World oil supply
and unconventional resources
Bottom-up perspectives on tight oil production

Henrik Wachtmeister
Abstract
Oil is the world’s largest primary energy source. It dominates the transportation sector which underpins the world economy. Yet, oil is a nonrenewable resource, destined not to last forever. In the mid-2000s global conventional oil production stagnated, leading to rising oil prices and fears of permanent oil scarcity. These fears, together with the high prices, receded with the unforeseen emergence of a new supply source: tight oil.

This licentiate thesis investigates unconventional tight oil production and its impacts on world oil supply in terms of resource availability and oil market dynamics, and in turn briefly discusses some possible wider economic, political and environmental implications of these impacts. The thesis is based on three papers. The first investigates the usefulness of bottom-up modelling by a retrospective study of past oil projections. The second looks at how unconventional tight oil production can be modelled on the well level using decline curve analysis. The third derives typical production parameters for conventional offshore oil fields, a growing segment of conventional production and a useful comparison to tight oil.

The results show that tight oil production has increased resource availability significantly, as well as introduced a fast responding marginal supply source operating on market principles rather than political ones. The emergence of tight oil production has altered OPEC’s strategic options and led to a period of lower and less volatile oil prices. However, this condition of world oil supply can only last as long as the unconventional resource base allows, and, at the same time, total fossil fuel consumption will have to fall to limit climate change. It is concluded that this breathing space with lower oil prices could be used as an opportunity to develop and implement policy for an efficient managed decline of global oil use in order to achieve the dual goals of increased human economic welfare and limited climate change, and in the process preempt any future oil supply shortage. Unconventional tight oil production can both help and hinder in this endeavor. Accurate models and analyses of oil production dynamics and impacts are therefore crucial when maneuvering towards this preferred future.
List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


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Other papers not included in this thesis:


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## Abbreviations

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>EIA</td>
<td>U.S. Energy Information Administration</td>
</tr>
<tr>
<td>EUR</td>
<td>estimated ultimate recovery</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>NPV</td>
<td>net present value</td>
</tr>
<tr>
<td>OECD</td>
<td>Organisation for Economic Co-operation and Development</td>
</tr>
<tr>
<td>OPEC</td>
<td>Organization of the Petroleum Exporting Countries</td>
</tr>
<tr>
<td>RRR</td>
<td>remaining recoverable resources</td>
</tr>
<tr>
<td>URR</td>
<td>ultimately recoverable resources</td>
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</table>
1 Introduction

1.1 Background

Discussions of future world oil production and price have been ongoing ever since the beginning of the modern oil era, often attributed to a well in Pennsylvania in 1859. Being a nonrenewable resource, much of the discussions have been concerned with the availability of future supply in relation to expectations of increasing demand. With over 150 years of growing global consumption and societal dependence the relevance of this discussion has only increased. Still, quite different views on future supply and demand exist, and have done so throughout the history of oil. The discussion has often been described as one between those concerned or not concerned of a relatively imminent constraint on supply due to depletion and oil’s finite nature. With such a large and complex system with many uncertainties and decision variables it is natural that many views of the future exist. Sometimes due to different backgrounds and schools of thoughts, or even more personal philosophical views, participants have stressed or focused on different aspects and their relative importance. In the academic domain the question of future oil supply has been framed as a tug of war between geology and technology (Benes et al. 2015) where predominantly natural scientists have focused on the physical constraints while economists have highlighted innovation, technological development and substitution.

Energy historian Daniel Yergin (Yergin 2012) writes that the most recent run up of oil prices during the beginning of the twenty-first century was in fact the fifth time a major fear swept the world that oil is running out. The first occurring already at the end of the nineteenth century, when the first Pennsylvanian oil fields began to decline. The second and third occurred after World War I and II, where in both oil’s strategic importance where recognized and scrambles for securing resources began. The fourth occurred in the 1970s with the first and second oil shock, ignited by the Arab oil embargo 1973 and the Iranian Revolution 1978.

With the benefit of hindsight, it seems that both sides of the discussion were right about the most recent oil shock during the 2000s. Conventional oil production has stagnated due to limited resources, meanwhile, the unforeseen technological development of unconventional tight oil production has proved a significant new supply source, causing another period of lower prices.
This thesis sets off in this new environment, where unconventional tight oil production is a major contributor to global supply, and investigates its production potential and impact on the world oil market. Based on this analysis some implications in regard to wider environmental, political and economic aspects are then discussed.

1.2 Aims and outline

The aim of this thesis is to increase the understanding of some of the involved factors in world oil production in order to identify potential future developments and their possible wider implications. More specifically, this thesis investigates unconventional tight oil production and its potential impacts on total world oil supply in terms of resource availability and market dynamics, and in turn possible wider economic, political and environmental implications of these impacts. By increasing the understanding of the dynamics of future world oil supply, the overarching aim is to increase knowledge on which developments are possible, currently likely and ultimately desirable in the future. The thesis aims to answer the following research questions:

- How can unconventional tight oil production affect world oil supply in terms of resource availability and market dynamics?
- What are the main potential economic, political and environmental implications of these effects?
- How can tight oil production be modelled?

The answers to these broader questions are derived from the more specific inquiries in the thesis papers Paper I-III. These papers ask more specific research questions, including the following:

- How useful are bottom-up methods for oil modelling and projections? (Paper I)
- How can tight oil production be modelled using bottom-up methods? (Paper II)
- How can conventional offshore production be modelled using bottom-up methods? (Paper III)
- What are the differences between conventional and unconventional tight oil production dynamics? (Thesis chapter)

In the Conclusions section answers to the three main research questions are given drawing on the results and findings from the different papers. Before the results and conclusions part, the thesis begins with a brief introduction to oil as a resource and an overview of the methods used to assess current and future supply.
This licentiate thesis is a part of a larger research project funded by the Swedish Research Council titled ‘Global oil supply outlooks: modelling conventional and unconventional oil production using bottom-up models integrating physical and economic parameters’ (project number 2014-5246). This project builds on previous oil focused research conducted at the Department of Earth Sciences at Uppsala University including work by Robelius (2007), Höök (2010), Söderbergh (2010) and Jakobsson (2012). In a coming doctoral thesis the author aims to cover all of world oil supply, both conventional and unconventional, and focus on future developments, exploring different scenarios by using the derived bottom-up framework.
2 World oil supply

2.1 A nonrenewable resource

Oil was formed millions of years ago by biological and geological processes. Although new oil is very slowly being formed, by any practical human time scale oil is a nonrenewable resource in a material sense (Höök et al. 2010; Walters 2006). The amount of oil in the ground is fixed, and determined by past physical factors. However, the amount of oil that is possible and likely to be produced depends on many nonphysical factors, including economic, political and environmental ones. For example, the volume of oil that is possible to produce can be increased due to new technology or increased geological knowledge and information. The volume that is likely to be produced, in the regard that it makes economic sense and is politically viable, can change due to high or low oil prices, political priorities or conflicts.

With this many influencing and interlinked factors, quantitative estimates of oil resources are very uncertain, or at least conditional on many uncertain or undecided factors. However, with increasing knowledge and exploration activities for over a hundred years, estimates of total global recoverable resources of conventional oil is seemingly converging to some extent. While instead, the main source of uncertainty has shifted to unconventional resources more recently unlocked by new technology.

There are many ways to classify resources and reserves and their different subgroups and conditions (Bentley et al. 2007). Energy consultancy Rystad Energy (Rystad Energy 2018) is one of only a few primary data sources that provides comprehensive global resource and reserve estimates. In Table 1 total world oil resources from their propriety database UCube are presented. The Rystad resources definition corresponds to expected total recoverable economical resources. Implicitly these estimates include known resources, expected future discoveries and expected future economic conditions and technological development. The recoverable oil resource estimates can be split into proved, probable, and expected reserves, as well as contingent and prospective recoverable resources according to the standard Petroleum Resources Management System (SPE 2007).
Table 1. Recoverable oil resources as of end 2017 in gigabarrels (Gb) according to Rystad Energy definitions and data. In this selection ‘oil’ includes crude oil, condensate and natural gas liquids. Biofuels are excluded. ‘Total’ corresponds to estimates of global ultimately recoverable resources (URR).

<table>
<thead>
<tr>
<th>Resources (Gb)</th>
<th>On-shore</th>
<th>Offshore shelf</th>
<th>Offshore midwater</th>
<th>Offshore deepwater</th>
<th>Oil sands</th>
<th>Tight oil</th>
<th>World total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discovered</td>
<td>1755</td>
<td>545</td>
<td>96</td>
<td>84</td>
<td>77</td>
<td>230</td>
<td>2786</td>
</tr>
<tr>
<td>Undiscovered</td>
<td>249</td>
<td>192</td>
<td>102</td>
<td>134</td>
<td>26</td>
<td>389</td>
<td>1093</td>
</tr>
<tr>
<td>Total</td>
<td>2004</td>
<td>737</td>
<td>198</td>
<td>218</td>
<td>103</td>
<td>618</td>
<td>3878</td>
</tr>
<tr>
<td>Produced</td>
<td>1111</td>
<td>298</td>
<td>58</td>
<td>19</td>
<td>11</td>
<td>15</td>
<td>1512</td>
</tr>
<tr>
<td>Remaining</td>
<td>892</td>
<td>439</td>
<td>140</td>
<td>199</td>
<td>92</td>
<td>603</td>
<td>2366</td>
</tr>
<tr>
<td>Total</td>
<td>2004</td>
<td>737</td>
<td>198</td>
<td>218</td>
<td>103</td>
<td>618</td>
<td>3878</td>
</tr>
<tr>
<td>Discovered/total</td>
<td>88%</td>
<td>74%</td>
<td>48%</td>
<td>38%</td>
<td>75%</td>
<td>37%</td>
<td>72%</td>
</tr>
<tr>
<td>Produced/total</td>
<td>55%</td>
<td>40%</td>
<td>29%</td>
<td>9%</td>
<td>10%</td>
<td>2%</td>
<td>39%</td>
</tr>
</tbody>
</table>

Estimates of remaining resources and reserves tend to increase due to conservative initial reporting, technological development and increased geological information (McGlade 2013). Increasing estimates is sometimes used as an argument against concerns about future supply constraints. It is informative however, to look at when the resources were discovered to assess the sustainability of current production levels in regard to available resources. Figure 1 shows annual oil discoveries and production globally. As seen, annual discoveries were the highest before the 1970s and have declined since. In the 1980s annual discoveries began to trend lower than annual production. The shift to deeper offshore resources and unconventional resources is clear, and the recent introduction of tight oil resources provides a clear break, at least temporary, in the declining trend. In the last few years annual discoveries have been record low, while production record high, leading to a resource deficit of over 30 gigabarrels (Gb) per year. Even if resource estimates can be deemed high, and can grow with time, the underlying discovery trend is currently unsustainable in a long term perspective.

The resources in Figure 1 underpins the production levels seen in Figure 2, which shows total world production by supply category as well as the real price of oil, in constant 2016 USD. As seen, conventional oil stagnated in mid 2000s, as many had warned (Aleklett 2012), leading to higher oil prices and the following surge in US tight oil production.
**Figure 1.** Annual oil discoveries by supply category and annual total world oil production in gigabarrels (Gb). Two years had higher discoveries than 70 Gb: 1948 with 201 Gb (including the Ghawar oil field, Saudi Arabia) and 1971 with 83 Gb. Source: Rystad Energy.

**Figure 2.** Annual total world oil production by supply category in million barrels per day (Mb/d), a common oil production unit, as well as the real price of oil, in constant 2016 US dollars (USD). Source: Rystad Energy and BP Statistical Review.
2.2 A hydrocarbon resource

Oil is a mixture of several variants and sizes of hydrocarbon molecules. The energy in oil is released by combustion where the energy rich bonds between hydrogen and carbon atoms are broken by the oxidation process. This process yields energy, water and carbon dioxide. Since oil is the number one energy source by volume it is a major contributor to total greenhouse gas emissions and global warming. Recent studies have shown that a significant portion of current oil reserves must remain unused to meet the 2 °C target (McGlade and Ekins 2015). According to for example the IEA’s Sustainable Development Scenario, which is in line with the 2 °C target, total world oil consumption will have to decrease immediately and be 32 Mb/d lower in 2040 relative to the New Policies Scenario, a scenario based only on current and announced polices (IEA 2017) and not in line with the 2 °C target.

Depending on the quality of the oil and how it is produced, the full life cycle emissions from one barrel can range from 460 to 740 kg CO2 eq. per barrel (Gordon et al. 2015), a 50 percent spread. Since 2005 conventional oil production has essentially been flat while incremental supply has come from unconventional sources, primarily oil sands and tight oil. This shift towards a more diverse supply mix has implications for carbon emissions and carbon budgets since different production technologies have different energy and carbon emission intensities. Specifically, some unconventional production technologies and old nearly depleted conventional fields have relatively higher carbon intensities (Brandt et al. 2018).

2.3 A political and economic resource

Oil dominates the transportation sector worldwide. Without transportation almost no economic activity is feasible. Oil is therefore a critical resource for the modern society. The price of oil affects the overall growth of the world economy, as well as allocations between different sectors and countries (Kumhof and Muir 2013; Hamilton 2009; Hamilton 1983). Because of this importance oil was ‘securitized’ early, in the sense that it became part of national security policy and strategy of both producing and consuming countries (Yergin 2006). Since the endowment of oil is determined by geological factors and its transportation routes by geographical ones, oil is a key subject of geopolitical considerations.

A large fraction of conventional oil resources are located in the Middle East. Many of these countries are members of the OPEC consortium. This group of countries has shaped the world oil market by controlling production levels by political decisions. Many of these oil rich countries are also heavily dependent on the revenues from oil, which affects their perspectives on ‘fair’ oil prices as well as on climate polices.
The US, being the world’s largest oil consumer, has long been involved in Middle Eastern affairs. One of its key objectives has been to secure the flow of oil from the region, at an affordable price. With tight oil being on track to make the US net import independent of oil, its geopolitical strategy and leverage can change significantly. On the other hand, rising consumers and importers such as China might have to engage more actively in oil rich regions and its politics to secure their growing oil dependence.
3 Methods

3.1 Bottom-up analysis (Paper I-III)

In general bottom-up analysis refers to any analysis that approaches the whole from aggregation of its underlying parts, in contrast to top-down analysis that approaches the whole directly. In oil production modelling, bottom-up analysis and bottom-up modelling refers to well-by-well, field-by-field or project-by-project analysis and subsequent aggregation to regional or global level. Depending on chosen detail, a bottom-up field-by-field oil model requires extensive and difficult to obtain data on field sizes, field production and costs. A bottom-up supply framework can be used to model future production and prices if connected to a demand function. This concept is underlying the projections of the IEA and the EIA in their World Energy Outlook and Annual Energy Outlook series. In such frameworks a decision algorithm representing oil industry behavior is applied. This algorithm calculates the net present value (NPV) of possible future projects at an assumed oil price, and projects with a positive NPV will be brought into production. If not enough projects are profitable at the assumed price to fulfil expected demand in the future, the algorithm increases the oil price one step and recalculates NPV for all projects. This procedure is repeated until supply equals future demand at several years ahead. The result is projections for production, price and required capital investments.

In theory, on the project or field level, the production and investment profiles observed for individual oil assets can be regarded as the solution to the developer’s optimization problem (Jakobsson et al. 2012). The developer can be assumed to choose a production strategy that aims to maximize his or hers profit. Usually this problem is specified as net present value optimization under certain geological, technical and economic constraints. The two key geological constrains being the resource size and the reservoir pressure where the pressure difference between the reservoir and the surface is the driving mechanism for production during primary recovery. Since reservoir pressure decreases in proportion with cumulative production, production rate from primary recovery will decline exponentially.

Important technical and economic constraints are costs and rate of adding production capacity and of course assumed future oil prices which determines the magnitude of the income stream. The used discount rate has high impact on this kind of calculations. For example, Rystad Energy (2016) uses a real
discount rate of 7.5 percent when estimating break even prices of new projects (oil price at which project NPV equals zero). Assumed discount rate can also vary between different types of projects, and are often used to account for country or project risks (McGlade 2013). In an economic evaluation of conventional versus unconventional tight oil production the discount rate will be a key determinant since the time aspects between the two production types are very different.

Typical asset production profiles can be derived from theoretical frameworks of NPV optimization as described above. In practice however, production and investment profiles can differ quite significantly from what would have been theoretically optimal. Local conditions or other circumstances can give unique production profiles. To include all these factors production profiles based on empirical data can be used in an analogue approach.

The bottom-up approach can be seen as the methodological foundation of this thesis and its papers. However, several complimentary and specific methods must be used in conjunction with this high level framework, for example depletion and decline rate analysis which is described further below.

In Paper I, the usefulness of bottom-up methods are evaluated by retrospective analysis, and conclusions drawn for potential improvements. In Paper II production parameters of unconventional tight oil wells are derived, which provide the building blocks for regional and global bottom-up models. In Paper III production parameters of conventional offshore oil fields are derived. In a similar way these parameters provide building blocks for conventional offshore production modelling. In Chapter 4.4, a conceptual bottom-up analysis is conducted to highlight the different dynamics between conventional and unconventional tight oil, and to serve as reference for the discussion on potential implications.

3.2 Retrospective analysis (Paper I)

In the context of scenarios, projections and forecasts, retrospective analysis can be defined as any careful analysis of projections that is conducted after the period covered by the projection has become history (Koomey et al. 2003). According to O’Neill and Desai (2005) analysis of performance of past projections can be useful for two main reasons:

i. to inform scenario users about implied uncertainty of current projections based on historical accuracy, and
ii. to identify accurate and inaccurate parts of projections to inform modelers and scenario developers where improvement efforts can be aimed.
The retrospective analysis conducted in Paper I aims to shed light on these two points by quantification of historical revisions and accuracy of oil projections in IEA World Energy Outlooks 2000 to 2016. Based on derived historical accuracy, uncertainty of current projections is also estimated by application of empirical prediction intervals.

3.3 Decline curve analysis (Paper II-III)

In petroleum production, decline curve analysis refers to analysis of production rates of oil and gas wells and fields. This method has been used for over century but was synthesized in a comprehensive manner by Arps in the 1940s (Arps 1945). At some point well production rate will begin to decline as a function of time due to loss of reservoir pressure or changing relative volumes of produced fluids. The central assumption of the method is that conditions and mechanisms controlling the historical production trend will continue to control the future production trend. Decline curve analysis is in principle empirical trend extrapolation, however with underlying theoretical foundations in fluid dynamics and reservoirs physics. The main advantage is the method’s simplicity, it only requires production data, while knowledge of the actual physical conditions and mechanisms driving the production is not needed directly. Once a stable production trend is identified mathematical models can be fitted to the production data and extrapolated into the future. The extrapolated production decline curve can then be used to estimate well lifetime or well resource size if combined with a production cut off criteria, usually based on an estimated economic limit.

In Paper II traditional decline curve analysis commonly used on conventional oil wells are applied to unconventional tight oil wells in Eagle Ford shale. In Paper III decline rates of different categories of conventional offshore oil fields are derived.

3.4 Depletion rate analysis (Paper III)

A useful complement to decline curve analysis is depletion rate analysis. In a similar manner this method looks at production rates of petroleum wells and fields, and even regions, but in relation to an estimate of the resource size of the producing well, field or region. The concepts of depletion rate and decline rate are linked (Höök et al. 2014; Höök 2014). For example, decline curve analysis can be used to estimate an unknown resource size of a producing asset by using production data. On the other hand, depletion rate analysis, can be used to estimate future production decline rates by using a known resource size.
The depletion rate $d(t)$ of remaining resources at time $t$ can be defined as

$$d(t) = \frac{q(t)}{RRR(t)}$$

where $q(t)$ is annual production and $RRR(t)$ is remaining resources defined as

$$RRR(t) = URR - Q(t)$$

where $URR$ is ultimately recoverable resources (equivalent to field size or initial resource size) and $Q(t)$ is cumulative production.

By empirical studies typical depletion rates can be estimated and by an analogue approach such typical depletion rates can be applied to known URR estimates to model annual production, and in the decline phase, annual decline rates. In Paper II empirical depletion rates for offshore oil fields are compiled together with other production parameters useful for oil field modelling by analogy.
4 Results

4.1 Retrospective analysis of bottom-up oil projections (Paper I)

Scenarios and projections are important for decision and policy making. Accuracy of past projections can be useful for both scenario users and developers, for insight on current projection uncertainty, and for guiding improvement efforts. Paper I compiles projections of oil production, oil prices and upstream investments from the years 2000 to 2016 from the annual World Energy Outlook by the International Energy Agency, and investigates revisions and accuracy of past projections and implied uncertainty of current ones. Revisions of world oil production, price and investments have been motivated by a combination of demand and supply factors. Downward revisions are mainly allocated to OPEC, while recent upward revisions are due to unconventional oil, in particular US tight oil. Non-OPEC conventional projections have been stable. Price and investments have been revised mostly upwards. Projection accuracy follows the size and directions of these revisions, with high accuracy for Non-OPEC (mean absolute percentage error of 4.8% on a 5 year horizon) and low for OPEC (8.9%) and unconventional (37%). Counteracting error directions contribute to accurate total World oil supply projections (4%) while price projections have low accuracy (37%).

The paper concludes that scenario users should be aware of implied uncertainty of current oil projections. In planning and decision making, uncertainty ranges such as those presented in the paper can be used as benchmarks. Scenario developers should on their side focus improvements efforts on three areas in particular: tight oil, OPEC and new technology.

The results of Paper I show that bottom-up modelling can be useful for accurate supply projections in the short to medium term. The high accuracy of Non-OPEC conventional oil production projections indicates the effectiveness of the World Energy Outlook modelling methodology when applied to well-known resources, technology and economical and political frameworks. In other words, a bottom-up, field-by-field, agent-based approach has predictive power in regions with market based economic systems and with functioning and transparent institutions. Increasing geological knowledge and cost estimations can potentially improve accuracy further. Since tight oil is currently only produced in the US, it is possibly to assume that this production, although with
a different dynamic, can be modeled in a similar accurate way based on geological and technical information and market dynamics. Increased understanding and precise modelling of tight oil has the potential to lead to higher accuracy in total world oil production projections because tight oil might in the future function as a relatively fast balancer of global supply and demand, operating on market principles rather than political ones.

4.2 Decline curve analysis of tight oil wells (Paper II)

Paper II derives typical production curves of tight oil wells based on monthly production data from multiple horizontal Eagle Ford shale oil wells. Well properties initial production (IP) rate and production decline rate are documented, and estimated ultimate recovery (EUR) is calculated using two empirical production decline curve models, the hyperbolic and the stretched exponential function. Individual well productivity, which can be described by IP level, production decline curvature and well lifetime, varies significantly. The average monthly IP was found to be around 500 b/d, which yields an EUR in the range of 150–290 kb depending on used curve, assumed well lifetime or production cutoff level. More detailed analyses on EUR can be made once longer time series are available. For more realistic modelling of multiple wells a probabilistic approach might be favorable to account for variety in well productivity. For less detailed modelling, for example conceptual regional bottom-up production modelling, the hyperbolic function with deterministic parameters might be preferred because of ease of use, for example with the average parameter values IP = 500 b/d, D = 0.3 and b = 1 resulting in an EUR of 250 kb with a 30-year well lifetime, however, with the recognition that this extrapolation is uncertain.

4.3 Depletion and decline rate analysis of offshore oil fields (Paper III)

Paper III derives empirical estimates of field depletion level, depletion rate, decline rate and characteristic time intervals in offshore oil production based on a global field-by-field database containing 603 offshore oil fields. Statistical distributions as well as arithmetic and weighted averages of production parameters are derived for different categories of fields specified by size, location and water depth. A significant tendency of small fields having higher depletion and decline rates is found. Similarly, OECD countries generally have higher rates compared to non-OECD countries. Trends related to water depth are not clearly distinguishable and require additional investigation of time related aspects. Resulting spreads in derived parameter estimates are
found to be well described by positively skewed probability distributions. Also, in line with theory, a strong correlation between depletion and decline rate is found. According to the study, the net share of global offshore production from smaller and deeper fields is increasing. A continuation of these trends would likely have implications for future aggregate offshore production behaviour, most notably, increasing global aggregate decline rates.

4.4 Production dynamics of conventional and unconventional tight oil – a comparison

Drawing on the findings of Paper II and III and complimentary data from the Norwegian Petroleum Directorate (NPD 2016) as well as from the Uppsala giant oil field database (Robelius 2007) a conceptual comparison between conventional giant oil fields and unconventional tight oil wells can be made to illustrate the different investment and production dynamics of these two supply sources. For this comparison investment figures are based on only Norwegian fields, which are offshore fields, while production rate parameters are based on fields from all over the world, both onshore and offshore.

Typical investment and production profiles for conventional giant oil fields and unconventional tight oil wells based on mean values of production parameters derived from empirical data are showed in Figure 3 and 4. For conventional oil, the typical production profile has a linear production build up phase of 4 years, a plateau period of 13 years with a maximum production rate of 250,000 barrels per day and an annual decline rate of 7.4 percent. Field life time is set to 80 years. This production profile yields a field estimated ultimately recovery (EUR) of 2.5 Gb. Assuming a capital investment cost (capex cost) of 20 USD per barrel required field investment equals 50 Bn USD. This amount is deployed by a triangle shaped investment profile with maximum investment 12.5 Bn USD per year at the year of the field’s first production. First investment occurs 4 year before maximum production, and grows and decreases linearly around its maximum, in line with empirical data.

For unconventional tight oil the typical annual well production profile is based on the mean maximum monthly production value of 550 barrels per day, and long term decline profiles estimated in Paper II using the hyperbolic function with decline parameters D = 0.3 and b = 1. Well life time is assumed to be 30 years, which yields a well EUR of 270 kb. Assuming the same capex cost of 20 USD per barrel, yields a required capital investment of 5.4 million USD per well. This amount is all allocated to the year prior to the year of first production, in this schematic comparison. In real operations production can follow first investment in a matter of months.

The difference in investment and production dynamics becomes clear when comparing the two typical production profiles in Figure 3 and 4. For tight oil,
production starts directly after investments are spent. For conventional, it takes a few years after spent investments for production to follow. Furthermore, tight oil production is heavily frontloaded with almost negligible production after a few years, while giant fields can produce high rates for several decades.

Figure 3. Typical investment and production profile of a conventional giant oil field.

Figure 4. Typical investment and production profile of an unconventional tight oil well.

The derived typical production profiles for conventional giant oil fields and unconventional tight oil wells are used to illustrate the difference in aggregate investment and production dynamics between the two kinds of production. Note however that the derived typical conventional field production profile represent a giant field, it is not representative of the average of all fields, where the majority is smaller than 500 million barrels. However, giant oil fields contain a large part of global production, about 60 percent, and a comparison of giants to tight oil wells can be useful as comparison of two extremes, making differences more distinct.
In Figure 5, the aggregate production profiles arising from constant and equal amount of annual investment for the two production sources are visualized. Here 500 Bn USD per year of total investment is used, roughly in line with current world upstream spending. As before, the 20 USD per barrel capex cost is assumed. This corresponds to an annual development of 25 Gb of oil. For conventional production this translates into development of 10 typical giant fields per year, each with an EUR of 2.5 Gb. For unconventional oil, the 500 Bn USD annual investment corresponds to a development of over 92,500 typical tight oil wells per year, each with an EUR of 270 kb. The production profiles of each year’s development are presented as individual areas in Figure 5 and consist of the typical production profiles times the annual number of fields and wells developed respectively.

Figure 5a show aggregate conventional production from constant development during 25 years and the resulting aggregate decline. On this timescale the aggregate production curve is similar to a bell shaped curve. In Figure 5b aggregate production from 50 years of constant development is presented. On this timescale an aggregate shape resembling a shark fin is emerging. This results from the end of the initial boost when a large share of all fields are in plateau production and have not yet started to decline.

In Figure 5c aggregate unconventional tight oil production stemming from 25 years of constant development is shown. Due to the high production rate in the first year for tight oil wells, aggregate production from the over 92,500 wells jumps up to over 20 million barrels per day immediately. This is highly unrealistic development in the real world, but is illustrative for this exercise. The rate of increasing aggregate production is then slowing down after the initial jump due to the relatively higher amount of wells with low production rates compared to new wells with higher rates. In Figure 5d, with 50 years of constant production, a full shark fin curve has emerged, consisting of the initial jump when there are only new wells, the decreasing share of new wells and the equilibrium between added new wells and decline and shut down of old wells (well life time 30 years). A mathematical way to describe these aggregate curves is simply by the convolution of the typical production curves and the annual investment curves. In fact, the conventional aggregate curve will emerge as a full shark fin too when development time is longer then the individual field life time (80 years).

In summary, Figure 5 illustrate the aggregate consequence of the front-loaded production profiles of tight oil wells, resulting in faster increase and faster decrease in production compared to conventional oil, which shows slower increase, and decrease, resulting in more legacy production after investment ends.
Figure 5. Aggregate production in million barrels per day (Mb/d) from constant capital deployment during 25 (a and c) and 50 (b and d) years of conventional giant oil fields (a and b) and unconventional tight oil wells (c and d) respectively.
5 Conclusions

Without the emergence of unconventional tight oil production, the current world oil market would likely be supply constrained, absent any other technological breakthrough. Tight oil production has increased resource availability significantly. Rystad Energy’s current base estimate of North American tight oil remaining resources is 250 Gb, and for total global resources it is 600 Gb. Tight oil production has also changed oil market dynamics by introducing a short cycle supply source, with lead times from investment to first production in the range of months compared to several years for conventional production. The introduction of more and faster potential supply has led to lower prices and less extreme price volatility, in economic terms supply has become more elastic. The rise of unconventional tight oil has decreased the price setting power of OPEC, or at least limited the group’s strategic options by introducing a marginal supply source operating on market principles rather than being politically controlled.

Looking ahead, this new situation with increasing production with relatively lower and less volatile prices can be expected to last for some time, but for how long is an open question. However, it can only last as long as the resource base allows. Appraisals of tight oil resources and production potentials in the US and in other countries are therefore key to future supply projections. With such appraisals available, detailed bottom-up modelling can be conducted to explore potential supply and demand scenarios. As seen in Paper I, bottom-up methods when applied to accurate data and transparent market and institutional conditions can be very useful and accurate in exploring potential future outcomes. As shown in Paper II, hyperbolic decline curves can be used as individual tight oil well models in such bottom-up frameworks. With such a comprehensive global bottom-up supply model, which takes the different investment and production dynamics of conventional and unconventional oil production into account, their interrelations and their further relation to OPEC strategic behavior can be studied in systematic and transparent ways.

Besides studies of unconventional tight oil’s impact on oil market dynamics, a comprehensive bottom-up supply framework can be used to identify and investigate other wider economic, political and environmental implications, such as oil price impacts, geopolitical power shifts and climate change strategy.
For the world economy, the price of oil affect overall economic growth as well as internal allocations between sectors and between producing and consuming nations. If tight oil yields a period of lower prices this will boost economic activity worldwide, compared to a high price scenario. It will benefit consuming nations while hurting producing ones.

Political power is to some degree coupled to economic strength and independence. Tight oil production decreases US dependence on Middle Eastern oil which can have far reaching geopolitical consequences. China, on the other hand, now the number one importer, might be forced to take a greater role globally to secure its oil supplies.

For greenhouse gas emissions and climate change unconventional tight oil production can be both helpful and unhelpful. If solely leading to overall cheaper fuel and more consumption it will yield higher carbon emissions compared to a more supply constrained scenario. But since tight oil has lower carbon dioxide intensity than many conventional oils, and especially than other unconventional oils such as oil sands, it can actually have benefits if handled together with the appropriate policy. Another benefit of tight oil production is its lower lock-in effects, since the production time scales are much shorter. If tight oil replaces oil sands and provides supply which can be reduced relatively fast without risking to strand assets, it might prove a favorable supply source compared to long-lived projects, from a climate strategy perspective as well as from an oil industry financial risk perspective.

The tight oil net positive effect on the world economy can arguably also be helpful for climate action if handled properly, since it could be difficult to arrange international climate agreements and raise funds for renewable investments in a world beset by high oil price induced economic recessions and geopolitical conflicts. On the other hand, from a strict climate perspective, it could also be argued that a radical decline in oil use and economic activity due to oil supply shortages would be positive, even if having negative impacts on human economic welfare.

In conclusion, unconventional tight oil production has pushed the world’s final oil supply constraint into the future, removing for now concerns of immediate oil scarcity and its negative impacts on the world economy. This breathing space could be used as an opportunity to develop and implement policy for an orderly, efficient and just managed decline of global oil use in order to achieve the dual goals of increased human economic welfare and limited climate change, and in the process preempt any future oil supply shortage. Unconventional tight oil production can both help and hinder in this endeavor. Accurate models and analyses of its dynamics and impacts are therefore crucial when maneuvering towards this preferred future.
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