Lecture Notes in Energy 34

R.W. Bentley

Introduction to Peak Oil

Springer

Lecture Notes in Energy

Volume 34

Series editor

Charles A.S. Hall
SUNY College of Environmental Science and Forestry
Syracuse, NY, USA

Lecture Notes in Energy (LNE) is a series that reports on new developments in the study of energy: from science and engineering to the analysis of energy policy. The series' scope includes but is not limited to, renewable and green energy, nuclear, fossil fuels and carbon capture, energy systems, energy storage and harvesting, batteries and fuel cells, power systems, energy efficiency, energy in buildings, energy policy, as well as energy-related topics in economics, management and transportation. Books published in LNE are original and timely and bridge between advanced textbooks and the forefront of research. Readers of LNE include postgraduate students and nonspecialist researchers wishing to gain an accessible introduction to a field of research as well as professionals and researchers with a need for an up-to-date reference book on a well-defined topic. The series publishes single- and multi-authored volumes as well as advanced textbooks. **Indexed in Scopus and EI Compendex** The Springer Energy board welcomes your book proposal. Please get in touch with the series via Anthony Doyle, Senior Editor, Springer (anthony.doyle@springer.com)

More information about this series at http://www.springer.com/series/8874

R.W. Bentley

Introduction to Peak Oil

Springer

R.W. Bentley
Department of Cybernetics
University of Reading
Reading
UK

ISSN 2195-1284 ISSN 2195-1292 (electronic)
Lecture Notes in Energy
ISBN 978-3-319-26370-0 ISBN 978-3-319-26372-4 (eBook)
DOI 10.1007/978-3-319-26372-4

Library of Congress Control Number: 2015956376

Printed on acid-free paper

This Springer imprint is published by SpringerNature
The registered company is Springer International Publishing AG Switzerland

Acknowledgments

This book could not have been written without the help and wise counsel from many people over the years, for which I am extraordinarily grateful. In particular I would like to thank:

In Europe: John Burton, Colin Campbell, Jean Laherrère, George Leckie, Ken Chew, Francis Harper, Richard Miller, Max Coleman, Bruce Sellwood, George Whitfield, Peter Dunn, Roger Booth, Chris Skrebowski, David Fleming, Rayner Mayer, Saad Mannan, Simon Wheeler, Lado Kurdgelashvili, Michael Smith, David Strahan, Richard Hardman, Jeremy Leggett, Peter Jackson, Steve Sorrell, Jamie Speirs, Richard O'Rourke, Hans DuMoulin, Michael Jefferson, John Busby, Chris Vernon, Godfrey Boyle, Pierre-René Bauquis, Jean Marie Bourdaire, Fatih Birol, Chris Besson, Peter Gerling, Klaus Illum, Jens Junghans, Kjell Aleklett, Mikael Höök, Kristofer Jakobsson, Bengt Söderbergh, Rui Rosa, Ugo Bardi, Susanne Peters, Sam Carmalt, Jörg Schindler, Werner Zittel, Rembrandt Koppelaar, Pedro Prieto and Luis De Sousa; in Australia and the Far East: Bruce Robinson, Matt Mushalik, Lianyong Feng, Q. Meng, Xu Tang and Jianliang Wang; and in the USA: Ron Swenson, L. Ivanhoe, Tom Alhbrandt, Gregory Ulmeshek, Ron Charpentier, Robert Hirsch, Mike Rodgers, David Greene, Ken Deffeyes, Charles Hall, Steve Andrews, David Lawrence and Hilary Smith.

In addition, I have much appreciated useful conversations with the following, though often disagreeing with the views expressed: Georges DuPont-Roc, Peter Davies, David Frowd, Hans Maters, Peter Odell, Alex Kemp, Paul Stevens, John Chesshire, John Mitchell, Robert Mabro, M. Adelman and Michael Lynch.

Particular thanks go to David Astor and Sarah Astor who, at David Fleming's suggestion, employed me at ODAC for a year to study peak oil and who kindly arranged for the purchase, at Colin Campbell's suggestion, of the invaluable IHS Energy PEPS '2P' dataset without which much of the research described here could not have been carried out.

The above is only a very partial list of those to whom debts are owed, and many more people have kindly provided invaluable data and advice over the years; my apologies to those I have omitted here.

Finally, heartfelt thanks are due to my wife, Yongmei Bentley, who has tolerantly borne far too many years of ‘oil study’.

Drafts of this book have been reviewed at various stages by Colin Campbell, Jean Laherrère, Richard Miller, Michael Smith, Steve Andrews, Sam Carmalt and Charles Hall, for which many thanks are due. The errors that remain are mine, and these are almost certainly many. Comments and corrections are therefore very welcome.

Please note that this is not intended to be a general book on peak oil. Though none of the topics involved is difficult, the book is for those who wish to understand the subject from a technical point of view. The text can be supplemented by any of a number of excellent books on the subject, including Kjell Aleklett’s (2012) *Peeking at Peak Oil* (which has a new edition currently in preparation), and Charles Hall & Carlos Ramírez-Pascualli’s (2013) *The First Half of the Age of Oil*.

September 2015 R.W. Bentley

Contents

Chapter 1
Introduction

1.1 The Purpose of this Book

For some years now the process of supplying the world with oil has been getting more difficult. Global production of *conventional oil* (the normal oil found in oil fields) is close to its *resource-limited maximum*, and to meet additional demand the world has had to turn increasingly to the production of non-conventional oils, such as tar sands oil and shale ('light tight') oil. This transition has led to a significant rise in the price of oil, and will probably at some point, possibly fairly soon, lead to an overall decline in global oil supply. The aim of this book is to explain the underlying causes for this fundamental change in oil supply, and also why the change is still not widely understood.

1.2 The Importance of Oil, and Hence the Difficulty of Transition

We start however by considering the importance of oil, and hence why a transition in its supply will not be easy.

Oil is a lifeblood of the modern economy, and it makes up the largest part of the world's traded energy, some one-third of the total. In particular oil fuels nearly all the extensive, cheap transport that is a major contributor to today's efficient global economic activity, whether in the production of food or goods, or provision of the services that we rely on. As most people appreciate, if oil is not available in the short term food does not get to the shops, nor workers to their jobs, and society is at risk. This was amply demonstrated during the European 'fuel protests' of 2000.

However the problems we face as global oil supply becomes increasingly difficult are somewhat different. This is because, first, oil can be substituted by other forms of energy in almost any activity. Aeroplanes, for example, can fly on biofuels

R.W. Bentley, *Introduction to Peak Oil*, Lecture Notes in Energy 34,
DOI 10.1007/978-3-319-26372-4_1

or liquid hydrogen; trucks be run on compressed natural gas; cars on gas or electricity; houses and offices be heated and cooled by electricity or by other fuels; and industrial chemicals produced from gas, coal or biomass, or directly from solar energy using ubiquitous feedstocks. Second, given sufficient warning, society can choose to change its activities and priorities so as to use less oil.

But several factors make the current transition to a world of expensive oil, and in time to a world of less oil, both difficult and painful.

The first is simply the very large quantity that we use. As mentioned, oil is currently the world's largest traded energy, and finding adequate substitutes to allow the world to replace this amount of energy over any medium timeframe looks technically very difficult, and also expensive in terms of the investment required. For example, the quantity of currently available biofuels falls far short of what is needed to replace oil; the global supply of *conventional* gas will see its own resource restrictions fairly soon; both coal and nuclear face significant constraints on increased production; and while the *potential resource* of solar energy is more than adequate, transitioning to this on a large scale has severe restrictions of cost and energy return when compared to the energy supplied by oil.

A second factor to consider in the coming energy transition is the impact of the price of oil on economic activity. For the half-century from 1920 to 1970 oil was very cheap, averaging about $15/barrel ('$/bbl') in today's money (its 'real-terms' price), and as a result the global use of oil expanded rapidly, and economic wealth in parallel. Later, for the nearly two decades between 1986 and 2003, the average real-terms price was about double, at $30/bbl, and the growth of oil use was slower, but still substantial. Only for the two periods from 1974 to 1985, and since 2004, has the oil price been significantly higher, reaching at times a real-terms price of $100/bbl or more. In both these periods the high price has resulted in considerable damage to the world's economy. Going forward the on-average high oil price that results from increasingly difficult supply is expected to continue to impact global economic activity; and hence also the world's ability to fund the increasing energy efficiency, and production of new energies, that will be required.

A third factor that makes transition away from oil likely to be difficult is the lower energy return of many of the alternatives. Energy return compares the energy generated by an energy source to that required to produce this energy. For quite a number of the alternatives to oil their energy returns are considerably less than that for oil.

An important final factor to consider is CO_2 emissions. While the oil we use today is no angel in this regard, some of the alternative fuels emit greater levels of CO_2 per unit of energy generated. As seems now well established, a significant percentage of all the world's oil, gas and coal must be left in the ground if the global limit of 2 °C warming is to be avoided.

This book does not look, however, at these broader issues of global all-energy supply; nor at what energy transition rates are possible; and nor at the likely corresponding levels of economic activity. These topics are complex, and require detailed modelling, and also generally better data than are currently available (particularly on energy return by energy source, and hence on corresponding net-energy limits to transition rate) to have a clear view of how the world's energy future can play out.

Instead this book looks at the simpler question of the future availability of oil, and in particular that of 'conventional oil'.

1.3 Conventional Oil Versus Non-conventional Oil

In understanding the rise in oil price since 2004, and also the limits to future oil supply, an important distinction to make is between the production of *conventional* oil and that of *non-conventional* oil.

Oil exists in many forms. It can be found at the land surface or on the seabed as oil seeps; in degraded form in tar pits and in extensive areas of tar sands; as oil's precursor, kerogen, still in the original rock in which it was laid down (and from which it needs retorting to yield 'oil shale' oil); and as light, flowable oil, either still captured in the original rock (as 'shale oil', that needs hydraulic fracturing, 'fracking', to release it); or after having migrated to an open-pored reservoir of rock (an oil field), from which it can be extracted by drilling.

It is this last class of oil, *the relatively light, flowable oil in fields* that is generally classified as conventional oil, and where the bulk of oil production currently, and by far the largest part historically, has been of this class of oil.

By contrast, non-conventional oil tends to be found in extensive regions (within which there may be 'sweet spots'), and where flow to a production well is not possible without significantly changing the nature of the oil itself (for example, by heating to reduce viscosity, addition of a solvent, or retorting), or that of the surrounding material (such as mining the sand in which the oil is contained, or by fracturing the rock in which it is trapped). Non-conventional oil thus includes very heavy oil, oil from tar sands and Venezuela's Orinoco fields, shale ('light tight') oil and oil produced from kerogen by retorting.

Oil, in addition, can be produced from yet other sources. It can come from the physical transformation of some of the gas from gas fields, as either condensate or natural gas liquids ('NGLs'); by chemical transformation of gas from a variety of fossil sources (yielding gas-to-liquids, GTLs), or similarly from coal (coal-to-liquids, CTLs); or alternatively from biomass, either directly as biofuels, or by chemical or biological change from a variety of types of biomass.

Note that NGLs are often included in conventional oil (though in this book we try to break them out separately where possible), while the oil produced from GTLs, CTLs and biomass is often classed as 'other liquids'. Annex 1 gives more detailed definitions.

To see why this distinction between classes of oil is important, we need to ask the following question: Why over a century and a half has the world, in the main, used conventional oil (i.e. oil in fields), rather than oil from the many other sources that exist, and where some of the latter (such as oil from biomass, and from coal and kerogen) were used extensively before conventional oil came to dominate?

The answer is simple: Up to now the oil in fields has usually been far cheaper to produce than these other oils. The reason for this generally lower cost of conventional oil relates principally to flow rate, and energy return.

Flow rate

As noted above, oil in fields is concentrated geographically and flows easily, and hence often yields large flow rates when produced by relatively simple drive mechanisms, such as own pressure, gas drive or water flood.

For example, while the 1859 Drake well, the first commercial oil well in the US, yielded up to about 20 barrels of oil per day ('b/d'), only 2 years later the first major US gusher yielded 4000 b/d, and in 1901 the Spindletop field in Texas flowed at 100,000 b/d. Admittedly in these early years such flows were often short-lived, but subsequent large fields typically have yielded over 500,000 b/d for considerable periods; while the Middle East giants produce 1 million b/d and above, and the world's largest field, Ghawar, averages over 5 million b/d. Thus once located, conventional oil from large oil fields has generally been cheap to produce due to relatively easy production methods and high flow rates.

As a result, while 'the petrol tank in your car does not care' what type of oil (conventional or non-conventional) is used, the user certainly does. The user would far prefer conventional oil at its pre-1973 long-term average real-terms price of \$15/bbl, or even at its post-1985 real-terms average price (up to the 2004 increase) of \$30/bbl, than to have to pay the ~\$60/bbl production cost for US light tight oil,[1] or the more than \$160/bbl for 'Canada oil sand mine upgraded' oil, currently estimated by IHS-CERA (see Fig. 16 of Miller and Sorrell 2014); or the production cost—whatever it will be—of retorted kerogen oil plus carbon capture, or of synthetic fuel made from electrolysis of water plus CO_2.[2]

Energy return

Another way to look at the relative ease of production of conventional oil is in terms of its energy return; nearly all of the non-conventional oils have lower energy returns. Though the data are hard to establish unequivocally, Guilford et al. (2011) and Hall (personal communication) suggest for example that in the US the ratio of energy return to energy invested (EROI) for conventional oil was about 30:1 in the 1930s, rising to 40:1 in the 1970s as scale increased and technology improved, and subsequently falling with production of the more difficult conventional oils, such as deep offshore or Arctic oil, to an average ratio of perhaps 14:1 today. By contrast, nearly all non-conventional oils have lower energy ratios; tar sands, for example, being quoted as having ratios of from 1.5 to 8:1, and corn ethanol as only perhaps 2 or 3:1 (probably higher in Brazil, and in some cases perhaps negative). Since Hall et al. (2009) and Lambert et al. (2014) calculate that modern society will have difficulty in functioning if its fuels have energy ratios of less than perhaps 5–10:1, the current transition from mainly conventional oil to increasing quantities of non-conventional oil is significant, and needs to be understood.

1.4 Oil Reserves Data: Proved Versus Proved-Plus-Probable

Recognising the difference between conventional and non-conventional oil is one part of understanding the current transition in oil supply, but by far the largest reason why this transition has been poorly understood has been confusion over the data, and in particular the reserves data.

The reserves of an oil field or a region estimate the amount of recoverable oil remaining at a given point of time, and the problem lies with the differences between the *proved* oil reserves (the so-called '1P' data), and the *proved-plus-probable* reserves (the '2P' data); see Bentley et al. (2007). The following two sections discuss this topic briefly, and it is discussed more fully in Annex 2.

1.4.1 Proved ('1P') Oil Reserves

Where annual summary tables of oil reserves data are given in the public domain they are usually of proved (1P) reserves, as for example in the BP *Statistical Review of World Energy*, the annual tables in *World Oil* or the *Oil & Gas Journal*, or on the US Energy Information Administration (EIA) website. Although such reserves data are used in company reports they have been extraordinarily misleading on the actual quantity of oil discovered, especially in the past, and they generally cannot be used to forecast oil production despite many analysts having done just this. (For an exception to this rule see Bentley 2015a). The issues with the proved reserves data are as follows:

Understatement

The term 'proved' reserves would seem to indicate solid, reliable data. The BP *Statistical Review* for example quotes such reserves as: '*Generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions*'.

In fact, this has been far from the case. Historically, proved reserves have been *very much less* than the quantities that 'with reasonable certainty can be recovered', where the latter were far better indicated by the oil industry's proved-plus-probable (2P) reserves data.

In the US and Canada in particular, the apparent size of individual fields, as given by their estimated initial proved reserves, has often grown massively over their lifetimes, typically from five to over ten times their original estimated volumes.

There are many explanations for this, but 'drilling-up' of early fields is likely a major factor, as under SEC rules proved reserves can largely refer only to oil in communication with existing wells. Though the US and Canada have typically shown the largest such proved reserves 'reserves growth', the phenomenon applies to many regions around the world. In the UK, for example, the total oil proved reserves have long stood at only about half the value given by the industry data for 2P reserves.

For *regions*, proved reserves will also be underestimates due to summation. This is because simple addition of any high-probability data, such as proved reserves, significantly underestimates the total at the same probability level.

Naturally, over time, as fields get produced, the conservative proved reserves data generally grow to become close to 2P estimates. This is now the case for many—but by no means all—oil-producing countries.

Overstatement

But the opposite problem also exists, where proved reserves are almost certainly significantly overstated.

Though most countries' public domain proved oil reserves are, as one would expect, smaller than the industry 2P data, in some anomalous but important cases the reverse is true, and the country's published 1P reserves significantly exceed the industry 2P reserves. These cases are mainly the result of the OPEC 'quota wars' step-changes in proved reserves that occurred in the 1980s, when OPEC's allowed production of individual members was based in part on the size of their reserves. This issue has been written about extensively, and may constitute an over-reporting, above the correct 2P reserves, by as much as ~300 Gb, close to a third of remaining conventional oil reserves.

Non-statement

Finally, in the main public-domain 1P databases (e.g. BP *Stats. Review*, or from the *Oil & Gas Journal*), the data on proved reserves are frequently not updated annually, and can remain static for sometimes very long periods of time. (For example, in the end of 2014 *O&GJ* data for 106 oil-producing countries, 66 reported no change in proved reserves during 2014.) For this reason also, such 1P data are significantly in question; and more importantly *trends* in these data are misleading.

1.4.2 Oil Industry Proved-Plus-Probable ('2P') Reserves Data

Now we turn to the proved-plus-probable ('2P') reserves data. Such data can be gathered for individual oil fields from a wide variety of published industry and government sources, but with considerable effort, as has been done for example by Richard Miller, Michael Smith at Globalshift Ltd., and Robelius and others at the University of Uppsala.

Large commercial *by-field* 2P datasets can instead be purchased from firms such as IHS Energy, Wood Mackenzie, PFC Energy and Rystad Energy. Here the data have been assembled and checked, and there is also much additional proprietary information. Such datasets tend to be very expensive. Fortunately, simpler 2P datasets are available at moderate cost. Certain by-field data can be purchased from Globalshift Ltd., and possibly from Peak Oil Consulting, Richard Miller and Uppsala University. In addition, extremely useful *by-country* 2P data are available from IHS Energy's 'PEPS' database, where researchers should use the version with data back to 1834 (but note that US and Canada non-frontier data are only 1P).

Some collected 2P data now are in the public domain. For conventional oil, adjusted global and by-country data are given by Laherrère on websites and elsewhere (including in this book, and as a chart in *The Oil Age,* January 2015); while charts for adjusted 'Regular conventional' oil for a wide range of countries, and including essays on the associated petroleum geology, are given in Campbell (2013). (In the latter, the key graphs are the 'Status of Oil Depletion' plots. These give, by-country, the cumulative backdated 2P discovery data to show how much oil has been found; the country's cumulative production; and also Campbell's judgement of the country's ultimately recoverable resource ('URR'). Evolution over time of a country's 2P reserves, and yet-to-find, are given by the differences between these data.)

Excellent plots of past and forecast production (but not of discovery) for all oil-producing countries, based on detailed by-field 2P data, are free on the Globalshift website (www.globalshift.co.uk). In addition, Rystad Energy's UCubeFree facility gives past and future production by-country, based on their estimates of 2P data.

Comparison of the evolution over time of global 1P oil data with 2P is given in Annex 2. Today, for *conventional* oil, the size of global 1P reserves is roughly the same as that of the 2P reserves. This is because the overstatement of OPEC 1P reserves is roughly matched by the understatement of the 1P reserves in most other countries. Nevertheless, in general 1P reserves data should *not be used* for understanding the future of oil production, and especially not their very misleading evolution over time. The data presented in the graphs and analyses given below are in general *2P data*, drawn from a variety of oil industry datasets.

1.5 Structure of This Book

Now we turn to the structure of this book:

Chapter 2 explains the concept of 'peak oil'. As used in this book, and also fairly generally, the term refers to the maximum in the production of oil that results from the *physical and economic characteristics* of an oil resource. It is shown that such peaks have very different causes, profiles and impacts depending whether they refer to peak of production in a field, in a region, or to the world as a whole. Similar differences also hold true if the peak refers to production of conventional oil only, or to that of 'all-oils' or 'all-liquids'.

Chapter 3 gives a brief history of some of the main forecasts of peak conventional oil production that have been made over the years. Such forecasts can be generated by a variety of approaches, including the 'mid-point' rule, PFC Energy's '60 %' rule, mirroring of production to discovery, Hubbert linearisation, summing logistic curves, or by detailed 'bottom-up' calculations by field.

Chapter 4 then examines oil forecasts from a variety of fairly recent sources to ascertain the likely dates for the global peak of the various types of oil, both conventional and non-conventional. It is shown that in contrast to the widely held view that 'all oil forecasts have been wrong', for over 40 years nearly all oil forecasts that have been based on an understanding of resource limitations have been substantially correct in predicting that the peak in the global production of conventional oil would occur roughly around the year 2000. Much greater attention should have been given to these technically based warnings of significant transition in the global oil supply.

Chapter 5 then turns to the question of why the concept of 'peak oil' has been so poorly understood, both in the past and still today. The primary reasons have been:

- As already mentioned, reliance on the very misleading proved reserves data; and in particular on the apparent *replacement* of these proved reserves over time.
- Not understanding the significance of the 'mid-point peak' in production.
- Reliance on global URR estimates significantly higher than that indicated by the trend of 'proved-plus-probable' (2P) oil discovery.

Chapter 6 sets out some caveats, and then summarises the book's main conclusions. Finally, a number of annexes are given; these give greater detail on topics in the main chapters, and also discuss briefly a number of topics not covered in the main text. The latter include the relationship between peak oil and climate change; peak oil demand; and the global peak of conventional gas production.

Chapter 2
Explaining Peak Oil: What It Is, and Why It Happens

This chapter explains the concept of ‘peak oil’. The term, as used in this book and also generally, refers to the point at which the production of oil from an oil field, a region, or the world as whole reaches a maximum and then subsequently declines due primarily to *limitations of resource availability*. Note that there can be several such ‘resource-limited’ maxima in the production history of a field or a region; in a field for example from the application of new technology or a significant increase in oil price; and likewise in a region, for example from successive phases of discovery.

The term therefore generally does not refer to a peak in production that occurs due to ‘above-ground’ factors, such as demand reaching a maximum, a country limiting access to the development of its oil, or the imposition of quotas or similar constraints on production.

The physical and economic reasons for a peak in oil production, the shape of the production profile before and after the peak, and usually also the economic significance of the peak, are very different in the case of an individual oil field, a region that contains many fields, and the world as a whole. Moreover, the economic significance of peak will be different if it applies to conventional oil only, or to conventional plus non-conventional oil, or to ‘all-liquids’.

Definitions used in this book for different categories of oil, and for extraction techniques, are set out in Annex 1. Importantly, recall from above that *conventional* oil is defined here as essentially *oil in fields*, i.e., primarily mobile oil that has migrated from a source rock to a discrete field (and usually one having an oil-water contact). The reason this definition is adopted is twofold: the generally intrinsically lower cost of this type of oil as already discussed; and because the physical factors that drive production of this oil result in the peak of production in a region as occurring typically when roughly only half of the region’s total recoverable oil has been produced; the so-called ‘mid-point’ peak.

In this chapter and the next we look primarily at the production of *conventional* oil, and look in turn at peak in individual oil fields, in regions, and then in the wold as a whole. We start by examining the production peak in fields.

R.W. Bentley, *Introduction to Peak Oil*, Lecture Notes in Energy 34,
DOI 10.1007/978-3-319-26372-4_2

2.1 The Production Peak in an Individual Oil Field

2.1.1 Typical Field Production Profiles

The production profiles of *individual oil fields* can vary considerably. Figure 2.1 gives examples of fairly typical production profiles for a range of field sizes and locations.

Figure 2.1 includes the 'fairly slowly up and down' production of larger older fields such as Romashkino, but with a very long production tail; the quickly up (then long decline) of relatively modern offshore fields such as Forties, where speed of financial return is important given the high up-front investment; and the relatively long plateaus of both a 'heavily-worked' field like Daqing (and where output was probably judged more important than rate of return), and of a large Middle East