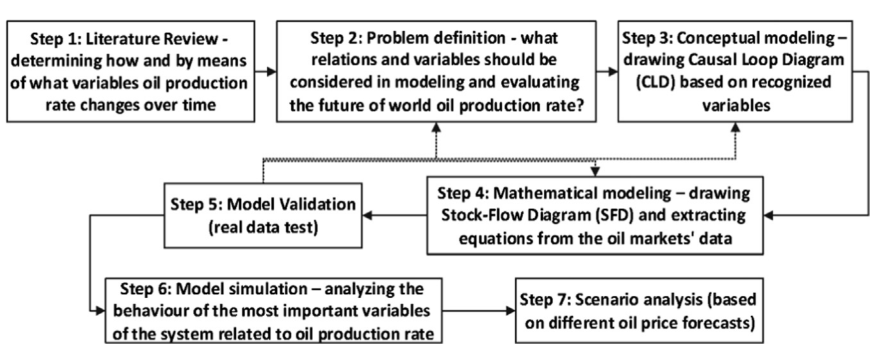

Fig. 3. Research methodology.

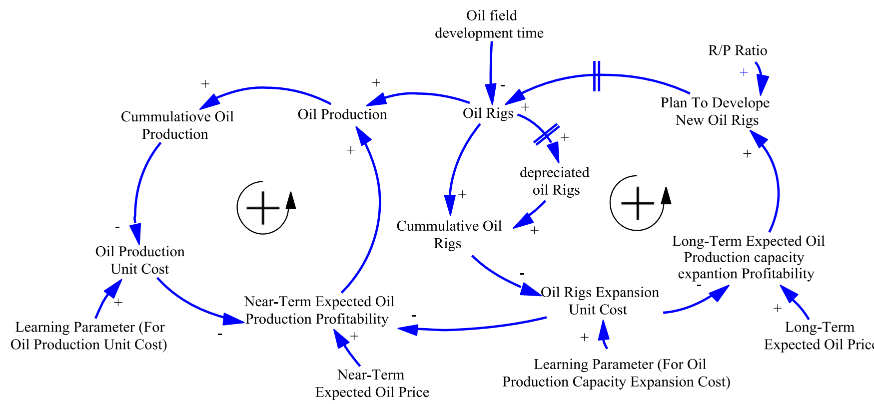

Fig. 4. effect of learning phenomenon.

iv. The effect of profitability variations on progresses in production technologies (recovery factor).

3.1. *Unit cost reduction due to learning curve (reinforcing loop)*

The phenomenon of *learning* affects production costs of a good or service over time. The phenomenon is always presented by so called *experience* or *learning curve* in which a decay in costs occurs by increasing in cumulative production and capacity expansion (Grübler et al., 1999). In oil production, the learning phenomenon occurs in the first half of reservoirs' life time; thereafter, costs increase (which is due to reserve depletion) and dominate the phenomenon, making the overall shape of oil production costs as a U-shaped curve over time (Tsuchiya and Kobayashi, 2004). In this research, learning causes decrease in the variable cost of oil production as well as the capital cost of new rig development which raises the motivation to produce more oil and to increase investments in new rig development programs respectively as shown in Fig. 4 (Méjean and Hope, 2008, 2013).

3.2. *Short-term profitability of oil production and proved reserves limitations (balancing loop)*

Evidently, oil resources are limited and will be depleted. This fact is the basis of the Hubbert theory (Campbell and Laherrère, 1998), where the mutual relationship between oil production rate and amount of oil reserves is considered. Fig. 5 depicts the relationships between the model variables determining oil production rate based on short-term profitability dynamics and availability of oil production capacity (i.e. number of active rigs). Moreover, a decrease in the oil proved reserves, which is calculated based on a given oil recovery factor (Statoilhydro and Ipc, 2007), affects reserve-to-production ratio (R/P) and finally causes a fall in investments for development of new oil rigs since R/P determines viability of the oil reserves.

3.3. *Recovery factor improvement process (reinforcing loop)*

Another reinforcing loop is formed by the oil recovery factor

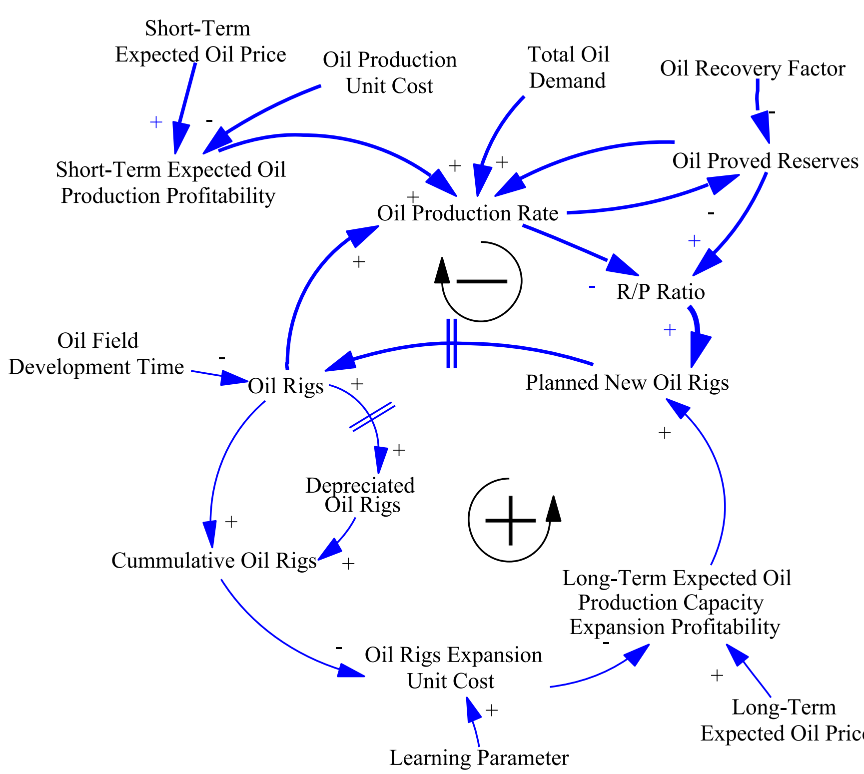

Fig. 5. Oil production rate dynamics.

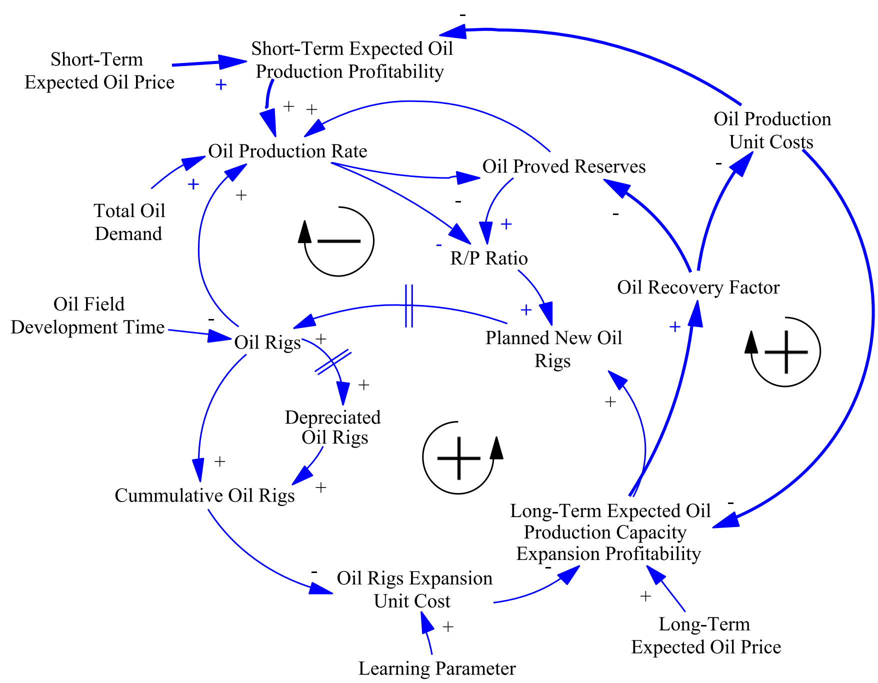

Fig. 6. Causal Relations showing effect of technological progress on oil production subsystem.

progress. An increase in the average oil recovery factor, which is stimulated by long-term profitability of oil production capacity expansion, causes a decrease in oil production unit costs. This, in turn, leads to an increase in Expected Long-term Profitability of Oil Production Capacity Expansion and finally brings on more investments on recovery factor improvement programs to gain more profit from oil producers, as shown by Fig. 6.

4. Mathematical model of unconventional and conventional oil production

The mathematical framework of the model is briefly described in this section.

1. *Oil Rigs Expansion Unit Costs*

The main equation in Fig. 4, which is about oil rigs expansion unit costs, is given as follows (Méjean and Hope, 2008, 2013):

$$C_t = C_0 .\ (X_t)^{\frac{\ln\ (b)}{\ln\ (2)}} \quad (1)$$

where C_0 is the initial oil rig expansion unit cost ($/rig), C_t is the oil rig expansion unit cost ($/rig), X_t is the cumulative number of oil rigs, b is the experience curve parameter for oil rig expansion unit cost (the learning coefficient, $b > 0$), and t is the time variable in years. Although in the real world the parameter b is varying because of variations of investments in R&D with oil price outlook changes, in this research its dynamics is not modeled.

1. *Expected Long-term Profitability of Oil Production Capacity Expansion*

As depicted in Figs. 4–6, the expected long-term profitability of oil production capacity expansion is an important variable which is calculated by the following equation. Here, oil production capacity is indexed by number of active rigs.

$$ELPOPCE_t = \sqrt[n]{\frac{NFV_t}{NPV_t}} - 1 \quad (2)$$

where:

$$NFV_t = LEOP_t \times RF_t \times \sum_{i=0}^{n-1} (1 - DR)^i \times (1 + MDR)^{n-i-1}$$

$$NPV_t = \sum_{i=0}^{k} \left(\frac{OREUC_t}{k \times (1 + FDR)} \right)^i + OPUC_t \times RF_t \times \sum_{i=0}^{n-1} \frac{(1 - DR)^i}{(1 + FDR)^{k+i}}$$

$ELPOPCE_t$: Expected Long-term Profitability of Oil Production Capacity (1/year)
$LEOP_t$: Long-term Expectation of Oil Price ($/barrel)
MDR: Market Discount Rate (1/year)
FDR: Finance Discount Rate (1/year)
RF_t: Recovery Factor (dimensionless)
DR: Decline Ratio (1/year)
n: Oil Rig Lifetime (year)
$OREUC_t$: Oil Rig Expansion Unit Cost ($/rig)
$OPUC_t$: Oil Production Unit Cost ($/barrel)
k: Oil Rig Development Time (year)

The equation has two main parts: the net future value of revenues from one unit of capacity, named NFV_t ($), and the net present value of operating and capital expenses for one unit of capacity, i.e. NPV_t ($) (Park, 2002).

1. *Short-Term Expected Oil Production Profitability*

Short-term expected oil production profitability affects the amount of oil production at a given time and is calculated by the following formula:

$$SEOPP_t = \frac{(EOSP1_t - OPTC_t)}{OPTC_t} \quad (3)$$

where:

$SEOPP_t$: Short-Term Expected Oil Production Profitability (1/year)
$EOSP1_t$: Expected Oil Spot Price 1Years Ahead ($/barrel)
$OPTC_t$: Oil Production Total Cost ($/barrel)

The oil production total cost is determined by the variable cost of oil production per barrel plus the prorated cost of the initial capacity expansion investment per produced barrel.

1. *Oil Production Unit Cost*

Oil production unit cost (*OPUC*) ($/barrel) is determined based on two main concepts as follows; effect of production technology progress (which is indexed here by the recovery factor (RF)) on cost drops and effect of resource depletion (Méjean and Hope, 2008, 2013).

$$OPUC_t = OPUC_{min} + \left(OPUC_0 - OPUC_{min}\right).\ \left(\frac{CPO_t}{CPO_0}\right)^{-\beta} + OPUC_{max}.\ \left(\frac{CPO_t}{UPO_t}\right)^{\gamma} \quad (4)$$

$$UPO_t = PR_t.\ RF_t \quad (5)$$

where:

$OPUC_t$: Oil Production Unit Cost ($/barrel)
PR_t: Proved Reserves (barrel)
RF_t: Average Recovery Factor (dimensionless)
CPO_t: Cummulative Produced Oil (barrel)
UPO_t: Ultimate Producible Oil (barrel)
β: Average Learning Rate for OPUC (dimensionless)
γ: Depletion exponent for OPUC (dimensionless)
$OPUC_0$: Oil Production Unit Cost at the first time of simulation ($/barrel)
$OPUC_{min}$: minimum Oil Production Unit Cost ($/barrel)
$OPUC_{max}$: maximumOil Production Unit Cost ($/barrel)

Moreover, some constraints are used, the important ones of which are presented as follows: the first one is the constraint of resource limitation, i.e. the amount of oil production could not be more than the amount of remained technically recoverable reserves. The second one is about the maximum production capacity of active rigs. Here, the value is calculated by the minimum ratio of active rigs number divided by oil production rate (*NAR/OPR*). The "*NAR/OPR*" ratio is calculated through a weighted average of countries data all over the world. Weights in weighted average function are calculated based on the relative amount of oil production of each country.

$$OPR_t \le RF_t \times PR_t \quad (6)$$

$$OPR_t \le \frac{NAR_t}{\min_i\left(\underset{k}{\text{weighted average}}\left(\frac{NAR_{i,k}}{OPR_{i,k}}\right)\right)} \quad (7)$$

where:

OPR_t: Oil Production Rate (barrel/year)
RF_t: Average Recovery Factor (dimensionless)
PR_t: Proved Reserves (barrel)
NAR_t: Number of Active Rigs (NO.)
k: Index for the studied countries with available yearly data of active rigs and production rate
i: time periods of historical data

Table 4 shows model parameters, initial values, and simulation time bounds for conventional and unconventional oil production subsystems.

Table 4
Model parameters for conventional and unconventional oil production.

Parameters	***Value***		***Unit***
	Conventional	***Unconventional***	
Initial Simulation time	1993		Year
Final Simulation time	2025		Year
Finance Discount Rate (*FDR*)	0.1		1/Year
Market Discount Rate (*MDR*)	0.1		1/Year
Oil Field Expansion time (*k*)	3	5	Year
Oil Field Lifetime (*n*)	20	25	Year
Initial Oil Rig Expansion Unit Cost (C_0)	7.945e+007	1.739e+008	$/Rig
Experience Curve Parameter for Oil Rig Expansion Unit Cost (*b*)	0.962	0.911	Dimensionless
Initial Oil Rigs	1933	10	Rig
Initial Oil Proved Reserves	1.00421e+006	301,898	MB
Initial Oil Recovery Factor	0.29	0.26	Dimensionless
Decline Ratio (*DR*)	0.054	0.024	1/Year
Average Learning Rate for Oil Production Unit Costs (β)	0.415	0.351	Dimensionless
Depletion exponent for Oil Production Unit Costs (γ)	4.659	2.328	Dimensionless

5. Results

5.1. Model Validation

Before one can analyze or use the results of a simulation model, it should be verified and validated. There are various validation methods among which one can choose one or some to assure that the simulation results are authentic and the model is reliable to analyze the problem situation and to propose policy recommendations (Sterman, 2000):

	• Behavior reproduction
• Boundary adequacy	
• Structure assessment	• Behavior anomaly
• Dimensional consistency	• Family member
• Parameter assessment	• Surprise behavior
• Extreme conditions	• Sensitivity analysis
• Integration error	• System improvement

To validate the developed model, the dimensional consistency is checked in the first step. In the next step, true behavior of the model is examined at extreme conditions. As the core validation test, model behavior reproduction test is used here as one of the main and common methods of validation. In this validation test, the ability of the model to reproduce the behavior of main system variables is qualitatively and quantitatively examined. Validation of the developed model is depicted in Figs. 7 and 8 for conventional and unconventional oil production rate and rigs number. Moreover, the qualitative behavior of the model for these variables are checked in the long run. The quantitative behavior of the models is checked based on normality test which is used to determine if a data set is well-modeled by a normal distribution and to compute how likely it is for a random variable underlying the data set to be normally distributed. The normality test results for simulation errors indicates that model's behavior is acceptable in 95% confidence level (Jarque-Bera (JB) statistics < 5.66) as shown in Fig. 9. However, the normality test for unconventional oil production rate is not as good as conventional oil production rate which is because of supporting activities in first development years by governments (especially US and Canada) but the behavior in recent years is satisfactory for unconventional oil production rate and rigs number.

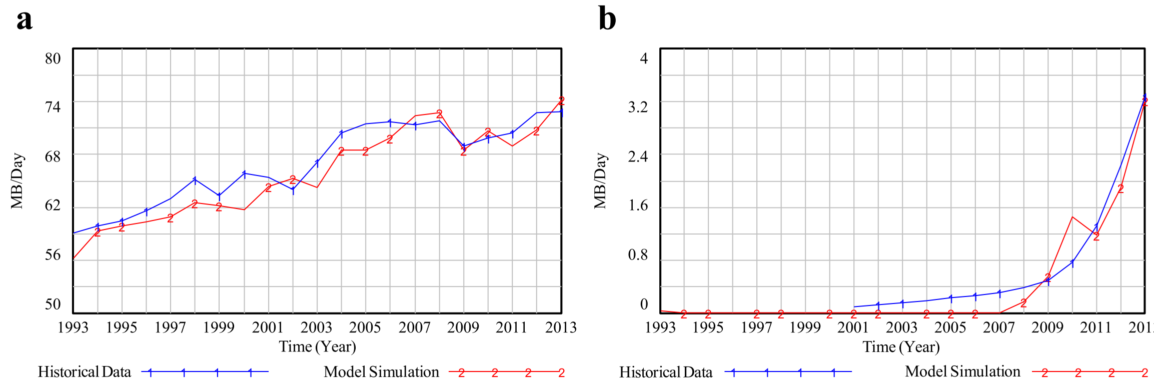

Fig. 7. Simulation results for oil production rates from the world (a) conventional, and (b) unconventional resources (historical data: blue, simulation: red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

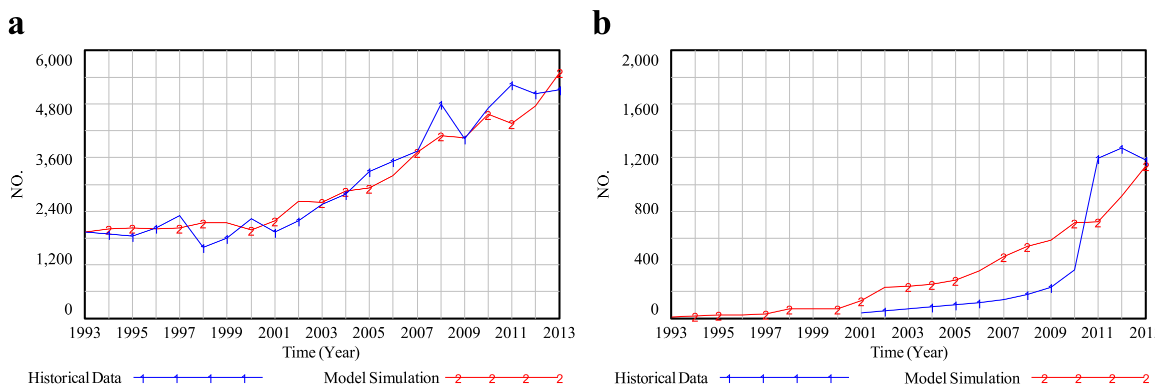

Fig. 8. Simulation results for oil rigs number for the world (a) conventional, and (b) unconventional resources (historical data: blue, simulation: red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5.2. Discussion: simulation results under different oil price scenarios

As the main index in the global energy system, the oil price is affected by different factors which include supply and demand side strategies, level of oil proved reserves, oil substitution rate, oil and its products storage strategies, level of energy intensity, economic growth perspective, futures and options prices, geopolitical events, etc. Since the model is developed in the supply-side, scenario analysis is defined in different options for the oil price based on the recently reported international outlooks on global oil and energy market (Annual Energy Outlook 2015, 2014; World Oil Outlook, 2014; Energy Outlook 2030, 2013). To do so, three levels of the oil price[4] is determined by low, medium, and high as shown in Fig. 10. The oil price in the low level scenario is determined via minimum of current officially published forecasts about low oil prices; the oil price in the high level scenario is determined via maximum of current officially published forecasts about high oil prices; the oil price in the medium level scenario is determined by average of current officially published forecasts about medium oil prices. As shown in Fig. 10, by 2025, the oil price shows −38.12, 11.78, and 73.62 percent growth rate relative to its current value in low, medium, and high oil price scenarios respectively.

Fig. 11 shows simulation results for conventional oil production rate under the defined oil price scenarios from 2013 to 2025. The conventional oil production rate in its minimum value reaches to 79.995 MB/day in 2025 which is equal to 80% of the total oil production rate in low price scenario and shows a yearly average growth of 0.78 percent from 2013 to 2025. Moreover, the conventional oil production rate in its maximum value reaches to the 87.044 MB/day in 2025 which is equal to 75% of the total oil production rate in high price scenario and shows a yearly average growth of 1.50 percent from 2013 to 2025.

Although in the defined oil price scenarios, conventional oil production rate does not decrease, its share of total oil supply decreases considerably from approximately 95% to 75–80%.

Fig. 12 shows simulation results for unconventional oil production rate under the defined oil price scenarios from 2013 to 2025. The unconventional oil production rate in its minimum value reaches to the 19.615 MB/day in 2025 which is equal to 20% of the total oil production rate in medium price scenario and shows a yearly average growth of 16.07 percent from 2013 to 2025. Moreover, the unconventional oil production rate in its maximum value reaches to 28.584 MB/day in 2025 which is equal to 25% of the total oil production rate in low price scenario and shows a yearly average growth of 19.77 percent from 2013 to 2025.

Although in the defined oil price scenarios, unconventional oil obtains a considerable marketshare in the global oil market in the short run, its long-term market share will be limited due to the fact that scarce resources and conventional oil will be the main source of supply in the market in the long-run.

As depicted in Figs. 11 and 12, conventional oil production does not increase considerably while unconventional oil can obtain a considerable marketshare in the short run as Maggio and Cacciola (2009) reported in their research, although our model shows higher marketshare of unconventional oil by 2025. Furthermore, the anticipated annual growth rate of unconventional oil production in this research is more than what stated by De Castro et al. (2009). Nonetheless, the results of our research are well-matched with the study conducted by Mohr and Evans (2010).

[4] Here, OPEC's reference basket price (in 1993 US $) is considered as oil price.

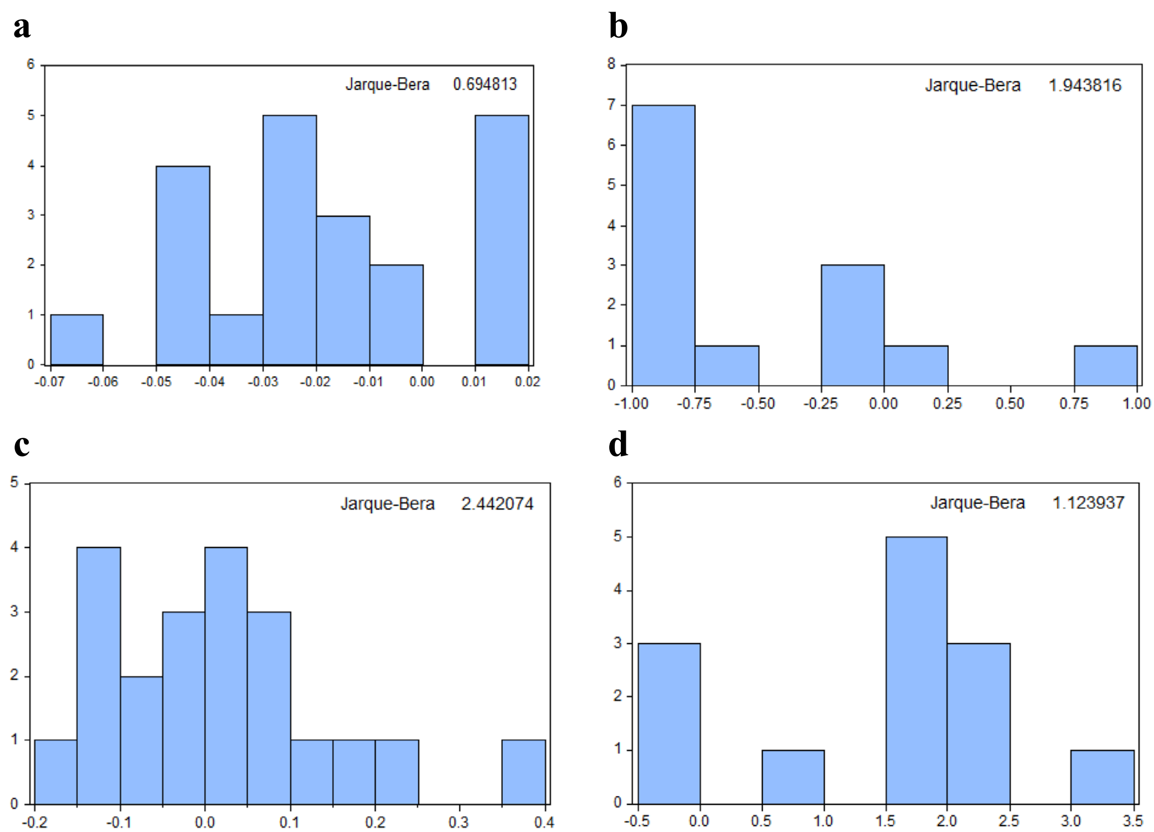

Fig. 9. Normality test results for simulation errors of conventional (a,c) and unconventional (b,d) oil production and rigs NO.

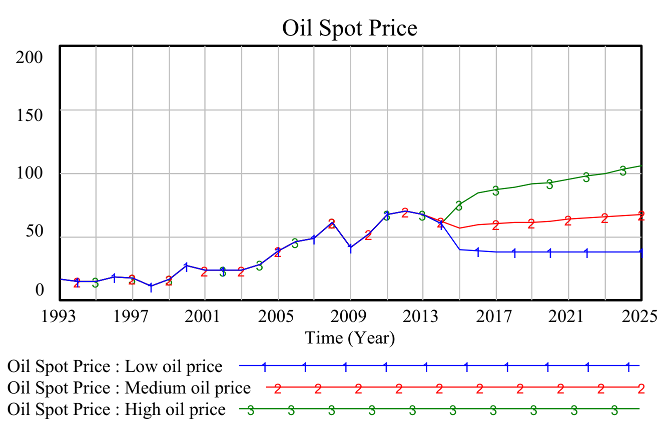

Fig. 10. World oil price scenarios (1993$/Barrel).

Furthermore, the results taken out of the research show that conventional oil peak is likely to be postponed by unconventional oil production increase in the short run. Regarding limited technically recoverable resources of unconventional oil (Kuuskraa et al., 2013), conventional oil marketshare will be considerable in the long run (Matsumoto and Voudouris, 2015; Mohr et al., 2015), although unconventional oil could change the arrangement of oil market supply-side in the short run.

6. Conclusion and policy implications

Oil market in the recent decade witnesses a considerable structural evolution caused by increasing exploitation of unconventional oil resources, especially by big demanders, which contributed to the oil price falls in 2014–2015. In this paper, we tried to model and analyze conventional and unconventional oil

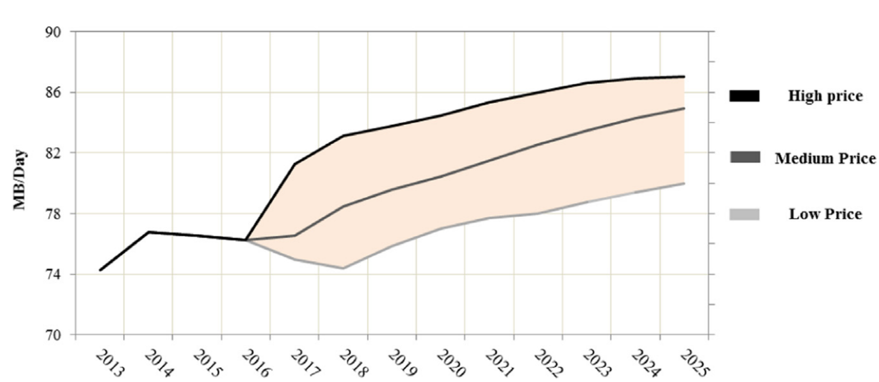

Fig. 11. Scenario result for conventional oil production.

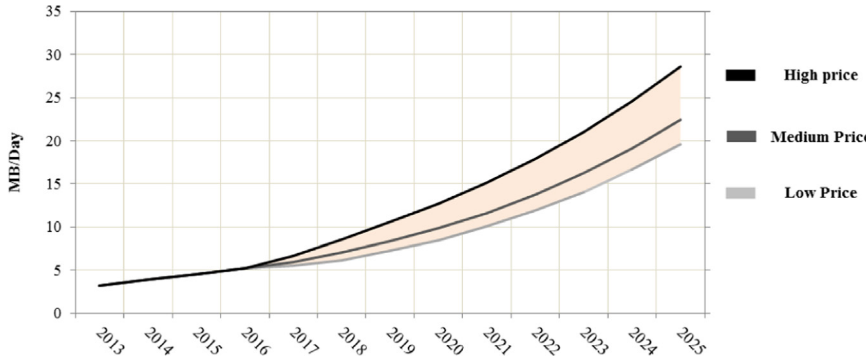

Fig. 12. scenario result for Unconventional oil production.

production shares in the global oil market until 2025 under three oil price scenarios (low, medium, and high), which are defined based on international oil and energy outlooks and forecasts. This research does not include the role of other rivals, i.e. the other energy resources; nevertheless, it appears to be one of the very rare works that can be found in the field, which considers interrelations between the two oil resources in one model. The near future growth of the emerging new technology of unconventional oil extraction is studied along with its old competitor, and a joint Hubert peak is estimated for both.

Based on the model's behavior under low, medium, and high oil price scenarios, conventional oil production rate ranges from 79.995 to 87.044 MB/day, which is equal to 75–80 percent of the total oil production rate with a yearly average growth of 0.78 to 1.50 percent from 2013 to 2025. On the other side, unconventional oil production rate ranges from 19.615 to 28.584 MB/day, which is equal to 20–25 percent of the total oil production rate with a yearly average growth of 16.07–19.77 percent from 2013 to 2025. The simulation results of the developed model show a relatively fast dynamics of unconventional oil in comparison with previous models related to the literature. It reveals that unconventional oil can gain a considerable marketshare in the short run, although conventional oil will be the main source of global oil market in the long run, given the current level of unconventional oil technically recoverable resources.

The results forecast a late peak for the conventional oil resources, regarding the increasing share of its competitor in the near future. However, the environmental impacts of tight oil extraction technologies may cause governments to limit drilling licenses, which will slow down such a fast blooming of the young technology. Moreover, excess supply by the oil exporting countries that partly lose their revenues may lead to an early peak for the conventional oil, while reducing the prices

References

Aleklett, K., 2008. Peak oil and the evolving strategies of oil importing and exporting countries. In: ITF round Tables Oil Dependence is Transport Running out of Affordable Fuel?: Is Transport Running Out of Affordable Fuel? 139, OECD Publishing, p. 37.

Annual Energy Outlook 2015, With Projections to 2040, 2014. Washington, DC 20585.

Bassi, A., 2006. Modeling US Energy with Threshold 21 (T21). In: Proceedings of International Conference of the System Dynamics Society, Nijmegen, The Netherlands.

Bodger, P.S., May, D.G., 1992. A System dynamics energy model of New Zealand. Technol. Forecast. Soc. Chang. 41, 97–106.

Bodger, P.S., Hayes, D.J., Baines, J.T., 1989. The dynamics of primary energy substitution. Technol. Forecast. Soc. Chang. 36, 425–439.

Budzik, P.M., Naill, R.F., 1976. Fossil1: a policy analysis model of the US energy transition, in: Proceedings of the 76 Bicentennial Conference on Winter Simulation. pp. 145–152.

Campbell, C.J., Laherrère, J.H., 1998. The end of cheap oil. Sci. Am. 278, 5–60. http://dx.doi.org/10.1038/scientificamerican0398-78.

Cavallo, A.J., 2004. Hubbert's petroleum production model: an evaluation and implications for world oil production forecasts. Nat. Resour. Res. 13, 211–221.

Chi, K.C., Nuttall, W.J., Reiner, D.M., 2009. Dynamics of the UK natural gas industry: system dynamics modeling and long-term energy policy analysis. Technol. Forecast. Soc. Chang. 76, 339–357.

Choucri, N., Heye, C., Lynch, M., 1990. Analyzing oil production in developing countries: a case study of Egypt. Energy J. 11, 91–115.

Chowdhury, S., Sahu, K.C., 1992. A system dynamics model for the Indian oil and gas exploration/exploitation industry. Technol. Forecast. Soc. Chang. 42, 63–83. http://dx.doi.org/10.1016/0040-1625(92)90073-3.

Davidsen, P.I., Sterman, J.D., Richardson, G.P., 1990. A petroleum life cycle model for the United States with endogenous technology, exploration, recovery, and demand. Syst. Dyn. Rev. 6, 66–93.

De Castro, C., Miguel, L.J., Mediavilla, M., 2009. The role of non conventional oil in the attenuation of peak oil. Energy Policy 37, 1825–1833. http://dx.doi.org/10.1016/j.enpol.2009.01.022.

Energy Outlook 2030, 2013. British Petroleum (BP).

Forrester, J.W., 1961. Industrial Dynamics. MIT Press Cambridge, MA.

Foster, J., 1996. Price discovery in oil markets : a time varying analysis of the 1990–91 Gulf conflict. Energy Econ. 18, 231–246.

Geller, H., Harrington, P., Rosenfeld, A.H., Tanishima, S., Unander, F., 2006. Polices for increasing energy efficiency: thirty years of experience in OECD countries. Energy Policy 34, 556–573. http://dx.doi.org/10.1016/j.enpol.2005.11.010.

Greene, D.L., Hopson, J.L., Li, J., 2006. Have we run out of oil yet? Oil peaking analysis from an optimist's perspective. Energy Policy 34, 515–531. http://dx.doi.org/10.1016/j.enpol.2005.11.025.

Grübler, A., Nakićenović, N., Victor, D.G., 1999. Dynamics of energy technologies and global change. Energy Policy 27, 247–280. http://dx.doi.org/10.1016/S0301-4215(98)00067-6.

Henriques, I., Sadorsky, P., 2008. Oil prices and the stock prices of alternative energy companies. Energy Econ. 30, 998–1010. http://dx.doi.org/10.1016/j.eneco.2007.11.001.

Hosseini, S.H., Shakouri, G.H., Kiani, B., MohammadiPour, M., Ghanpari, M., 2014. Examination of Iran's crude oil production peak and evaluating the consequences: a system dynamics approach. Energy Explor. Exploit. 32, 673–690.

Hubbert, M.K., 1956. Nuclear energy and the fossil fuels, American Petroleum Institute drilling and production practice. In: Proceedings of Spring Meeting, San Antonio, TX, p. 7025.

Hubbert, M.K., 1982. Techniques of Prediction as Applied to the Production of Oil and Gas. In: Glass, S. (Ed.), Oil and Gas Supply Modeling 631. Special Publication, National Bureau of Standards, Washington, D.C., pp. 16–141.

Kiani, B., Hosseini, S.H., Amiri, R.H., 2009. Examining the Hubbert peak of Iran's crude oil: a system dynamics approach. Eur. J. Sci. Res. 25, 437–447.

Kiani, B., Mirzamohammadi, S., Hosseini, S.H., 2010. A Survey on the role of system dynamics methodology on fossil fuel resources. Analysis. Int. Bus. Res. 3, P84.

Kuuskraa, V.A., Stevens, S.H., Moodhe, K.D., 2013. Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States (Analysis & Projections). U.S. Energy Information Administration (EIA) – Prepared by Advanced Resources International, INC., U.S.

Liddle, B., 2012. Breaks and trends in OECD countries' energy–GDP ratios. Energy Policy 45, 502–509. http://dx.doi.org/10.1016/j.enpol.2012.02.061.

Lund, H., 2007. Renewable energy strategies for sustainable development. Energy 32, 912–919. http://dx.doi.org/10.1016/j.energy.2006.10.017.

Lund, H.Ã., Mathiesen, B.V., 2009. Energy system analysis of 100% renewable energy systems — the case of Denmark in years 2030 and 2050. Energy 34, 524–531. http://dx.doi.org/10.1016/j.energy.2008.04.003.

Maggio, G.Ã., Cacciola, G., 2009. A variant of the Hubbert curve for world oil production forecasts. Energy Policy 37, 4761–4770. http://dx.doi.org/10.1016/j.enpol.2009.06.053.

Matheny, A.P., 2010. Reducing the Impact of Price Shocks in Energy-intensive Economies. John F. Kennedy School of Government., USA.

Matsumoto, K.Õ., Voudouris, V., 2015. Potential impact of unconventional oil resources on major oil-producing countries : scenario analysis with the ACEGES model. Nat. Resour. Res. 24, 107–119. http://dx.doi.org/10.1007/

s11053-014-9246-8.
Méjean, A., Hope, C., 2008. Modelling the costs of non-conventional oil: a case study of Canadian bitumen. Energy Policy 36, 4205–4216. http://dx.doi.org/10.1016/j.enpol.2008.07.023.
Méjean, A., Hope, C., 2013. Supplying synthetic crude oil from Canadian oil sands : a comparative study of the costs and CO_2 emissions of mining and in-situ recovery. Energy Policy 60, 27–40.
Mohr, S.H., Evans, G.M., 2010. Long term prediction of unconventional oil production. Energy Policy 38, 265–276. http://dx.doi.org/10.1016/j.enpol.2009.09.015.
Mohr, S.H., Wang, J., Ellem, G., Ward, J., Giurco, D., 2015. Projection of world fossil fuels by country. Fuel 141, 120–135. http://dx.doi.org/10.1016/j.fuel.2014.10.030.
Nashawi, I.S., Malallah, A., Al-Bisharah, M., 2010. forecasting world crude oil production using multicyclic Hubbert model. Energy Fuels 24, 1788–1800.
Owen, N.A., Inderwildi, O.R., King, D.A., 2010. The status of conventional world oil reserves — Hype or cause for concern? Energy Policy 38, 4743–4749. http://dx.doi.org/10.1016/j.enpol.2010.02.026.
Park, C.S., 2002. Contemporary Engineering Economics. Prentice Hall, Upper Saddle River.
Ratner, M., Tiemann, M., 2014. An Overview of Unconventional Oil and Natural Gas: Resources and Federal Actions. Congressional Research Service (CRS) Report, R43148. Retrieved from: 〈http://www.fas.org/sgp/crs/misc/R43148.pdf〉.
Reynolds, D.B., 2014. World oil production trend: comparing Hubbert multi-cycle curves. Ecol. Econ. 98, 62–71. http://dx.doi.org/10.1016/j.ecolecon.2013.12.016.
Reynolds, D.B., Kolodziej, M., 2008. Former Soviet Union oil production and GDP decline: Granger causality and the multi-cycle Hubbert curve. Energy Econ. 30, 271–289.
Salameh, M.G., 2003. Can renewable and unconventional energy sources bridge the global energy gap in the 21st century? Appl. Energy 75, 33–42. http://dx.doi.org/10.1016/S0306-2619(03)00016-3.
Samii, M., Teekasap, P., 2010. Energy policy and oil prices : system dynamics approach to modeling oil market. J. Glob. Commer. Res. 2, 1–7.
Silvério, R., Szklo, A., 2012. The effect of the financial sector on the evolution of oil prices: analysis of the contribution of the futures market to the price discovery process in the WTI spot market. Energy Econ. 34, 1799–1808. http://dx.doi.org/10.1016/j.eneco.2012.07.014.
Statoilhydro, I.S., Ipc, R.S., 2007. Global Oil Reserves-1: Recovery factors leave vast target for EOR technologies. Oil Gas. J. 105, 44.
Sterman, J., 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World. McGrawHill, USA.
Sterman, J.D., Richardson, G.P., Davidsen, P., 1988. Modeling the estimation of petroleum resources in the United States. Technol. Forecast. Soc. Chang. 33, 219–249.
Tao, Z., Mingyu, L., 2007. System dynamics model of Hubbert Peak for China's oil. Energy Policy 35, 2281–2286.
Tsay, R.S., 2005. Analysis of Financial Time Series, Third ed., John Wiley & Sons, Chicago.
Tsuchiya, H., Kobayashi, O., 2004. Mass production cost of PEM fuel cell by learning curve. Int. J. Hydrog. Energy 29, 985–990. http://dx.doi.org/10.1016/j.ijhydene.2003.10.011.
USGS, 2000. US Geological Survey (USGS). World Petroleum Assessment—Description and Results. Series–DDS-60., US Geological Survey Digital Data. Reston.
World Oil Outlook, 2014. Austria: Organisation for Petroleum Exporting Countries (OPEC).