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Curve-fitting variants to model Brazil's crude oil offshore post-salt production

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ABSTRACT

This study estimates oil production curves applying single and multi-cycle Hubbert models and Hubbert variants for the case of Brazil. The application of a top-down modeling approach is necessary, as the size of oil fields discoveries is usually confidential data and therefore not disclosed in Brazil. Despite fragilities of curve fitting methodologies, this approach therefore continues being widely used, due to its simplicity and relatively low data requirement. The classic Hubbert methodology was improved in this study by considering the asymmetry of production. Additionally, a hybrid model considering techno-economic aspects explains the deviation of the crude oil production rate from the prediction of the Hubbert curve by means of regression analysis. This analysis indicates that the deviation of the crude oil production rate from the Hubbert curve follows, with a four-to five-year lag, changes in oil price. The findings show that the URR of Brazil's post-salt offshore basins hover between 15 and 21 billion barrels of oil. An annual average growth rate of 8% in the pre-salt oil fields can compensate for the decline in post-salt offshore oil production for the period 2016-2025. Error and URR estimates stabilize after peak production for single and multi-cycle Hubbert curves, though the single cycle model proved to be more unstable before peak production than the multi-cycle models.

1. Introduction

Forecasting oil production is crucial for long-term energy planning, and for policy making in various economic sectors, in particular the petroleum one, of a country or region. Particularly investments in upstream, refining infrastructure, and energy diversification require long-term forecasts of oil production. But also, studies that assess long-term reductions in greenhouse gases rely on estimates of possible future oil production.

Yearly, Petrobras — the Brazilian National Oil Company (NOC) — publishes the Business and Management Plan (Petrobras, 2017), which shows the expected oil production profile for the next five years. Annually, the Brazilian regulatory National Agency for Petroleum, Natural Gas and Biofuels (ANP) publishes reserves and contingent resources data for oil and gas (ANP, 2017a). Regularly, the Brazilian federal Energy Planning Company (EPE) publishes the Ten-Year Energy Expansion Plan (PDE). However, government studies addressing long-term forecasts of oil production are scarce in Brazil and are the focus of this paper.

The principal methodologies to model oil production supply curves are summarized by Brandt (2010) and Sorrell et al. (2010). Curve-fitting methods are simple to implement and therefore broadly used. However, they require a suitable theoretical basis and neglect important variables. In contrast, simulation models do not predefine the form of the production curve, but generate it by simulating the interaction of economic and physical factors. This approach requires a lot of data, which is often not publicly available. Bottom-up models are promising for short to medium term projections, but restricted by their dependence on proprietary data, lack of transparency, uncertainty over major variables, and the need to consider numerous premises. Economic models focus on investments, optimal extraction paths, and the effects of oil prices rather than on physical or technological aspects. This approach often is unsatisfactory because it does not account for geological conditions that become important in the long-term. In this study, we rely on curve-fitting methods, as they can be run with publicly available data.

Hubbert's theory of oil depletion (Hubbert, 1956) is the pioneer curve-fitting model. Hubbert's well-known projection of future US oil

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Nomenclature

Q_t	Accumulated oil production up to time t estimated by Hubbert
BBO	Billion barrels of oil
BP_t	Brent Price of oil at year t adjusted to 2015-dollars
CV	Coefficient of variation factor
α, ε, β	Coefficients of regression
a	Constant of the Hubbert curve, which accounts for the slope of the curve
a_i	Constant of the Hubbert curve, which accounts for the slope of the curve in cycle i
a_{inc}	Constant of the variant Hubbert curve, which accounts for the left side slope of the curve
k	Constant of the variant Hubbert curve, which accounts for the rate of change from the left side to right side standard deviation
a_{dec}	Constant of the variant Hubbert curve, which accounts for the right-side slope of the curve
Np	Cumulative oil produced
PC'_t	Dummy variable to check the curve symmetry
t_m	Estimated time of peak oil production
t_{mi}	Estimated time when production reaches the peak of a cycle i
P_t	Historical oil production data at time t
Mbpd	Million barrels of oil per day
e	Neperian number
Q'_t	Oil production at time t estimated by Hubbert
Q'^{peak}_i	Oil production peak production rate estimated by Hubbert in cycle i
a(t)	Parameter for the slope of the variant Hubbert curve
$P^{estimated}_{T,t}$	Production estimated at year t using historical data from 1954 to T
R_t	Relative difference between $Q'^{observed}_t$ and Q'_t
RMSE	Root Mean Squared Error
kbpd	Thousands of barrels of oil per day
N	Total number of cycles
Q_∞ , URR	Ultimately recoverable resources
$Q_{\infty i}$	Ultimately recoverable resources of a cycle i
t	Variable of the time (year)
ΔP_t	Variable to evaluate the inertia on production

production, proposed in the late 1950s, used a bell-shaped curve and showed to be accurate as US oil production in the lower 48 states peaked in 1970 (Laherrère, 1997), as predicted before by Hubbert.

Hubbert's theory assumes that the first discovery well is drilled and oil production begins. Then, as additional wells are drilled and the rate of production increases, further exploration is stimulated and new fields are discovered. However, as more and more fields are discovered and the number of fields is fixed, the last fields are the most expensive and the smallest ones. Finally, the undiscovered fields become too scarce to justify exploratory drilling (Hubbert, 1982).

Several authors have used Hubbert models (or their variants) to forecast world oil production (Al-Jarri and Startzman, 1997; Bartlett, 2000; Brecha, 2012; Campbell and Laherrère, 1998; Gallager, 2011; Hubbert, 1962; Maggio and Cacciola, 2009; Nashawi et al., 2010; Rehrl and Friedrich, 2006; Reynolds, 2014; Wang et al., 2011) and some of these studies are based on Hubbert to assess the production in single countries or regions in parallel with worldwide projections (see Table A1 in Appendix).

As the Hubbert theory of oil depletion states that oil production in large regions follows a bell-shaped curve over time, Brandt (2007) tested the quality of fit of Gaussian, linear and exponential models, being symmetric or asymmetric, to oil production data of 139 producing areas. The results showed that the asymmetrical exponential models show better fits than the symmetric models in most cases, with slower rates of decline than rates of increase.

The multi-Hubbert cycle analysis of oil production in the US developed by Patzek (2008) emphasizes the existence of new populations of reservoirs, in which the main cycle provides the original Hubbert estimate of ultimately recoverable resources (URR), while the smaller cycles describe the new populations of reservoirs, for example in Alaska, the Gulf of Mexico, the Austin Chalk and the California Diatomites, and new recovery processes, as waterflood, enhanced oil recovery (EOR), and horizontal wells.

Multi-cycle approaches can explain the production patterns in many countries, which have more than one peak in their production profiles, as shown by Nashawi et al. (2010). Nevertheless, these authors recognize that oil production is, additionally to geological conditions, also affected by socio-economic, and political factors. Hubbert's theory embodies the physical aspects of oil formation, but economic and political events may cause annual rates of production to deviate from Hubbert's curve in a systematic way (Kaufmann, 1991). Once little effort is spent to explore and produce oil resources unless a cost-effective recoverability can be expected, all discovery and production cycles depend on the expected profitable recoverability of the oil resources (Rehrl and Friedrich, 2006). Understanding these deviations is a second focus of this paper.

A single Hubbert approach was proposed by Szklo et al. (2007) for Brazil. Furthermore, Saraiva et al, (2014) estimated Brazil's oil production curves with different URR scenarios by adding productive cycles following a Hubbert variant proposed by Maggio and Cacciola (2009).

To improve the previous analyses and test a variant of the Hubbert model for the case of Brazil –that could also be adopted in other countries – this study developed:

(i) Primarily, single and multi-cycle Hubbert models to project Brazilian post-salt oil production, including asymmetrical production cycles — based on the adapted methodology proposed by Brandt (2007) — to estimate endogenously the URR in post-salt[1] offshore production;
(ii) Secondly, a hybrid model — based on the methodology developed by Kaufmann (1991) — that assesses the influence of techno-economic parameters on production cycles. We aim at understanding how the residuals of the Hubbert model are influenced by these parameters.

This study focuses on the Brazilian post-salt oil production only: despite the increasing and representative amounts of reserves and oil production from the pre-salt layer, curve-fitting is not applicable for this layer, since pre-salt oil has only recently been started to produce and fitting Hubbert models at such an early stage generate unstable results (Sorrell and Speirs, 2009).

The remainder of this paper contains a review of the historical oil production development in Brazil (Section 2); a description of the Hubbert models (including the hybrid Kaufmann-Hubbert study) and the stability test (Section 3); a presentation of results (Section 4); a discussion of our work (Section 5), and conclusions (Section 6).

[1] Post-salt layer is above the salt layer. It consists primarily of sandstone, but it is also home to carbonates, and spans from shallow to deep water depths.