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Depletion rate analysis of fields and regions: A methodological foundation

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HIGHLIGHTS

- Establishment of a theoretical foundation for depletion rate analysis.
- Discussion on the connection to physical forces acting within the reservoir.
- Empirical and statistical analysis of individual oilfields and regions.
- The theory was found to be well supported by the data.
- Discussions on the implications for peak oil.

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ABSTRACT

This paper presents a comprehensive mathematical framework for depletion rate analysis and ties it to the physics of depletion. Theory was compared with empirical data from 1036 fields and a number of regions. Strong agreement between theory and practice was found, indicating that the framework is plausible. Both single fields and entire regions exhibit similar depletion rate patterns, showing the generality of the approach. The maximum depletion rates for fields were found to be well described by a Weibull distribution.

Depletion rates were also found to strongly correlate with decline rates. In particular, the depletion rate at peak was shown to be useful for predicting the future decline rate. Studies of regions indicate that a depletion rate of remaining recoverable resources in the range of 2–3% is consistent with historical experience. This agrees well with earlier "*peak oil*" forecasts and indicates that they rest on a solid scientific ground.

1. Introduction

Non-renewable fossil fuels supply more than 81% of the global primary energy supply. Oil remains the single largest fuel, satisfying 33% of the world's energy needs in 2009 [1]. Given the high reliance on oil, particularly within transportation and other important sectors, it is evident that policymakers and the public need reliable forecasts of future oil supply.

The most authoritative oil forecasts are those published annually by the International Energy Agency (IEA) and the Energy Information Administration (EIA) of the US Department of Energy. Policymakers and media often assume that the IEA's Reference Scenario represents the best available knowledge of the future oil production. However, recent studies uncovered a number of errors and unrealistic parameters in their models [2,3]. The problem primarily lies in the depletion rate, i.e. the rate at which the oil can be extracted. The IEA assumed that available oil could by extracted faster than ever seen in history; using realistic values provided significantly less optimistic production outlooks [2]. Similarly, the EIA relied on a defective analogy for depletion rates that postponed the global production peak in their models. In this case, using historically realistic depletion rates also indicated that oil production could start to decline well before 2030 [3].

Depletion rates have been studied for a long time in various forms and the oldest known studies go back to the late 1970s [4]. Many papers, studies and forecasts have been done using depletion rate analysis since then. However, the concept is still hard to grasp for many people. Analysts have used different definitions of depletion rates, inconsistent theory or perplexing terminology. Therefore, to determine how well depletion rate theory fits with reality, this study summarizes the topic, presents the theory of depletion rate analysis with more clarity and tests it against empirical data.

1.1. Data gathering and considerations

There is certainly an issue with obtaining good and openly available data sets. This study uses the latest updated version of

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the Uppsala giant oilfield database, originally described in more detail by Robelius [5] and later by Höök et al. [6,7]. It contains over 300 giant oilfields worldwide accounting for over 1100 Gb of oil in 2P-terms (proven + probable reserves as of 2005 or later). Complementary data for hundreds of oilfields in Europe, the USA, China and other parts of the world has been combined with the giant oilfield data. In total, the analysis covers 1036 fields (Fig. 1). The Middle East/OPEC is well represented with nearly 50% of the giant fields, but data for smaller fields were rarely available and most small fields in this study are from Western or Asian countries. Regardless, the data set is believed to give a good global picture because it contains fields of various sizes and types from different production strategies and socioeconomic conditions.

There are many possible reserve measures that can be used when analysing fields. This study primarily uses available 2P data to approximate the URR of each field. Bentley et al. [8] highlights how 2P data is close to true 50% probability estimates, and just as likely to see a decrease as an increase over the lifetime of the field. In a few cases, no 2P estimates were available and more traditional curve fits were used to estimate the URR. In the aggregated dataset some fields are surely overestimated, while others are just as likely to be underestimated. However, these effects tend to cancel each other out when aggregated.

A number of regions have also been included in the dataset. This is to see whether the regional behaviour echoes the mechanisms displayed at the field level. The URR estimates of the regions have been derived by various techniques such as field-size distributions [9] or curve fitting [10]. In some cases, URR estimates were derived from Campbell and Heapes [11] and BGR [12]. Here, generally high URR estimates have been chosen to account for potential reserve growth in the future and new discoveries.

Naturally, there are intrinsic shortcomings in the studied data. Different agencies and companies may use diverse terminology and definitions may simply have changed over time. Artifacts, such as terrorist strikes or major accidents, have severely influenced some fields, especially in Nigeria, but also events like Piper Alpha in the North Sea. Fields with severely disturbed behaviour were omitted from analysis.

Some fields exhibit a clear peak, commonly quite early in the field's life, followed a decline phase. Other fields can have long, possibly ranging for decades, plateau phases followed by the onset of decline. This study focuses on fields that are mature and have undergone most development stages. Consequently, only fields that have "*peaked*" and clearly reached the onset of decline have been included in the data set. For fields with a plateau, "*peaking*" was defined as the point where production lastingly leaves a 4% fluctuation band around the plateau level, just as earlier used by Höök et al. [7].

2. Defining depletion rates and depletion level

In principle, depletion is a fairly simple concept. Production of a non-renewable resource will always lead to depletion as there only is a limited amount available for recovery and production by definition will exhaust the available resource. Virtually any type of resource may show depletion behaviour, including forests or animals — despite their "*renewable nature*". If the annual extraction is greater than the corresponding replenishment, the resource will be subject to depletion [13]. To fully understand depletion rate analysis, a solid mathematical framework is needed. A particularly important parameter is the remaining resource. It is defined as follows:

$$R_r = R_0 - Q_t + \sum r \tag{1}$$

where R_r is the remaining resource at time t, R_0 is base year resource estimate, Q_t is cumulative production at time t, r is subsequent annual revisions of the base year estimate at time t. The resource base may be fixed (where $r = 0$) or dynamic (i.e. changing over time). Introducing a time dependent estimate of the ultimately recoverable resources (URR) or estimated ultimate recovery (EUR) allows a simplification of Eq. (1):

$$R_r = URR_t - Q_t \tag{2}$$

From this, the URR may be expressed as the remaining resource plus cumulative production at an arbitrary point in time. The next step is to define some kind of measure of how much of the resource that has been depleted. This may be called a *depletion level* and is here denoted $D_{\mathrm{URR},t}$:

$$D_{URR,t} = \frac{Q_t}{Q_t + R_r} = \frac{Q_t}{URR_t} \tag{3}$$

The depletion level parameter can vary from 0% to 100%, which gives a sound assessment of how much of the URR remains for production at a given time. For example, one may think of a cup that is half full (i.e. half empty) and note that it would have a depletion level of 50%.

When it comes to defining a depletion rate one is with two choices. Should one base it on ultimate reserves or on the remaining recoverable resources? Secondly, one may also ask whether this makes a difference in practice. If q_t denotes annual production one can now define two different depletion rates. First one obtains a *depletion rate of URR*, denoted $d_{\mathrm{URR},t}$ (Eq. (4)). This parameter is useful if one has access to URR-estimates and reflects how much of the URR that is extracted annually:

$$d_{URR,t} = \frac{q_t}{Q_t + R_r} = \frac{q_t}{URR_t} \tag{4}$$

In contrast, the other choice gives a measure of how fast the remaining recoverable resources are becoming exhausted. This may be used to define a *depletion rate of remaining recoverable resources* at time t, here denoted $d_{RRR,t}$:

$$d_{RRR,t} = \frac{q_t}{R_r} = \frac{q_t}{URR_t - Q_t} \tag{5}$$

The $d_{RRR,t}$-parameter has also been called *depletion rate of remaining reserves* and various similar things. In addition, it can also be expressed as a *production-to-reserve ratio* (P/R), since it is the reciprocal of the frequently used *reserves-to-production ratio* (R/P). Caution should be exercised not to mix values from the two different definitions. Jakobsson et al. [3] explored this further.

$$d_{RRR,t} = \frac{\text{production}}{\text{remaining recoverable resources}} = \frac{q_t}{R_r} = \frac{1}{\frac{R_r}{q_t}} \tag{6}$$

2.1. Depletion rates for regions

Any oil region, whether a single country or group of countries, consists of an arbitrary number of fields. First, we let $URR_{reg,t}$ denote the aggregated URR in a region with n fields. We also let Q_{reg} refer to the aggregated cumulative production and q_{reg} refer to the aggregated annual production in the same region at a given time. If $Q_{n,t}$ is the cumulative production of field n at time t, the depletion level of the URR of a region may now be expressed as follows:

$$D_{URR,t} = \frac{Q_{reg,t}}{URR_{reg}} = \sum_{1}^{n} \frac{Q_{n,t}}{URR_{reg,t}} \tag{7}$$

This shows that the depletion level of a region is dependent only on the current depletion level of its subparts, i.e. a weighted average of its subcomponents. The depletion rate of the URR in a region is the next thing to delineate. We let $q_{n,t}$ denote annual production of field n giving: