Limits of Technological Efficiency of Shale Oil Production in the USA

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Abstract

The development of the shale oil extracting technology revolution in the United States led to the rapid growth of its production and reduced the related costs to an acceptable level. The shale oil revolution dramatically influenced the global oil market and was a key factor in the reduction of oil prices in 2014-2016. This paper investigates the problems of long-term forecasting of shale oil production and the productivity of drilling rigs. This research applies an asymmetric bell-shaped function using the OLS approach. This function is derived as an analytical solution of the differential equation of oil production. Another contribution of this study is the asymmetric function, which correlates better with the data on the extraction of traditional and non-traditional oil resources.

An analysis of the empirical data with the derived asymmetrical bell-shaped curve shows that the productivity of drilling rigs would peak by 2026 at 1,200 bbl per day, which is two times higher than the current level. The peak of production would correspond to the maximum oil production of 11.3 mln bbl per day and to technically recoverable resources of 96 bln bbl. This could mean that starting from 2023, the volume of oil shale oil production in the US may not be enough to meet growing global demand for oil and other resources with even higher production costs. The theoretically grounded and practically tested asymmetrical bell-shaped curve can serve as one of the tools for assessing the long-term impact of technological innovation over the course of Foresight studies for the oil and gas complex.

Keywords: shale oil production; technological efficiency; institutional factors; bell-shaped curve fitting; rig productivity.

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Increased shale oil production in the United States was one of the major factors behind the dramatic decline in oil prices in 2014-2016. Shale oil is light with a low sulphur content contained in tight reservoirs [*Mănescu, Nuño,* 2015]. The short investment cycle allowed the US shale oil industry to push OPEC out of its position as the price regulator on the global oil market [*Baffes,* 2015].

Oil production is affected by several groups of factors (geological, technological, economic, and political), including specific features of the industry's regulation. In the long term, geological and technological factors become decisive [*Benes et al.,* 2012]: the more rapidly exploration and production technologies improve, the more hydrocarbons can be extracted and marketed under comparable economic conditions, and the higher the revenues will be.

Several engineering- and geology-based approaches were applied to model the geological and technological factors affecting oil production [*Brandt,* 2010]. We mean a set of hypotheses concerning production profiles throughout the oil field's life, usually presented in the form of bell-shaped curves. The most popular is the symmetric bell-shaped Hubbert curve which allowed researchers to predict the peak of oil production in the United States between 1965 and 1970 [*Hubbert,* 1956].

The main advantage of the geological engineering approach is its taking into account the non-linear nature of production growth over time, plus there is no need to predict oil price behavior in the long term. The flaws of this approach include its insufficient consideration of major oil production limitations (such as the need to maintain material balance and natural production decline). Production profiles are set a priori, while the quality of empirical data approximations is verified using mathematical procedures [*Semenychev et al.,* 2014].

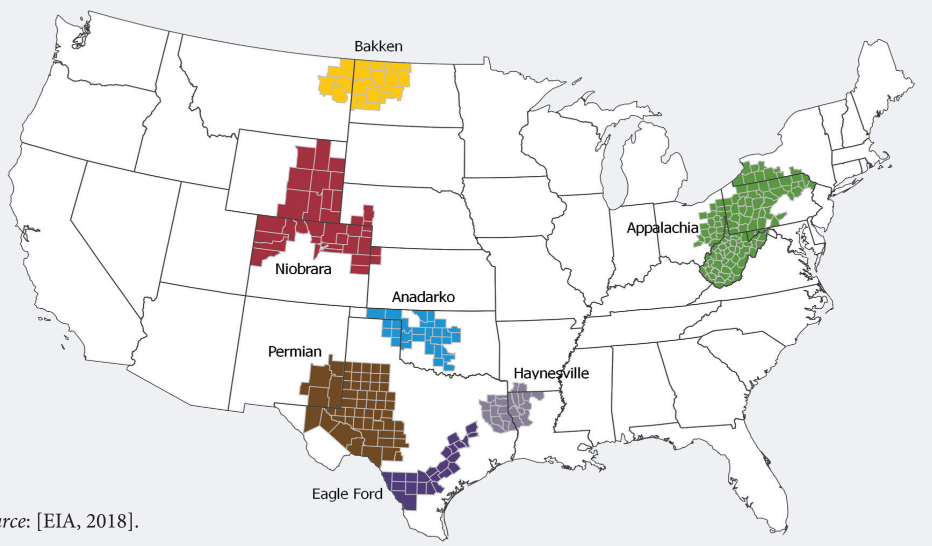
To deal with these shortcomings, [*Malanichev*, 2017a] proposed an ordinary differential equation that describes oil production growth taking into account the need to maintain material balance in oil reservoirs and the natural production decline. The Hubbert symmetric bell-shaped curve is a particular solution of this equation. However, since long-term oil production dynamics mostly remain asymmetrical (*Sorrel et al*., 2009), the proposed method required certain adjustments.

The first objective of this paper is to find an analytical solution for the oil production differential equation precisely in the form of an asymmetric bell-shaped curve. This will allow one to take into account physical conditions, clearly interpret the curve's coefficients, and ensure better compliance with observational data. The practical result of empirical data analysis based on the above curve will be a long-term production forecast and an estimate of technically recoverable reserves in US shale oil fields.

The second objective is to review key technologies, and other prerequisites that made the "shale revolution" possible in the United States by identifying a key technological efficiency indicator for oil production and preparing a long-term forecast of its growth. It is assumed that the technological curve is less variable than production volume, as it is less dependent upon the price factor.

This study was based on shale oil production data at seven key US fields for 2007-2017 (Fig. 1), presented in the Drilling Productivity Report of the US Energy Information Administration (EIA) [EIA, 2018]. Total oil production is measured using a set of indicators for individual formations, while drilling rig' productivity is calculated as a weighted average.

Figure 1. **Location of US shale oil fields under consideration**



Source: [EIA, 2018].

Technological and Institutional Factors of the "Shale Revolution"

The rapid growth of hydrocarbon production from tight reservoirs in the United States is due to a number of favorable technological and institutional factors. The first group includes the development of horizontal drilling and multiple fracturing technologies, new tools and capabilities for the development of complex wells, an extended range of chemical and physical methods of affecting the reservoir to increase the flow of hydrocarbons to the bottom of the well, and so on. Institutional factors include ownership guarantees, a transparent mechanism for getting access to oil-bearing areas, a developed service market, small and medium oil and gas businesses, good transport infrastructure, and a large financial market [*Shafrannik*, *Kryukov*, 2016].

The increased share of hydrocarbons produced from non-conventional fields by the US oil and gas sector was achieved after a long period of developing and improving relevant production technologies (Table 1).

Due to the lack of breakthrough inventions, the existing approaches to combining horizontal drilling, hydraulic fracturing, and 3D seismic surveying have been improved over the past 10-15 years [*Ivanov*, 2017a]:

- *Repeated hydraulic fracturing*. According to Halliburton, this technology increases recoverable reserves by 80% and cuts costs by 66%. In 2015, the number of fracturing stages reached 50 and their density was reduced to 3 meters. Proppant concentration increased to 3 t/m. Length of horizontal trunk exceeded 3 kilometers. Production via carbon dioxide injection after fracturing is now being promoted.
- *Cluster drilling*, which is applied at 58% of wells, amounts to drilling vertical wells in a section of the grid and then connecting them with horizontal wells. This reduces well costs by 15–30% and significantly reduces drilling time.
- *Analytical methods for processing 3D seismic data, "big data", and computer modeling* are being developed by oil and gas companies and by technology services providers. For example, the FracFit™ Baker Hughes technology allows one to collect and analyze data to quickly and efficiently complete and stimulate shale wells, resulting in a 45% increase in production.

Along with improved production technologies, a key prerequisite of the "shale revolution" in the US was the development of financial technologies. While oil prices remained high (in 2005-2014), the tight oil sector has managed to attract significant financial resources from leading world markets, among other things because money was readily available due to the Federal Reserve's low interest policy [*Zhukov, Zolina*, 2017]. When the market situation deteriorated in 2015-2017, the hedging of price-related risks prevented US crude oil production from dropping below the June 2014 level (when prices exceeded $100 per barrel). Guaranteed sales at a relatively high price in a falling market helped to maintain the financial stability of oil-producing companies in the US and provided them with a steady flow of liquidity.

In contrast, on a growing market hedging turns out to be a constraining factor. According to Bloomberg, in 2018 63% of expected revenues were hedged at the average price of $48.2 per barrel, while the actual price of a barrel of WTI oil at the beginning of the year was $64 [Denning, 2017]. Thus, hedging on the oil market turns out to be ineffective with an upward price trend, but ensures companies' stability with a downward one.

Hedging was a financial driver of the US "shale revolution" and remains an essential element of the developed institutional business environment in the United States. Other components of this environment include the following tools and characteristics [*Shafrannik, Kryukov*, 2016]:

- The *established institution of private land and subsoil ownership*. In the US, the landowner owns the subsoil and has the right to geological exploration, development, and mining by default, while the advanced rules and mechanisms make obtaining relevant authorizations simple and straightforward.
- The *largest fleet of drilling rigs* (in 2011 the number of simultaneously operating rigs exceeded 1,800); most of them allow one to drill long horizontal wells. This is more than the combined fleet of the former Soviet republics, Saudi Arabia, and Canada. It should be noted that after the rig fleet stabilized at 800, the growth of drilling volumes was mainly due to increased productivity, as the equipment was upgraded.
- *Investment and tax incentives* to keep marginal wells operational. The resulting huge number of drilled wells, combined with the newly acquired and systematized knowledge, facilitated the US oil and gas sector's taking a new development path.
- *Developed transport infrastructure*, including road and special-purpose networks (such as pipelines and terminals), with free and non-discriminatory access.
- *Numerous independent small and medium oil companies* that are more flexible and willing to take on the risk of working with small fields and hard-to-reach resources. Such players' share is almost 60%

of hydrocarbon production in the United States, which was the reason why the oil recovery rate in the US over the past 20-30 years grew from 25-28% to 40%.

- *Less strict environmental requirements for hydraulic fracturing*. Influenced by the US Vice President (formerly Executive Director and Chairman of the Board of Directors of Halliburton) Dick Cheney, in 2005 the US Congress took fracturing technology out of the Environmental Protection Agency's (EPA) supervision and removed it from the coverage of the federal water laws [*Glushenkova*, 2015]. Shale oil production in the country is mainly concentrated in sparsely populated areas of non-agricultural states such as Oklahoma, Texas, Nevada, etc. However, even there the development of shale deposits may pose a threat to the environment. Firstly, if technologies are applied carelessly, drinking water extracted from underground reservoirs can be polluted. Secondly, oil production exacerbates seismic instability, even in relatively safe areas. Thirdly, it may be accompanied by emissions of methane and other greenhouse gases. Fourthly, there is a risk of contamination and subsidence of soil in production areas and the associated problem of cleaning and disposing of drilling mud and water used for hydraulic fracturing.

The favorable institutional environment for the development of production technologies in the US contributed to the development of unconventional hydrocarbon deposits, while the "learning curve" has led to increased oil recovery from the drilled wells (Fig. 2).

At the key Permian formation reviewed above, the average well oil recovery was steadily growing over the observation period (from 2007) and by 2017, the new flow rates have exceeded 450 bbl./d. The average well output is a representative indicator for describing the quality of hydrocarbon reserves and productivity, but not the drilling efficiency. The oil production per drilling rig is a more comprehensive indicator. This data is readily available due to the monthly monitoring of the seven key formations published in the Drilling Performance Report [EIA, 2018].

Growth of Drilling Rig Productivity

The productivity of drilling rigs is directly reflected in the level of oil production in the US shale deposits and technically recoverable reserves. The higher the productivity, the higher the output given the same number of active rigs.

Since 2007, the productivity of the average drilling rig grew by 15 times reaching 625 bbl./d by the end of 2017 and it continues to increase (Fig. 3). In the context of high oil prices in 2010-2014, this indicator grew due to the technological factor, i.e., the classic proliferation of innovations [EIA, 2016]. Since the end of 2014, productivity growth was also influenced by low oil prices.

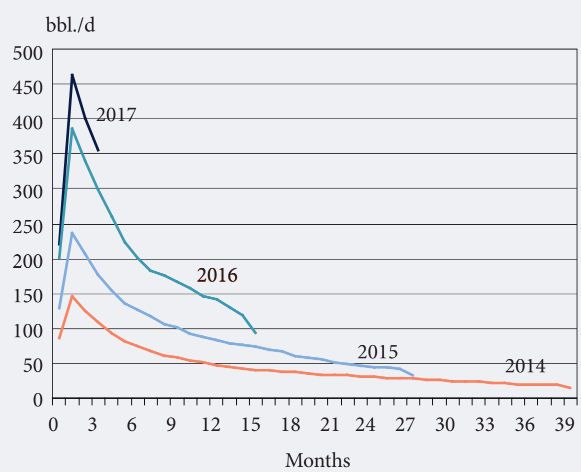
As a result of the falling oil prices in 2014-2016, the number of active drilling rigs dropped from 1,549 in October 2014 to 317 in May 2016. Such a rapid decrease resulted in an equally fast increase in productivity, which by August 2016 peaked at 711 bbl./d, mainly due to cyclical rather than technological factors [Rystad Energy, 2016]. While the volume of drilling and the fleet of rigs were being reduced, only the

Table 1. **The main stages of developing key tight oil production technologies in the US**

Year	Technology, application
1929	Drilling of the first horizontal well in Texas
1947	First hydraulic fracturing in Kansas
1949	First cost-effective hydraulic fracturing in Oklahoma
1979	Development of the Barnett Formation begins: the first shale formation fracture
1986	The first multistage hydraulic fracturing of a shale formation (seven stages)
1992	The first 3D seismic survey in Texas
1997	The first application of a water-based reagent for fracturing the Barnett formation
2000	Drilling of the first horizontal well in the Barnett formation
2002	Horizontal drilling combined with hydraulic fracturing in the Barnett formation

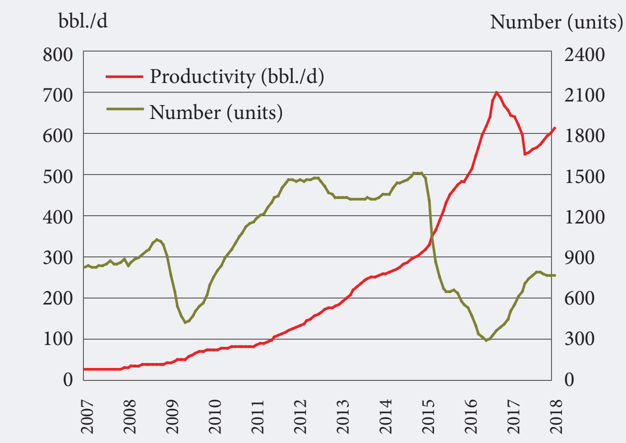
Source: [*Zolina*, 2014].

Figure 2. **Oil production from the average well in the Permian formation in 2014-2017**



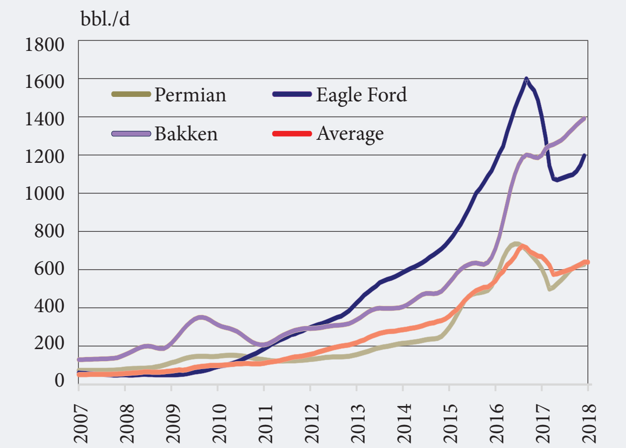
Source: composed by the author based on [EIA, 2017].

Figure 3. **Weighted average productivity of drilling rigs in seven fields, and the number of drilling rigs**



Source: composed by the author based on [EIA, 2018].

Figure 4. **Drilling rigs' productivity in the largest US fields, and the weighted average for seven fields**



Source: composed by the author based on [EIA, 2018].

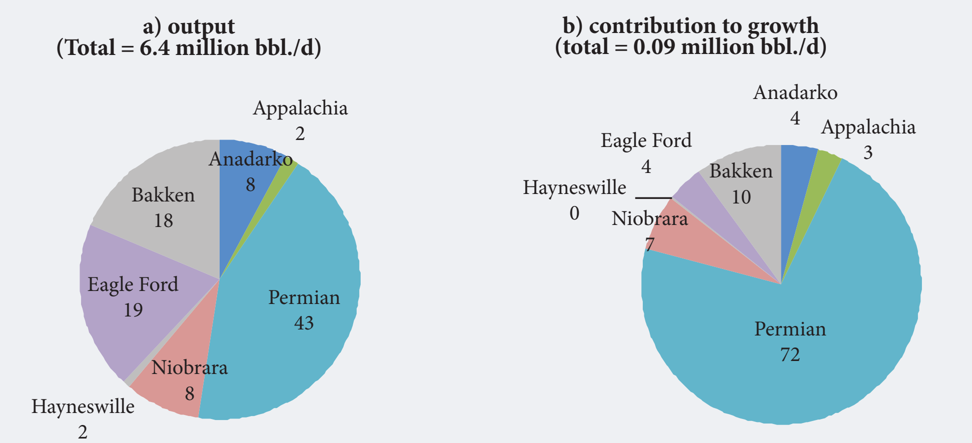
most promising areas were developed and only the most efficient (high grade) rigs remained in operation [*Hoza*, 2015]

The upward price trend of 2016 led to an increase in drilling activity beginning in June. However, the growing fleet of operating drilling rigs, increased drilling volumes, and the development of less rich areas resulted in a cyclical decrease in productivity, from 711 bbl./d in August 2016 to 586 bbl./d in August 2017. The stagnation of drilling, in its turn, "suspended" the cyclic factor, so productivity began to grow again due to the long-term technological trend associated with increased production efficiency. Accordingly, by the end of 2017 it reached 625 bbl./d.

Thus, in the short term, drilling rigs' productivity is significantly affected by production volume and the level of drilling (the cyclical factor), while the geological (gradual depletion of deposits) and technological factors act as long-term ones [*Hughes*, 2016]. Along with them, the average drilling productivity for all fields (Fig. 4) is also affected by the fourth factor, namely the spatial one. It amounts to the fact that drilling rig productivity and output vary between different fields, depending, among other things, on the rate of their reserves' change.

At the end of 2017, the largest Permian oil field in the US produced 2.8 million barrels per day, or 43% of total shale oil production in the country (Fig. 5). Furthermore, the production at this field is growing at

Figure 5. **Structure of production at US fields (as of December 2017)** (%)



Source: composed by the author based on [EIA, 2018].

the most rapid rate, while Permian's contribution to the growth of shale oil production reached 72%. This is followed by the Eagle Ford and Bakken fields (20% and 18%, respectively), with a much more modest contribution to production growth (at 4% and 10%, respectively). This is due to the reduced number of operating drilling rigs, so production only grows due to increased per rig output.

The geological features of the fields and the degree of their depletion are quite different, leading to significant variations in drilling rig productivity levels. For example, at the most valuable Permian field at the end of 2017, productivity was close to the average value (614 bbl./d), while the maximum of 1,383 bbl./d was recorded at Bakken and almost 1,185 bbl./d at Eagle Ford. However, the contribution of such high indicators is offset by the low drilling activity at the last two fields (Fig. 5b), so the average productivity for all fields is close to that of the Permian field (see Fig. 4).

The fifth factor affecting drilling rigs' efficiency is the share of wells drilled at the completion stage: the installation of casing, cementing, perforating, hydraulic fracturing, and so on, i.e., the operations that allow one to begin production. Part of the drilled wells go straight into the so-called backlog of drilled but uncompleted (DUC) wells. Well completion is often delayed due to the lack of available equipment and consumables, insufficient economic efficiency of production, or for speculative reasons [Rystad Energy, 2016]. The latter include rising oil prices or accelerated commissioning of wells if there is a downward price trend.

The number of DUC wells by the end of 2017 exceeded 7,000 [EIA, 2018], raising legitimate concerns about a significant increase in production when these wells are commissioned (completed) during an upward trend in oil prices [*Ivanov*, 2017b]. However, such expectations are subject to high uncertainty. For example, at the moment it is impossible to estimate the share of "dry" DUC wells, i.e., those unsuitable for commercial production, or their production costs, the rate of fleet deployment for hydraulic fracturing, the prospects for overcoming the shortage of proppant, and various other logistical constraints [IHS, 2015].

The dynamics of reserve wells' numbers display a growing trend when drilling and output grow amid rising oil prices. The reverse was observed only from February to November 2016, when, due to the insufficient volume of drilling, the queues to rent hydraulic fracturing equipment got shorter: in 10 months' time the number of reserve wells decreased by 925, i.e., on average at the rate of 9.25 wells per month. Given the average per well output of 400 bbl./d, the added capacity provided an increase of 0.0037 million barrels per day, or just 1.5% of the new flow rates for the period under consideration.

As we see, out of the five drilling rig efficiency factors, only the technological (the development of production technologies) and geological ones (the depletion of hydrocarbon fields) are worthy of attention in the long term. The spatial factor and production from reserve wells along with output variations seem to have a significantly smaller impact. In the next section, a hypothesis is presented regarding the shape of the curve describing drilling rig productivity following the application of technological innovations and geological changes.

Growth of Drilling Rig Productivity throughout the Field's Life Cycle

The classic approach to studying the proliferation of innovations is based upon the technology life cycle concept [*Mansfield*, 1968]. In the course of numerous studies, it was found that the process of innovative products' penetration (diffusion) is best described by a logistic function whose graph can be presented as an S-shaped non-linear curve that reaches a certain saturation level [*Little*, 1981; *Rogers*, 2002]. Productivity growth at the early stages of technology implementation is slow, since the lack of experience requires a considerable amount of time to master it. The accumulation of experience by researchers, engineers, managers, and businessmen triggers a positive feedback loop that accelerates the diffusion of innovations and productivity growth.

Technology developers make significant efforts to maximize their returns but after a while the diminishing marginal utility law triggers negative feedback. When the technological limits of growth are reached, the cost of each unit of change increases exponentially and the S-shaped curve smooths over. Such dynamics are typical for most industries including the production of automobiles, ships, internal and external combustion engines, semiconductors, vacuum tubes, disk drives, etc. [*Foster*, 1986].

However, there are many limitations to using S-curves as prognostic tools [*Schilling, Esmundo*, 2009]. Firstly, the actual limits of a technology's efficiency are rarely known in advance and experts from different companies may have different opinions about this issue. Secondly, unexpected changes on the market, complementary (replacement) technologies, or individual components can both speed up and slow down a technology's life cycle. Thirdly, S-curves do not describe the proliferation of innovations in all industries equally well. For example, for fossil fuels (coal, gas, oil), energy generation technologies have the form of not S-shaped, but rather bell-shaped curves (Fig. 6).

The bell-shaped curve describing the productivity of technologies for the extraction and use of fossil fuels can be explained as follows. After reaching its peak, productivity begins to decline due to two factors. The first is a significant slowdown or stabilization of the innovation's effect. The second is the exhaustion of the learning curve combined with the depletion of deposits and exhaustion of attractive sites ("sweet spots"), which forces companies to drill deeper and deeper and develop increasingly less rich deposits with lower extraction rates [*Montgomery, O'Sullivan*, 2017].

Industry experts also point out that a decline in drilling productivity is inevitable.

How long productivity will be growing is, of course, highly uncertain. However, the cyclical component will sooner or later lead to a growing trend changing to a downward one. The growth of productivity based on choosing the "sweetest spots" for development will soon come to an end [IHS, 2016].

In addition to the depletion of promising areas, a pressing problem with shale deposits is the reduced distance between wells.

A site can be drilled only once. In addition, productivity growth is limited by the distance between adjacent wells. An excessively dense grid of wells leads to reduced productivity. Empirical evidence suggests that adjacent wells may adversely affect one another. Though oil can be extracted more efficiently when wells are located close to each other, the per well recovery rate will drop and the overall output in the area will not increase [*Hughes*, 2016].

Thus, a hypothesis was suggested, and illustrated, that drilling rigs' productivity within the life cycle of a field can be described by a bell-shaped curve. Next, a mathematical formula will be derived for an asymmetric bell-shaped curve suitable for describing shale oil production and the growth of drilling rig productivity.

The Asymmetrical Bell-Shaped Function

The mathematical description of oil production technologies' efficiency can be found in literature that analyzes and forecasts hydrocarbon supply. Table 2 presents a classification of the various approaches to modeling this supply and references to sources with typical examples. A more complete review of the most common approaches can be found in [*Brandt*, 2010].

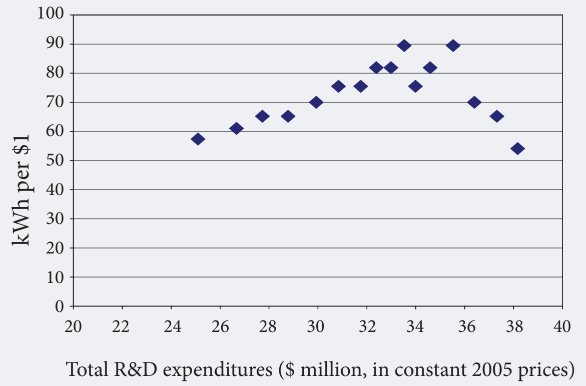
For the purposes of this paper we are primarily interested in the fourth approach, namely predicting production by fitting a bell-shaped curve. In our previous study [*Malanichev*, 2017a] we considered a set of assumptions for describing a theoretical oil production and drilling rigs productivity model using a symmetric bell-shaped curve proposed in 1838 for modeling population size [*Verhulst*, 1838] and then for predicting oil production volume in the United States [*Hubbert*, 1956].

Table 2. **Main approaches to forecasting oil production growth**

No.	Approach	Description	Sources
1	Fitting natural production decline curve	Short-term production forecast for individual wells. Geological and technological factors are taken into account.	[*Arps,* 1944; *Clark,* 2011; *Malanichev*, 2017c]
2	Superposition of natural production decline curves	Geological, technological, and economic factors are taken into account.	[*Sorrel et al.,* 2009; *Malanichev*, 2017b]
3	"Bottom up"	Based on plans for the development of new sites or fields and their empirical production profiles.	[*Sorrel et al.,* 2009]
4	Fitting bell-shaped curve	Long-term production forecast for the field. Geological and technical factors are taken into account.	[*Hubbert,* 1956; *Semenychev et. al.,* 2014; *Malanichev*, 2017a; *Kozlov,* 2018]
5	Solving a differential equation with a lagging argument	Analysis of conditions leading to economic fluctuations. Forecast based on analytical solution of a differential equation. Geological and economic factors are taken into account.	[*Malanichev*, 2018]
6	Econometric	Forecast based on economic factors.	[*Kaufmann, Cleveland,* 2001; *Afanasiev*, 2016; *Ermolina,* 2017]
7	Optimal planning	Solving the problem of optimal production planning, taking into account the time value of money.	[*Hotelling,* 1931; *Okullo et al.,* 2014]
8	Combined	Combines fitting of bell-shaped curve with economic factors such as oil prices.	[*Benes et al.,* 2012; *Zolina,* 2014; *Ermolina,* 2017]
9	System imitation	Takes into account numerous interconnected factors and models the process of oil producers' making investment decisions.	[*Davidsen,* 1990; *Makarov et al.,* 2011]

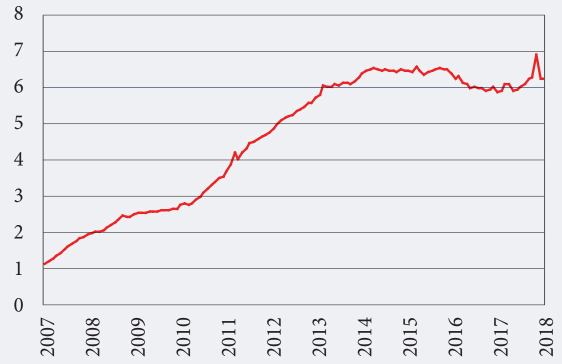
Source: composed by the author.

Figure 6. **Technological curves for the extraction and use of fossil fuels: technology performance (kWh per $1) vs R&D costs, 1990–2005**



Source: [*Schilling, Esmundo*, 2009].

Figure 7. **Production decline rate *b* (%)**



Source: composed by the author based on [EIA, 2018].

However, empirical evidence indicates that the production curve is asymmetrical. Rapidly increasing at the beginning of the development of a field, it reaches a peak and then slowly decreases. This asymmetrical bell-shaped profile with a flatter right side is typical of both conventional [*Bierman, Biryukov*, 2017] and unconventional [*Coyne*, 2017] hydrocarbon deposits.

In order to obtain an asymmetric bell-shaped curve, we will find an analytical solution of the differential production equation, making a number of simplifying assumptions [*Malanichev*, 2017a]. In the shale oil production case, the changes include the development of new wells drilled in the current month and reduced production from existing wells (drilled before the month in question). This balance can be described using an ordinary differential equation of the first order:

$$\frac{dq}{dt} = e \cdot N - b \cdot q, \qquad (1)$$

where:

Q is oil production volume (million bbl./d);

$e \cdot N$ is oil production from new wells (million bbl./d). The well is considered new for one month after it was completed and commissioned;

e is drilling rig productivity (bbl./d). Calculated as the number of barrels of oil extracted during the month from the wells drilled by one rig during the same period;

N is the number of active rigs that drilled new wells during the same month;

$b \cdot q$ is the rate of natural production decline in line with the exponential decline law. [*Malanichev*, 2017c] also considers other laws that affect the dynamics of production decline (the harmonic and hyperbolic ones).;

b is the empirical production decline rate.

A distinctive feature of shale oil is the high rate of production decline from the well, often by 60%-70% during the first year of operation. This is reflected in higher natural production decline rates compared with conventional oil, where this value varies between 2%-14% depending on the field, with the average of 6.2% [*Fustier et al.*, 2016].

Another specific feature of shale oil is the insufficient accuracy of the exponential natural production decline law when applied to it, compared with the harmonic or hyperbolic laws [*Clark*, 2011; *Malanichev*, 2017c]. Nevertheless, the use of these non-linear laws in expression (1) complicates the integration of the equation and requires further research.

To find an analytical solution for equation (1) in the form of an asymmetric bell-shaped function, two simplifying assumptions were made regarding its coefficients. First, in line with [*Saussay*, 2018; *Kozlov*, 2018], we take production decline rate *b* as a variable, which is consistent with the observational data (Fig. 7). We shall use the following specification:

$$b = k \cdot (\gamma + 1) \cdot \left(\frac{Q}{EUR}\right)^{\gamma}, \tag{2}$$

where:

k and γ are positive empirical coefficients;

Q is the accumulated production volume, $q = dQ/dt$;

EUR (estimated ultimate recovery) is the initial amount of recoverable resources (the sum of already extracted oil and technically recoverable resources).

The Q/EUR ratio serves as the resource depletion rate whose value ranges between 0-1. As the field's reserves deplete, the natural production decline rate gradually increases (Fig. 7).

Next, we assume the new flow rates $e{\cdot}N$ are proportional to production volume q:

$$e{\cdot}N = k{\cdot}q. \tag{3}$$

Regression analysis shows a significant correlation by the t-statistic criterion between new flow rates and production (Fig. 8). The regression constant is close to zero and statistically indistinguishable from it.

Substituting expressions (2) and (3) in equation (1) and integrating it over time results in an ordinary differential equation describing cumulative production dynamics:

$$\frac{dQ}{dt} = k \cdot Q \cdot \left(1 - \left(\frac{Q}{EUR}\right)^{\gamma}\right). \tag{4}$$

In form, this is the Bernoulli equation whose analytical solution is an S-shaped Richards function [*Richards*, 1959]:

$$Q(t) = \frac{EUR}{\left(c{\cdot}e^{-k\cdot\gamma t} + 1\right)^{\frac{1}{\gamma}}}. \tag{5}$$

The differentiation of this expression over time produces an asymmetrical bell-shaped function:

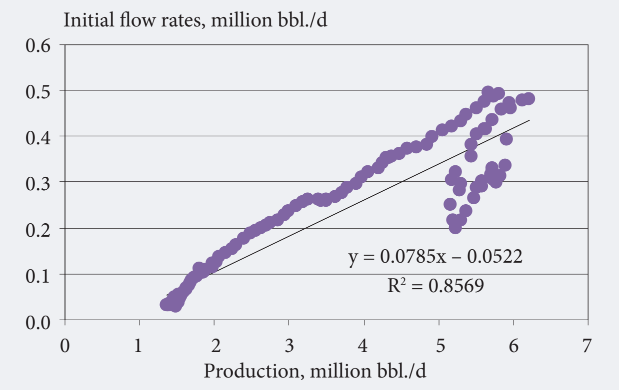
$$q(t) = Q'(t) = \frac{c{\cdot}k{\cdot}EUR}{e^{-k\cdot\gamma t}{\cdot}\left(c{\cdot}e^{-k\cdot\gamma t} + 1\right)^{\frac{1}{\gamma}+1}}, \tag{6}$$

where the constants c, k, EUR and γ can be found by fitting the production curve to the actual data, for example, by the least-squares method. The inflection point of the logistic curve $Qinf$ which corresponds to the peak of production is calculated using the following formula:

$$Q_{inf} = \left(\frac{1}{1+\gamma}\right)^{\frac{1}{\gamma}} \cdot EUR. \tag{7}$$

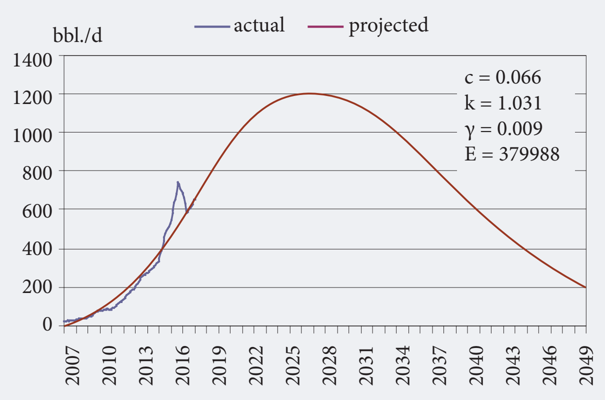
According to assumption (3), the bell-shaped function (6) is used to approximate drilling rig productivity $e(t)$. The curve constants c, k, γ, and E (cumulative performance, an analogue of EUR) were found using

Figure 8. **Correlation between new flow rates and production in 2007-2017**



Source: composed by the author based on [EIA, 2018].

Figure 9. **Average drilling rigs' productivity**



Source: composed by the author based on [EIA, 2018].

Figure 10. **Main models based on the differential oil production balance equation**

Economic fluctuations of oil production [*Malanichev*, 2018]

$$\frac{dq}{dt} = e \cdot N\,(t - \tau) - \varphi\,(q)$$

t – time
τ – time lag between the investment solution and its implementation

Differential oil production balance equation

$$\frac{dq}{dt} = e \cdot N - \varphi\,(q)$$

Natural production decline rate laws [*Malanichev*, 2017c]:

$\varphi\,(q) = b \cdot q$ — exponential
$\varphi\,(q) = b \cdot q^2$ — parabolic
$\varphi\,(q) = b \cdot q^a$ — hyperbolic

Symmetrical bell-shaped curve [*Verhulst*, 1838; *Hubbert*, 1956; *Malanichev*, 2017a]

$$\frac{dQ}{dt} = b \cdot Q \cdot \left(1 - \frac{Q}{EUR}\right)$$

$eN = qQ2b/EUR$

Richards asymmetrical bell-shaped curve [*Richards*, 1959]

$$\frac{dQ}{dt} = k \cdot Q \cdot \left(1 - \left(\frac{Q}{EUR}\right)^{\gamma}\right)$$

$$b = k\,(\gamma + 1) \cdot \left(\frac{Q}{EUR}\right)^{\gamma} \qquad eN = kq$$

Source: composed by the author.

the least-squares method over the course of approximating the empirical data on drilling rig productivity averaged for the seven shale formations in the US for the period between 2007-2017 [EIA, 2018]. The optimization procedure was carried out using Excel Solver. The calculations show that productivity will peak by 2026 at e = 1,200 bbl./d (Fig. 9)

The calculations show that the development of oil production technologies will allow one to double drilling rig productivity compared with the current level. The relevant indicators of the Bakken, Eagle Ford (Fig. 4), and Permian formations confirm that it is physically possible. The latter field also has good growth prospects [*Malanichev*, 2017c].

If the current level (N = 800 units) is taken as the number of active rigs, then according to equation (3) their productivity will peak at the maximum oil production at 11.3 million bbl./d and technically recoverable reserves at 96 billion barrels. Similar values are presented in the literature: for example, the amount of technically recoverable reserves is estimated at 92 billion barrels [EIA, 2015].

The above estimate of the potential shale oil production matches the results obtained using a bell-shaped curve [*Malanichev*, 2017a], which confirms the validity of the calculations. Under the conservative scenario for the growth of global demand (1 million bbl./d), the potential for increasing production at shale deposits in the United States will be exhausted in five years' time. This may mean that by 2023 they would no longer be able to meet global demand for oil, so other resources, even those with higher production costs, would have to be developed.

Discussion and Conclusion

At the end of 2017 oil production at shale fields in the United States exceeded 6.3 million bbl./d (6% of the global oil sales), turning it into a key factor of the emergence of a new market balance. The "shale revolution" became possible due to sufficiently large explored hydrocarbon reserves in tight reservoirs, improved production technologies, and a number of institutional factors. The latter include developed competitive oilfield services markets, the largest drilling rig fleet, an established institution of private land and subsoil ownership, investment and tax incentives for developing low-yield wells, advanced transport infrastructure, environmental requirements favorable for hydraulic fracturing, efficient financial markets including stock exchange insurance tools, and so on.

The main shale oil production technologies (horizontal drilling and hydraulic fracturing) were developed as early as in the first half of the 20th century. Their continuous improvement, the introduction of multicore drilling and multi-stage fracturing, establishing the optimal length of horizontal well sections, and the amount of proppant led to significantly reduced shale oil production costs and made it commercially viable.

A key factor for reducing shale oil production costs was increased well productivity. For example, at the largest formation in the United States, the Permian field, the average new well production rate steadily grew, from 150 bbl./d in 2014 to 450 bbl./d in 2017. The entire production cycle is more comprehensively measured by drilling rig productivity, which by the end of 2017 had reached an average of 625 bbl./d.

Oil rig productivity in the US is affected by five main factors: the development of production technologies, the depletion of deposits, uneven productivity at different fields, the commissioning of reserve wells, and production volume. In the long run, the development of technologies and the amount of technically recoverable reserves turn out to be the most important ones.

In conventional industries, the proliferation of technological innovations that result in productivity growth is typically described by S-shaped curves. However, in the mining industries where technology development has natural limits (i.e., the depletion of natural resources) the situation is different. Technological development initially leads to increased production, but when the reserves in the area being developed are depleted, it decreases. No matter how powerful drilling rigs' drives and injection pumps for hydraulic fracturing are, the laws of natural production decline and depletion of reserves will ultimately lead to reduced oil production and drilling rig productivity.

This paper presents an attempt to develop an analytical tool for the long-term forecasting of shale oil production and the estimation of drilling rig productivity, which would allow one to assess the limits for these indicators' growth. In particular, an asymmetric bell-shaped function was proposed as an analytical solution of the differential production equation (Fig. 10), which describes long-term oil production and drilling rig productivity growth.

An analysis of empirical data based on using the suggested asymmetrical bell-shaped curve shows that the average drilling rig productivity at US shale oil fields may peak by 2026 at 1,200 bbl./d or two times the current level. Production volume will reach 11.3 million bbl./d and technically recoverable reserves will be 96 billion barrels. If that is how things will develop, as early as by 2023, US shale oil producers may be unable to meet the growing global demand for oil, so they would have to start developing other resources with even higher production costs.

The asymmetrical bell-shaped curve, theoretically substantiated and tested on empirical data, can be recommended as a practical and effective tool for conducting Foresight studies of the global oil and gas sector taking into account prospective technological developments.

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