



PLUGGING THE GAP

A survey of world fuel resources and their impact on the development of wind energy



PLUGGING THE GAP:

A survey of world fuel resources and their impact on the development of wind energy

Contacts

This report was prepared by Francisco Varela under the direction of Dr Ian Mays (ian.mays@res-ltd.com) and Stephen Balint (stephen.balint@res-ltd.com). Specific information regarding the contents or preparation of this publication may be obtained from Francisco Varela (varela@eoleres.com).

Acknowledgement

The author would like to acknowledge Dr Gareth Davies from Oxera for reviewing this report. His advice and additional inputs are greatly appreciated.

Disclaimer

This Survey (the "Report") has been prepared by Renewable Energy Systems Ltd ("RES") by reference to internal and published materials. RES has endeavoured in preparing this Report to ensure that it is accurate and objective, its purpose being to inform a wider audience of the current status of world fuel resources. As a company whose business is derived from wind energy and other renewable resources, RES has its own perspective on the subject matter of this Report. Nonetheless, RES has tried to ensure that the Report is accurate and balanced.

It is hoped that readers of this Report will find it helpful and informative, but it is not RES's intention that it may be relied upon by others, and anyone utilising the Report for any reason does so at their own risk. Accordingly, RES shall not be deemed to make any representation regarding the accuracy, completeness, methodology, reliability or current status of any material contained in this Report, nor do RES or any of its affiliated companies or employees assume any liability with respect to any matter or information referred to or contained in the Report.

This Report is subject to copyright protection. This Report may be reproduced free of charge provided that it is reproduced accurately and that the source and copyright status of the material is made evident in so doing.

© Renewable Energy Systems Limited 2007.

May 2007

FOREWORD

This report is an updated version of the Plugging the Gap report published by RES and the Global Wind Energy Council in May 2006. It includes updated figures on energy demand and fuel resources from the most recent energy outlook reports, notably IEA's 2006 World Energy Outlook.

It is interesting to note that, since the publication of Plugging the Gap, the IEA has acknowledged the twin challenges of availability of fuel resources and increased energy demand, as we highlighted. This change of tone, cautioning about the sustainability of our current energy strategy, is to be welcomed. However, the figures contained in the body of the IEA report, based on the same sources and models as before, still fail to reflect the true nature of the challenge we face, as they over-estimate the availability of future fossil fuel resources. In our report we demonstrate the true statistics on world energy resources in the 21st Century and reveal the looming gap between supply and demand that needs to be plugged

EXECUTIVE SUMMARY

The world's energy resources are not sufficient to sustain expected growth trends. A growing gap is developing between energy demand and the available supply of oil and gas. High energy prices are here to stay and the world's energy mix will change.

An unforeseen and additional potential will become available to wind energy as a result of gas supply limitations. Up to 950 GW of extra capacity could potentially be installed by 2030 without major policy efforts as wind power enters its 'market era' sooner than expected.

This report assesses the resource base and future production capability for oil, gas, coal and nuclear fuel and compares this to projected demand for each. It offers an insight into the role that different energy sources are likely to play in the future and the implications of this on the development of wind energy.

The report, written by Renewable Energy Systems Ltd (RES) in co-operation with the Global Wind Energy Council (GWEC) and EUREC Agency's European Master in Renewable Energy, was first published in 2006. This is an updated version that includes figures on energy demand and fuel resources from the most recent energy outlook reports, notably the International Energy Agency's 2006 World Energy Outlook.

Rising Energy Demand

According to the International Energy Agency (IEA), the world's primary energy demand will rise by 55% between 2002 and 2030. Two-thirds of the increase will come from developing countries. Electricity demand will double and the requirements for all fossil fuels are expected to grow at sustained and substantial rates. More importantly, the IEA suggests that fossil fuels will still account for more than 80% of the energy mix in 2030, just as they do today. But are the world's fossil fuel resources abundant enough to feed such growth? Unreliable and over-optimistic mainstream forecasts have given a false impression of how much longer the world's oil and gas supplies will last.

Oil

In 2005 global oil production averaged 84 million barrels per day (Mb/d). The IEA predicts that it will reach 116 Mb/day by 2030. Historically the oil discovery record has been presented in a way which gives the impression that reserves are plentiful and growing. But these mainstream energy outlook studies are based on a questionably optimistic assessment by the US Geological Survey (USGS), which does not appear to align with detailed records of actual worldwide discoveries.

Drilling logs from individual wells provide a more reliable resource estimate that challenges the outlook studies and suggests that production of oil will in fact peak in around 2014 (± 2 years) at around 90 Mb/day. We are already consuming more than three times as much as we discover and have used up around half of the world's regular oil resources.

The comparison with projected demand reveals a considerable gap reaching 40 Mb/d by 2030, equivalent to more than four times the current production of Saudi Arabia.

Natural Gas

Gas has been the fastest growing fossil energy source in the last two decades, boosted by its increasing share in the electricity generation mix. It is expected to supply 23% of the world's energy needs by 2030.

As with oil, mainstream energy outlook studies, which are based on the USGS assessment, appear to have overestimated the Ultimate Recoverable Resource (URR) for conventional gas. The URR is actually expected to be around 10,000 trillion cubic feet (Tcf), 90% of which has been discovered already. Unconventional resources, including coalbed methane, tight gas and gas shale, are expected to yield another 2500 Tcf, although this figure bears a great deal of uncertainty.

The implications are serious. Global gas production will peak at about 140 Tcf/year in 2030 (± 5 years). By then, demand will have doubled and the resulting gap would be equivalent to the current combined production of Russia and Africa. We have already started to use more gas than we find. In addition, gas is not a perfect global market like oil. Transport is restricted and expensive. Therefore, regional shortages should be expected to occur well before the global peak.

North America on a cliff edge

In North America, gas discoveries fell off very rapidly from 1977, and production has mirrored the discovery curve, but shifted by 23 years. This means that production from gas wells will shortly decline dramatically. Prices have already risen substantially and a considerable amount of imported LNG will be needed very soon. We should expect intense international competition for these LNG supplies.

Coal – A Plentiful Resource but with Environmental Constraints

Today coal provides a quarter of the world's energy, a share it is expected to keep by 2030. Global proved recoverable reserves amount to 909 Gtons, equivalent to twice the remaining oil. Coal is plentiful and more equally distributed throughout the world. Moreover, prospective

big energy consumers, like the US, China and India are self sufficient in coal and will be in the foreseeable future, unlike for oil and gas.

However, by 2030 the world will have consumed 23% of its current reserves rising to 45% by 2050 and if it continues to be depleted at the same rate reserves will be exhausted by around the end of the 21st century. And while the coal market today is booming, with two thirds of the coal consumed used for power generation and coal the leading source for global electricity production (39%), environmental issues are constraining its use, especially in developed countries.

However, the rise of two technologies – 'clean coal' and coal-to-liquids – could steer a transition to a new coal era, boosted by the decline of oil and gas supplies and growing concerns of energy security and independence. The development of CO₂ capture and storage (CCS) combined with coal gasification has the potential to lead to power plants producing electricity, hydrogen and liquid fuels with almost zero emissions. Clearly, though, this will have significant cost implications and will deplete reserves even more rapidly. The future for electricity generation from coal will depend critically upon its availability and price in a world where this remaining fossil fuel resource is called upon for uses traditionally supplied by oil and gas.

Nuclear Power – Medium-term Uranium Shortage

Nuclear power stands in the midst of an intense debate over its future, with environmental and cost concerns leading to a phase out in many countries and talks of a renaissance in support of emissions targets and energy security in others. However, there should be concerns over the availability of uranium fuel supplies.

Only 60% of current supplies now come from mines. The rest, since the end of the 'Cold War', is from stockpiles and reprocessing. This has kept production and prices at a low level for the last 15 years and deferred investments in new mining capacity. Stockpiles are expected to last 10-15 years while new mining projects have a lead time of 10 – 25 years. This clearly points to a medium-term shortage and uranium prices have skyrocketed, all of which could undermine an incipient nuclear renaissance.

Present uranium reserves will last about 60 years (in the highest 'business as usual' demand scenario), which is the probable lifetime of a new generation of nuclear reactors. Although reserves are expected to grow in the coming years as high prices revitalise exploration, alternative sources would have to follow in the long-term, especially if a further new generation of reactors is built. Substantial R&D and capital investments are required for these alternatives to reach the market and they also raise issues of concern, such as nuclear proliferation.

Nuclear power currently only provides around 6.5% of world energy demand and resource constraints, combined with security issues, are likely to limit the extent to which it can grow to help to meet the gap opening up in fossil fuel supplies.

A Growing Energy Gap After 2010

A growing gap between oil and gas supply and demand becomes evident after 2010. But oil and gas will, according to the IEA, be called upon to provide 60% of the world's energy in 2030. Supplies can be expected to fall short and the combined gaps are likely to represent 8% of the primary energy demand in 2020 and 15% by 2030.

The oil gap is the most urgent and the hardest to fill because no alternative to liquid fuels have been developed on a large scale so far and the time to do so is running out. Eventually, the oil gap will be filled by a mix of demand reduction and vehicle efficiency, liquids from coal, biofuels and natural gas.

The gas gap opens up as soon as 2015 and accounts for 16% of the demand in 2030. In the longer term, it will be filled inevitably with a mix of energy efficiency, power generation from renewables coal and nuclear, and heat production from renewable sources. Wind power presents a key element of the solution, being rapid to deploy, low in environmental impact and low cost. The mix of technologies forming the solution will depend critically upon the availability and acceptability of coal for generation in and oil and gas constrained world.

New Opportunities for Wind Energy

Wind energy has been the fastest growing energy source of the last decade, at an annual global rate of 28%. The growth of this zero-carbon, fuel-independent and indigenous energy source has been driven by environmental and, to an increasing extent, energy security concerns. Today, the installed capacity worldwide has reached nearly 75GW, two thirds of which is located in Europe.

The Global Wind Energy Council forecasts in its Moderate scenario that the global installed capacity for wind power will reach 1129GW by 2030 if supportive regulatory frameworks are deployed worldwide. Their Advanced scenario, by contrast, describes how 2107GW could be installed by that time if more radical policy changes are made. However, none of these analyses take into account the supply gaps described above.

Gas supplies can only support 350GW of the 1300GW of new gas-fired power plant capacity additions planned to 2030, leaving a gap of 950GW for other power sources. Thus the gas gap offers an enormous additional potential for wind power that was not foreseen in the wind capacity forecasts.

This potential is technically realisable. Market dynamics will end up raising gas prices in a way that will make wind energy cost-competitive as fuel costs account for around 70% of the generation cost of Combined Cycle Gas Turbines (CCGTs). Although wind power would have to vie against other alternatives for this new market, it clearly stands in a privileged position as one of the most cost-effective and most environmentally-acceptable energy technologies. Another particular attraction of wind in a world that will become increasingly concerned about the security of its energy supplies is that it is naturally indigenous.

The world's energy resources are diminishing and the rate of decline of oil and gas is faster than official estimates suggest. Huge opportunities exist for the gas gap to be filled with wind - a safe, carbon-neutral, economic, fuel-free and indigenous energy resource that can help meet national environmental and energy security targets.

CONTENTS

INTRODUCTION6

2.0 SCOPE AND METHODOLOGY6

3.0 ENERGY DEMAND PROJECTIONS6

4.0 OIL7

5.0 GAS11

6.0 COAL14

7.0 NUCLEAR FUEL17

8.0 IMPLICATIONS19

9.0 CONCLUSIONS22

10.0 REFERENCES23

GLOSSARY OF TERMS25

ANNEX A – UNCONVENTIONAL OIL27

ANNEX B – UNCONVENTIONAL GAS30

INTRODUCTION

This report is an independent survey of world fuel resources, offering an insight into the role that different energy sources are likely to play in the future and the implications of this on the development of wind energy.

The global economy has now enjoyed two centuries of steady and unprecedented growth supported by the exploitation of the Earth's fossil fuel resources. Not only is this impressive growth trend set to continue, but it is widely believed that the world will still rely largely on fossil fuels for its energy needs well into the first half of this century.

In the last two decades, growing concerns have arisen over the environmental effects of releasing pollutant and greenhouse gases into the atmosphere from fossil fuels, and of the generation of long-life radioactive wastes as a by-product of the use of nuclear fuels. Such concerns have boosted the development of renewable energy sources, owing to their neutral impact on the environment.

However, the fact that 'conventional' energies have so far fulfilled the promise of delivering cheap, abundant energy has obscured the simple reality that fossil fuels are a finite resource. Indeed, renewable energies are mainly praised as 'clean', while the argument of them being inexhaustible, and in many cases virtually fuel-free, is often overlooked. This paper offers a critical assessment of the future availability of fossil and nuclear fuel resources and briefly considers the impacts of this on the 'case for wind energy'.

Although a handful of energy outlook studies from government bodies and trans-national organisations is available, these analyses present a comforting picture looking to the future: soaring energy needs will be met by an ever expanding supply base. These studies, trusted and quoted by key business players and policy makers, have lately been challenged by a growing faction of dissenters who question their basic assumptions. Concerns over the adequacy of resources have been stirred in the context of rising energy prices. This paper aims at clarifying the debate by assessing the evidence behind both viewpoints.

2.0 SCOPE AND METHODOLOGY

As the focus of this study is on energy supply, it relies on published work for the demand side projections, which do not usually forecast beyond 2030. This constraint limits the scope of the quantitative analysis, although a qualitative insight is offered for the longer term.

First, energy demand and fuel mix projections from the mainstream publications are examined to evaluate the supply performance expectations for each source. Then, the main fossil fuel resources are reviewed in detail: oil, natural gas, coal and nuclear fuels; both conventional and unconventional sources are assessed. For each one, the following questions are addressed:

- how reliable is the publicly available information?
- how abundant was the resource originally and how much is there left?
- what production rate can be achieved in the future?
- how long can the supply match the expected demand?

Finally, the study investigates the potential implications the supply-demand match might have on the development of wind energy.

3.0 ENERGY DEMAND PROJECTIONS

Securing a constant and affordable energy supply is a crucial aspect in the governance of nations. In the pursuit of such an important goal, governments endorse a continual effort in energy research to guide and support effective policy making. The most visible face of this effort is a series of national and transnational agencies who periodically issue 'international energy outlook' studies summarising the results of their research. The OECD's International Energy Agency (IEA), the US Department of Energy's (US DOE) Energy Information Administration (EIA) and the European Union's Directorate-General for Research (DGR) stand out as the most quoted, representative and highly regarded of these organisations.

The studies conducted by these agencies ([1], [2] and [3] respectively) project the evolution of the world's energy demand and supply 20 or 25 years in the future. Demand, in particular, is forecasted using complex models that calculate energy needs from the bottom up, adding up the consumption of the different sectors. Initial key assumptions are made on economic activity, population growth and energy prices. Although these studies are mutually independent, their assumptions and findings have proved very similar in the past. For the sake of this report, IEA's latest publication, the 'World Energy Outlook 2006', is selected as a reference for demand projections² because its parent organisation, the OECD, is the most representative of the three quoted above.

1: Real prices, corrected by the US Consumer Price Index. Oil price is the Refiner Acquisition Composite Cost from the US Energy Information Administration (EIA, www.eia.doe.gov). Uranium price is the U308 spot price from 'The Ux Weekly' (www.uxc.com). Gas price is the wellhead price in the US from EIA. Coal price is the Central Appalachian Coal futures price from NYMEX (www.nymex.com).

According to the IEA, the world's primary energy demand will rise by 55% between 2004 and 2030; more than two-thirds of the increase will come from developing countries. In the meantime, electricity demand will double. As shown in Figure 1, the requirements for all fossil fuels are expected to grow at sustained and substantial rates. What is more important, it is expected by the IEA that fossil fuels will still account for more than 80% of the energy mix in 2030, just as they do today (Figure 2).

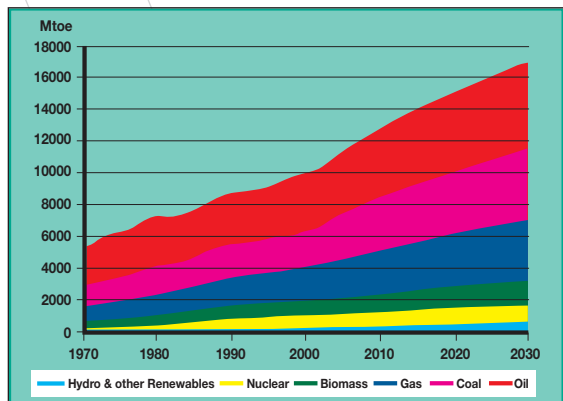


Figure 1. World primary energy demand

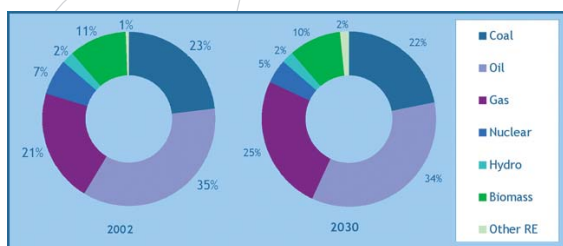


Figure 2. World primary energy mix

Although renewable energies are the fastest growing of all sources, their base is currently so small that they are expected by the IEA to have a minor share in the future energy mix (only 2%, excluding large hydro and biomass).

In brief, the IEA predicts that the world energy demand will expand consistently in the future and will remain largely dominated by fossil fuels. However, it should be clear that this is not only a demand forecast, but a supply one as well. The resource base and the technology are actually thought to be adequate to cope with the demand.

In a much needed position change, IEA has voiced in its latest report a sharp warning regarding the access to resources and the huge scale of the investment needed to bring resources to the market. Sadly, their tone change hasn't been backed up by a reassessment of fuel resources. And so, a crucial question arises: are the world's fossil fuel resources abundant enough to feed such impressive growth? In the following sections, each one of these resources is assessed in detail in search of an answer.

4.0 OIL

Oil is the blood of the modern global economy, as the effects of the supply disruptions of the 70s (the 'oil shocks') made very clear. It is the number one source of energy, providing 35% of the world's needs and the almost exclusive fuel for vital uses like transportation. In 2005 production averaged an impressive 84 million barrels per day (Mb/d) and the IEA predicts that it will reach 116 Mb/day by 2030. However, a passionate debate has developed regarding the ability of supply to meet this challenging target, obscured by poor information and stirred by soaring prices.

4.1 The reserves chaos

Public data about oil and gas reserves is strikingly inconsistent. Furthermore it seems to be unreliable for legal, commercial, historical and sometimes political reasons. In fact, the most widely available and quoted figures, those from the industry journals Oil & Gas Journal and World Oil, have limited value. These sources report the reserve figures provided by companies and governments without analysis or verification. Moreover, as there is no agreed definition of reserves or standard reporting practice, these figures usually stand for different physical and conceptual magnitudes. Confusing terminology ('proved', 'probable', 'possible', 'recoverable', 'reasonable certainty') only adds to the problem.

Historically, private oil companies consistently underestimated their reserves to comply with conservative Stock Exchange Commission (SEC) rules, designed to protect shareholders from fraud, and generally for mere commercial caution. Whenever a discovery was made, only a portion of the geologist's estimate of recoverable resources was reported as reserves; subsequent revisions would then increase the reserves from that same field over time. Underreporting had other advantages such as tax benefits, and it gave a comforting, though misleading, idea of perpetual growth [4].

National oil companies, almost fully represented by OPEC, are not subject to any sort of accountability so their reporting practices are even less clear. In the late 80s, OPEC countries blatantly overstated their reserves while competing for production quotas, which were allocated as a proportion of the reserves (see Table 1). Although some revision was needed after the companies were nationalised, between 1985 and 1990 OPEC countries increased their joint reserves by 82%. Not only were these dubious revisions never corrected, but many of these countries have reported untouched reserves for years even if no sizeable discoveries were made and production kept its pace [5]. Additionally, the Former Soviet Union's (FSU) oil and gas reserves are overestimated by about 30% because the original

2: Throughout this report, the IEA's figures refer to its Reference Scenario.

assessments were later misinterpreted [6].

	Abu Dhabi	Iran	Iraq	Kuwait	S. Arabia	Venezuela
1980	28	58	31	65	163	18
1981	29	58	30	66	165	18
1982	31	57	30	65	164	20
1983	31	55	41	64	162	22
1984	30	51	43	64	166	25
1985	31	49	45	90	169	26
1986	30	48	44	90	169	26
1987	31	49	47	92	167	25
1988	92	93	100	92	167	56
1989	92	93	100	92	170	58
1990	92	93	100	92	258	59
1991	92	93	100	95	259	59
1992	92	93	100	94	259	63
1993	92	93	100	94	259	63
1994	92	89	100	94	259	65
1995	92	88	100	94	259	65
1996	92	93	112	94	259	65
1997	92	93	113	94	259	72
1998	92	90	113	94	259	73
1999	92	90	113	94	261	73
2000	92	90	113	94	261	77
2001	92	90	113	94	261	78
2002	92	90	113	94	259	78

Table 1. OPEC's reserves (Gb) revisions [7]

Owing to the circumstances described above, the discovery record has been greatly distorted, giving the impression that reserves are plenty and growing. Figure 3 shows the discovery record as reported in contrast with an inherently more accurate one [8] where revisions are backdated to the original discovery of the field.

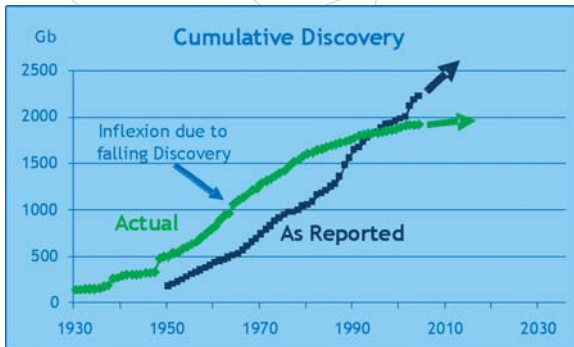


Figure 3. Cumulative oil discoveries, reported vs. backdated

While private companies are now becoming more realistic regarding the dimension of their resources, the OPEC countries hold by far the majority of the reported reserves, and information on their resources is as unsatisfactory as ever. In brief, these information sources should be treated with considerable caution.

A correct evaluation of oil resources must rely on the fact that reserves are best represented as a probability function, being P_X the minimum amount of oil a field will yield with an $X\%$ certainty. 'Proved' reserves are generally equated to P_{90} , meaning there is only a 10% chance that the total output ends up being lower, but a 90% chance that it will be higher. 'Proved and probable reserves' usually means P_{50} ; in that case the probability of underestimation and overestimation are the same. However, the best estimate is always the mean

(mathematical expectancy of the function, usually around P_{40}) because it represents the most likely outcome. More importantly, the mean values of several fields and regions can be summed to calculate the global expected value. That is not the case for the other estimations: the sum of the proved reserves of all countries is not equal to the proved reserves of the world (the world's P_{90} reserves would be higher).

In short, to estimate the world's oil resources properly a regional assessment of the mean backdated (ie 'technical') discoveries would need to be performed.

4.2 Oil resources

Undeniably the most reliable information source for oil resources are the drilling logs from the individual wells. So-called 'scout companies' have compiled these geological records and assessments into detailed databases of worldwide technical discoveries that are generally used by the industry and, lately, by independent consultants and interest groups raising awareness of fossil fuel scarcity, such as the Association for the Study of Peak Oil & Gas (ASPO). Although the full detail of these databases is not public, the discovery records for the most important oil regions and the global total can be found in many published papers and proceedings [7-10]. Once a proper discovery record has been established, the ultimate recoverable resource (URR, meaning the total production of the field/region in its lifecycle) can be calculated using a creaming curve, or other statistical tools.

Creaming curves plot the cumulative discoveries as a function of the cumulative number of exploratory wells drilled (called new field wildcats), compensating for the effect of ups and downs in exploration due to wars or low oil prices. The biggest fields are always found first simply because they extend over larger areas, whereas the subsequent findings bear less and less oil. As a result, the curve can be fitted with a hyperbola converging to the URR value. Figure 4 shows the creaming curve for the world, as an example. In some cases, the fitting involves compound hyperbolas to reflect new exploration cycles like deepwater, as in the US for example.

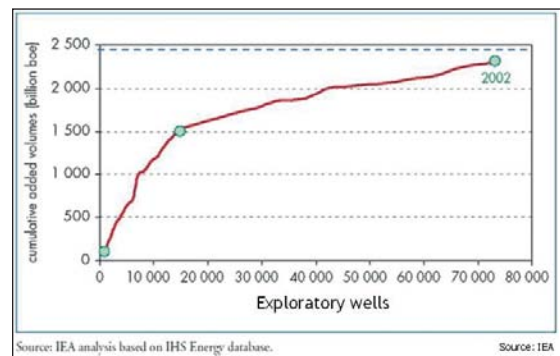


Figure 4. World liquid hydrocarbons creaming curve³

3: Crude + NGL, from IEA, does not include the correction of the Former Soviet Union's (FSU) reserves. See section 5.1 for more details

Acknowledging the complexity and uncertainty intrinsic to estimating oil resources, this report proposes a quantification closely derived from the work of Jean Laherrère, Collin Campbell and IHS publications [7-13]. In fact, no data source covers the complete scope presented in Table 2 so the estimation is a composite.

	Crude	Crude + NGL	Unconventional	Total
Discovered	1930	2080	410	2490
Produced	990	1040	10	1050
Reserves	940	1040	400	1440
Yet-to-find	70	170	150	320
Ultimate Recoverable Resource (URR)	2000	2250	560	2810

Table 2. World oil resources (Gb)

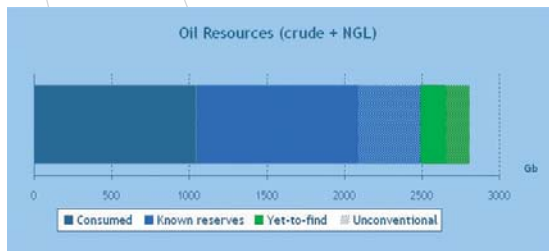


Figure 5. World oil resources (Gb)

The unconventional sources taken into account are the Canadian oil sands and the Venezuelan extra-heavy oil, which are already supplying 2% of the world's production. Oil shale, present mainly in the US, is disregarded because it is not expected to be developed in the foreseeable future due to technological and environmental constraints. Annex A deals with unconventional oil resources in detail.

The resource estimate presented above challenges the mainstream energy outlook studies [1-3], which suggest an URR significantly higher. In fact, they all quote the same study from the US Geological Survey published in 2000 [14] that introduced an optimistic model of reserves growth extrapolating the behaviour of US fields to the world. Moreover, USGS predicts an ambitious future discovery trend that has so far proved impossible to match. Table 3, Figure 6 and Figure 7 compare both estimates and illustrate how the USGS URR is clearly out of the commonly accepted range. Although exploration efforts were relatively modest in the 90s due to low oil prices, new investments will not guarantee new discoveries, as the creaming curves show.

Gb	Crude		Crude + NGL	
	This report	USGS	This report	USGS
Discovered (1995)	1850	1601	1980	1676
Reserves Growth	-	688	-	730
Undiscovered	150	732	270	939
Ultimate Recoverable Resource (URR)	2000	3021	2250	3345

Table 3. Conventional oil estimate vs. USGS 2000 (mean)

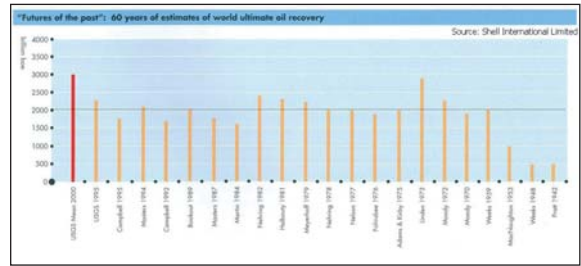


Figure 6. Estimates of URR for conventional oil from different studies [15]

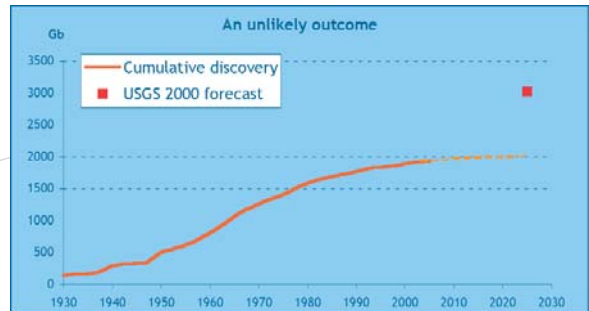


Figure 7. Conventional oil discovery vs. USGS 2000 assessment

According to the resource estimate and the creaming curves, more than 90% of the conventional oil has been found and no surprise discoveries are expected, no matter how hard we drill. The fact that we have only consumed half of that resource so far does not at first sight look particularly alarming. However, asking how much oil there is left is not a helpful approach; a more appropriate question would be: how much oil can be produced?

4.3 The depletion dynamic

The production of an oil field over time is constrained by its geological nature. After drilling, oil migrates to the surface and the pressure in the reservoir starts a continual decline. In the initial phase, the flow is limited by the production infrastructure, so it ramps up from zero and plateaus when the nominal production rate is reached. Eventually, the ever dropping pressure undermines the plateau and the well starts declining. In this second phase, stimulation methods such as pumping and steam or water injection are used to ease the decline, but only temporarily. In the end, production decreases gradually until the well runs dry (in fact, 40-70% of the oil remains underground, unrecoverable). Figure 8 illustrates the production cycle of an oil well.

Production from an oil region is the sum of individual wells that are subsequently tapped as they are discovered. Hence, given a sustained demand driving force, production follows a bell-shaped curve with a peak when about half the oil has been consumed. After the peak, production declines steadily and inevitably.

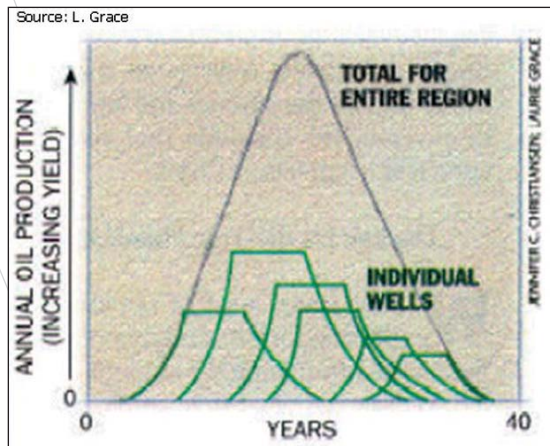


Figure 8. Schematic production from an oil region [5]

Dr. King Hubbert, a Shell geologist, first postulated this in 1956 when he predicted that US oil production, in full growth then, would peak in 1969 and decline ever after. Although he faced heavy scepticism at the time, his theory was proved right when the US actually peaked in 1970, one year after his forecast (see Figure 9). Since then, the phenomenon was observed in different oil provinces around the world as they approached maturity, with deviations in some cases due to demand constraints.

The theory is based on the simple assumption that production is proportional to two opposing forces: the cumulative amount produced (dominant in the growth phase) and the percentage of the total that is left to produce (dominant in the decline phase). Such dynamic, easily emulated in a stock-flow model, is observed in many analogous systems of 'installed capacity vs. finite resource depletion': spreading of epidemics, installation of wind turbines, etc. In fact, oil discovery follows the same cycle (oil has to be found before it is produced!), so production generally mimics discovery after a time lag.

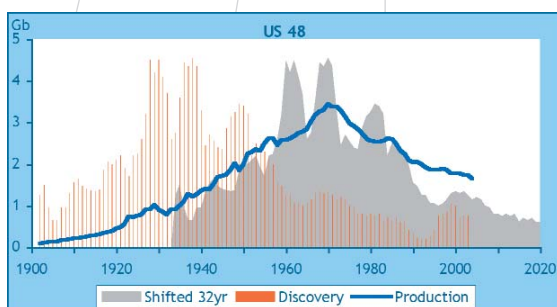


Figure 9. Oil discovery and production in the US (lower 48)

To model production and forecast its future trend using a Hubbert-type curve, two parameters need to be calibrated: the URR, which equals the area under the production curve, and a production constant that sets the speed at which resources are deployed (the slope). The production constant is determined by fitting the model to the historical production data, whereas the URR can be obtained as discussed in section 4.2.

4.4 Forecasting production

Although public data might show a comfortable picture, the world oil resources are quite advanced in their depletion cycle. Discoveries peaked in the 60s and have been declining ever since with a predictable trend. Moreover, production overtook discoveries in the 80s opening a growing gap: we are consuming every year more than three times as much oil as we can replace (Figure 10).

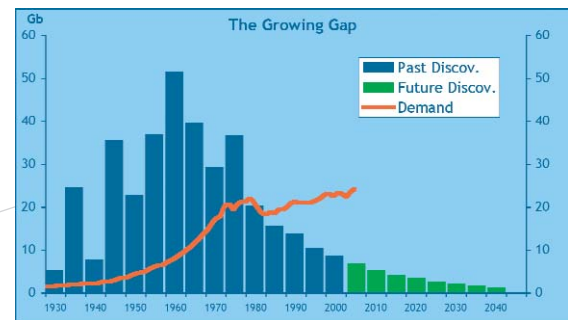


Figure 10. Conventional oil discoveries and production

As the world's production is the sum of the different regions' output, it will also go through a peak and decline. Although this is a widely accepted fact, the timing and the level of the peak, which ultimately depend on the URR, are the subject of intense dispute. Two camps arise in the controversy: the 'early toppers', predicting a peak before 2020 and below 100Mb/day (a view supported in this report), and the 'late toppers', stating the peak will not happen before 2030, when production will reach 120 Mb/day. Most 'late topper' studies, including the IEA's, use the USGS 2000 assessment for their forecast, thus incurring the inaccuracies discussed above.

If the supply forecast is to be matched with the demand projections, it must include all the sources that feed liquid hydrocarbons consumption, namely:

- Conventional oil
- Natural Gas Liquids (NGL)
- Unconventional oil: synthetic crude from oil sands and extra heavy oil
- Refinery processing gains and other sources: coal-to-liquids (CTL), gas-to-liquids (GTL), ethanol from biomass.

As a rough estimate to complete the forecast, the latter component's URR is set at 250 Gb in Laherrère's work [10], adding up to a total ultimate of about 3000 Gb⁴. A composed Hubbert-type forecast including global production from all 4 liquid sources shows a peak around 2014 (± 2 years) at around 90 Mb/day. Furthermore, the comparison with the projected liquids demand reveals a considerable gap reaching 40 Mb/day by 2030, or more than four times the current production of Saudi Arabia (Figure 11).

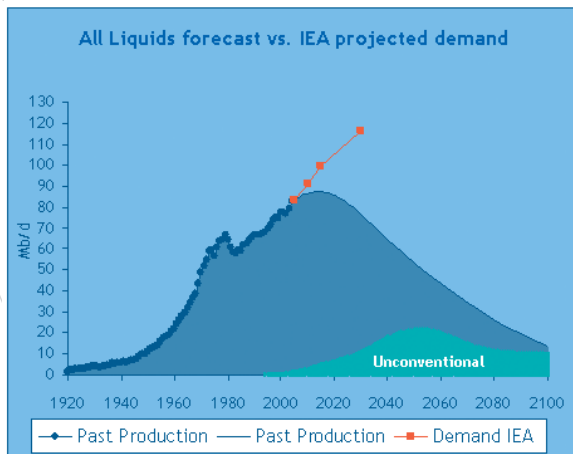


Figure 11. All liquids forecast vs. projected demand

Interestingly, even if unconventional resources were more abundant than expected they could not reverse the situation because they can not be deployed in time. Sure enough, as the larger fields decline, the supply is being eroded from its base. It must be stressed though that if the coming shortage causes prices to soar high enough to reduce demand below the forecasted supply line, the peak could be replaced by a 'bumpy plateau' with extremely volatile price cycles⁵.

The 'peak oil' phenomenon is clearly one of the most severe crises humanity faces, due to the world economy's addiction to fossil fuels. The lack of information that is delaying any constructive response can only worsen the problem.

5.0 GAS

Natural gas has been the fastest growing fossil energy source in the last two decades, boosted by its increasing share in the electricity generation mix. Moreover, it is expected to supply 23% of the world's energy needs by 2030. Gas is generally regarded as a largely abundant resource and public concerns about depletion are limited to oil, even though few in-depth studies address the subject. To determine whether gas will continue to play such an important role in the world's energy future, a comprehensive assessment of the available resource has been undertaken.

5.1 Natural gas resources

Contrary to popular belief, natural gas is not a poorly explored resource. In fact, gas exists in the same formations as oil or in exclusive reservoirs as non-associated gas and most reserves were found when exploring for oil. Moreover, gas resources are more concentrated than oil so they were discovered faster because a few massive fields make up for most of the reserves: the largest gas field in the world holds 15% of the URR, compared to 6% for oil.

Unfortunately, information about gas resources suffers from the same bad practices as oil data because the same stakeholders are involved. Most reserves are initially understated and then gradually revised upwards giving an optimistic impression of growth. In contrast, Russia's reserves, the largest in the world, have been stated to be overestimated⁶ by about 30%.

Owing to geological similarities, gas follows the same depletion dynamic as oil, and thus the same discovery and production cycles. Therefore, to gain a realistic insight into the situation of gas resources the procedure presented in section 4.2 is repeated: analysis of mean backdated discoveries from independent data sources, creaming curves, discovery-production shift. Unfortunately, existing data for gas is of worse quality than for oil and some ambiguities arise as to the amount of gas already produced, considering that flared and vented gas is not always accounted for. In general, information is poor, especially for unconventional resources, because gas is at an early stage in the depletion cycle.

As opposed to published reserves, the technical ones have been almost constant since 1980 because discoveries roughly matched production. This balance was broken in the past few years when discoveries failed to replace the consumed gas, opening a new gap (Figure 12).

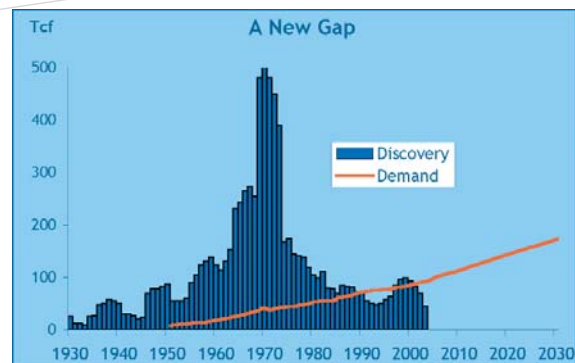


Figure 12. Gas discoveries and production

Based on the work of Laherrère [10] [16], the URR for conventional gas is estimated at 10,000 trillion cubic feet⁷ (Tcf), 90% of which has been discovered already. Unconventional resources, including coalbed methane, tight gas and gas shale, are calculated to yield another 2500 Tcf, although this figure bears a great deal of uncertainty (see Figure 13 and Figure 14). Methane hydrates were not included as recoverable resources because research does not indicate that a sizeable gas output could be obtained from them with a favourable energy balance in the foreseeable future. Annex B reviews unconventional gas resources in more detail.

4: These sources do not necessarily follow a Hubbert-type depletion dynamic and their share in the supply could be altered in the future as a result of aggressive deployment policies, as discussed in the last chapter.
 5: The US followed Hubbert's curve accurately because exogenous supply (imports) could fill the gap with demand, preventing prices from rocketing. The world, though, will not have an external oil source to rely on.
 6: The former Soviet Union's oil and gas reserves are treated as proved when in fact they are close to P10, as stated by Khalimov, the Russian expert.

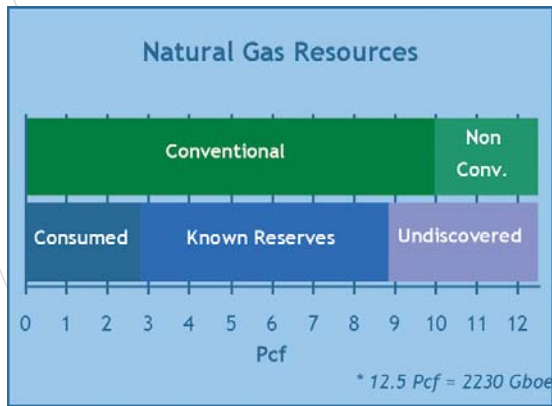


Figure 13. World natural gas resources

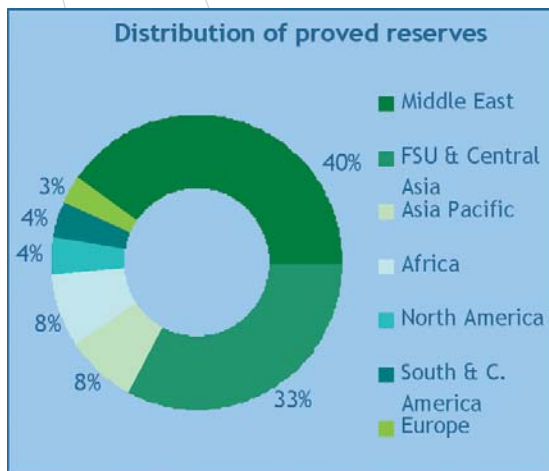


Figure 14. Distribution of proved gas reserves (from BP [17])

As in the case of oil, the URR estimated in this report is lower than the one considered in the energy outlook studies that are based on the USGS assessment of 15,400 Tcf of recoverable conventional resources. USGS' figures for undiscovered gas are very optimistic and, judging by the discovery trend, quite unlikely (see Figure 15).

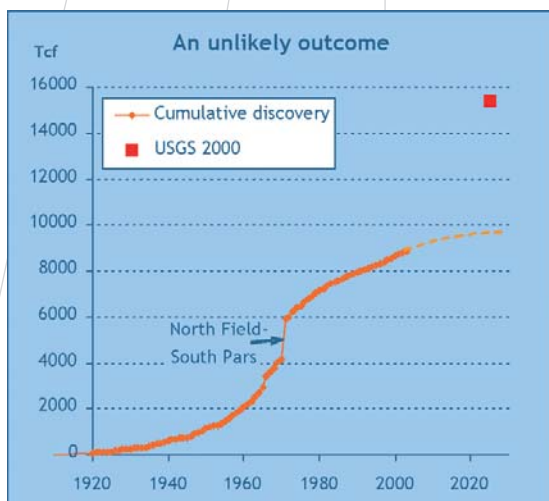


Figure 15. Conventional gas discoveries vs. USGS 2000 assessment

7: 10,000 Tcf ≈ 1800 Gb of oil equivalent

Once the resource has been evaluated it is possible to model future production.

5.2 Production outlook

Gas fields follow the same depletion dynamic as oil, meaning their production can also be modelled using Hubbert-type curves. The main difference is that their recovery rates are about twice those of oil because gas is lighter than air and flows more easily through the source rock pores, leaving less room for speculation on the enhancement of recovery by technology.

Figure 16 shows the production forecast for natural gas using a Hubbert model with an URR of 12,500 Tcf, peaking at about 140 Tcf/year around 2030. By then, the resulting gap with the projected demand would be equivalent to the current combined production of Russia and Africa. The world will still be producing as much gas as today in 2055, but the ambitious demand forecast will be impossible to meet.

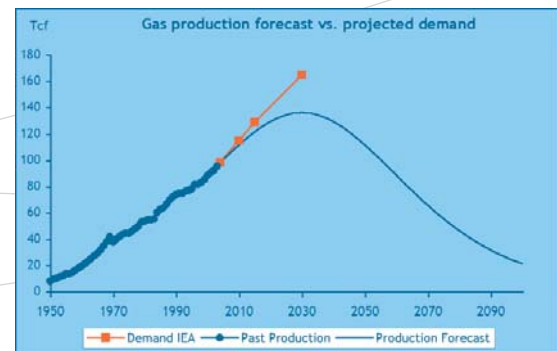


Figure 16. Gas production forecast vs. projected demand

As pointed out in the oil analysis, this forecast assumes that demand will not fall below the projected supply level as a result of an over-reaction to high prices. In practice, this might happen, and the production would plateau, postponing the decline.

The presented model deals with the world's production as a whole. However, gas is not a commodity traded as freely in a global market as oil. In fact, there is no such thing as a global gas market because transporting and storing it is expensive and requires a substantial infrastructure. Only 1/4 of the production is traded currently, as opposed to 60% for oil. Indeed, most countries consume the gas they can produce or import through pipelines. For regions without access to gas resources, the only option is to import Liquefied Natural Gas (LNG), which requires a specific infrastructure comprising liquefying and de-liquefying terminals at origin and destination and refrigerated tankers. As a result, there are currently 3 distinct gas markets with virtually no trade between them: North America, Eurasia and Asia Pacific, as shown in Figure 17.

LNG trade has been growing consistently in the past years and it will gradually merge the different markets into a global one, but it still represents only 7% of the gas demand today. So regions with an indigenous production approaching its peak might experience shortages well before the global peak, as LNG availability will be tied to the pace of capacity building and intense competition for supplies. That is indeed the case of the US, which is briefly reviewed in the following section as a telling example of the importance of accurately assessing depletion.

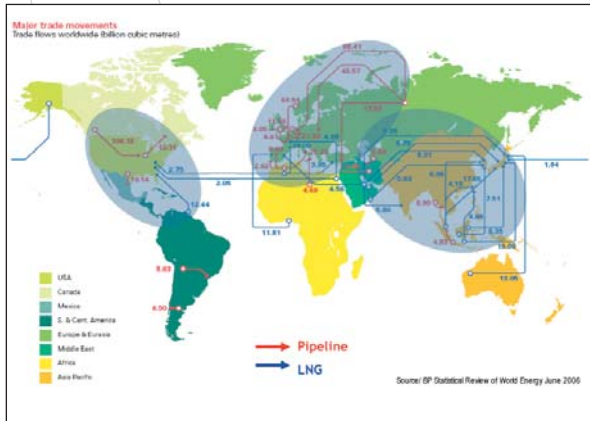


Figure 17. Gas markets and trade movement (from BP [17])

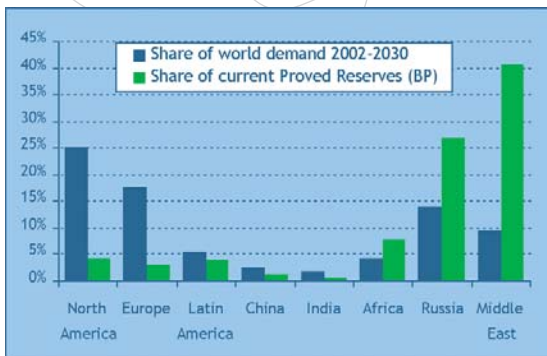


Figure 18. Distribution of gas demand and reserves⁸

5.3 Depletion and poor information: the case of gas in the US

US energy policy has become increasingly reliant on natural gas in the past 15 years. With the introduction of Combined Cycle Gas Turbines (CCGT), gas was assumed to be a clean, cheap and abundant fuel. As shown on Figure 19, 160 GW of gas-fired power plant capacity has been added since 1999. Government studies declared resources were adequate and forecasted a healthy, ever growing production, complemented by pipeline imports from neighbouring Canada.

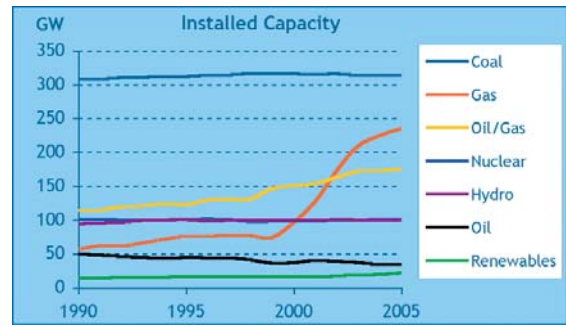


Figure 19. Installed capacity of US power plants

Reality quickly showed that gas fields were declining at higher and higher rates. In fact, it was only exploiting unconventional tight gas reservoirs through advanced technology that kept production from falling. In recent years, industrial users had to switch away from gas as high prices proved that increasing production could no longer be sustained, no matter how hard companies drilled. Moreover, it became evident that Canada could not deliver the expected growth either, as their own needs are rising (for the oil sands industry amongst others) and their production approaches its peak in the coming years. Figure 20, which plots the combined gas production of North America against the discovery trend shifted 23 years, suggests that the region is actually on a cliff edge and faces a steep decline in indigenous gas supply.

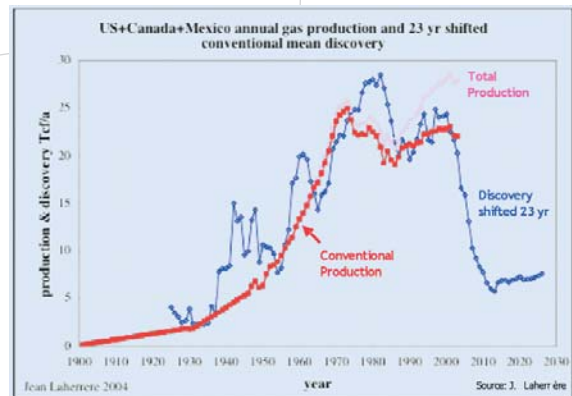


Figure 20. North American gas production vs. shifted discovery trend

Clearly, the US will need considerable amounts of imported LNG very soon. Only 4 LNG terminals exist so far, all on the East coast, and although many are planned, building permits are proving hard to obtain. According to the DOE, the US will need a 5 fold increase in its LNG capacity by 2015 (Figure 23).

An important lesson arising from the case of the US is that so-called 'official' forecasts can prove misleading and delay the prompt response required to deal with the problem of resource depletion. Figure 21, Figure 22 and Figure 23 show the consecutive forecasts from the EIA's Annual Energy Reviews for domestic gas production,

⁸ Proved gas reserves data (from BP) is shown in a qualitative basis as a proxy of the distribution of gas resources. The objections to public reserves data raised in previous sections hold true.

Canadian gas, and LNG imports. The projected trends reflect more and more the depletion reality, but still remain far too optimistic (comparing Figure 20 and Figure 21). Most probably, the US will require more LNG than expected and an intense capacity building schedule will be embarked upon. Otherwise, industrial consumers and power generators will be forced to switch back to more abundant and cheaper fuels, like coal.

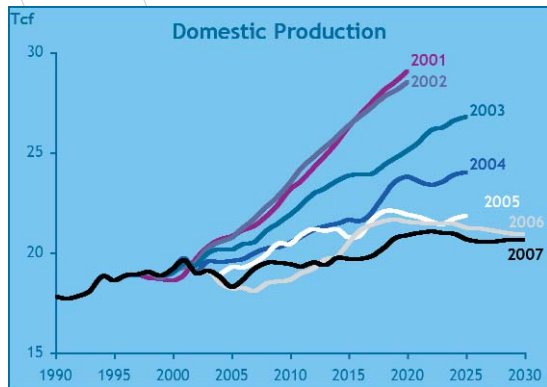


Figure 21. EIA's forecasts of domestic gas production

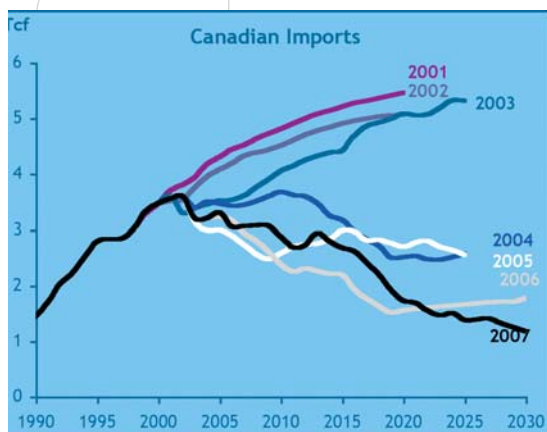


Figure 22. EIA's forecasts of Canadian gas imports

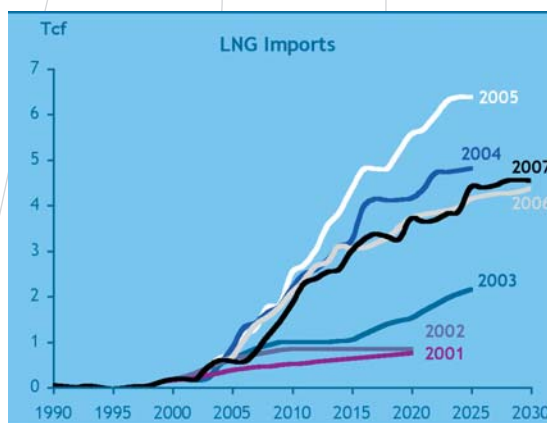


Figure 23. EIA's forecasts of LNG imports

6.0 COAL

Coal was the world's largest source of primary energy until it was overtaken by oil in the 1960s. Today, it provides 25% of the world's energy, a share it is expected to hold until 2030. Despite being the most abundant of fossil fuels, coal's development is currently threatened by environmental concerns, hence its future will unfurl in an uncertain range bound by energy security and global warming.

6.1 Coal resources

Coal is abundant and more equally distributed throughout the world than oil and gas. Global recoverable reserves amount to 909 Gtons [18], or about 3900 Gboe, and most countries have at least some. Moreover, existing and prospective big energy consumers like the US, China and India are self sufficient in coal and will be in the foreseeable future, unlike for oil and gas (see Figure 24).



Figure 24. Distribution of coal reserves

Coal fuelled the Industrial Revolution and has been exploited on a large scale for two centuries so both the product and the available resources are well known; no substantial new deposits are expected to be discovered. Extrapolating the demand forecast, the world would consume 23% of its current reserves by 2030 and 45% by 2050. Hence, if the current trends are maintained, coal would probably last to the end of the century, but not beyond.

6.2 A growing market

After a decade of stagnation that saw China and India's growth offset the decline of Europe and the Former Soviet Union's production, the coal market has boomed since 2000, with China doubling its output in 4 years to become the clear market leader and driver, with a 38% share.

Two thirds of the coal consumed today is used for power generation, while the remaining, higher quality, production goes mainly to the steel industry. Moreover, coal is the leading source for electricity production in the world (39%

share), and especially so in fast growing countries like China (77%) and India (70%), as shown in Figure 25. China is now building 15 GW of coal-fired power stations a year to supply electricity to the 700 million people that were connected to the grid since 1990. These booming, coal-fuelled nations have seen their electricity demand more than double and triple respectively since 1990, and yet have a long way to go to reach the per capita consumption level of mature economies (see Figure 27 and Figure 27).

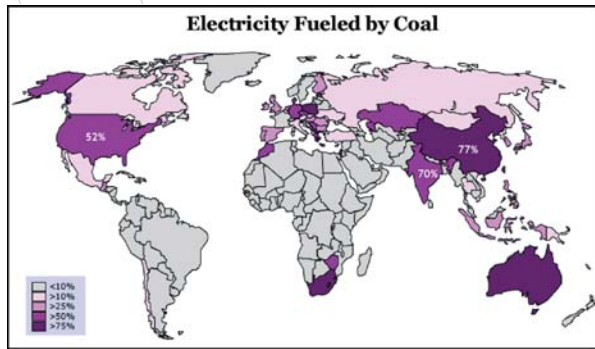


Figure 25. Share of coal in the electricity production mix

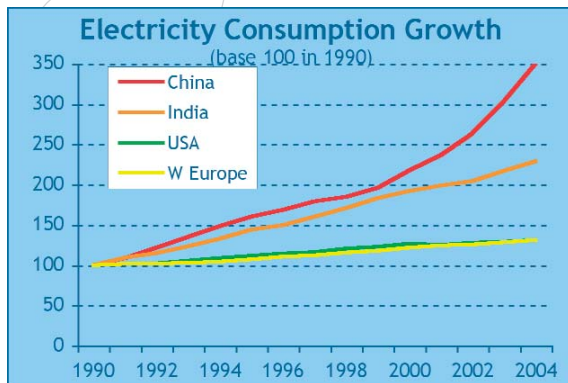


Figure 26. Electricity consumption growth

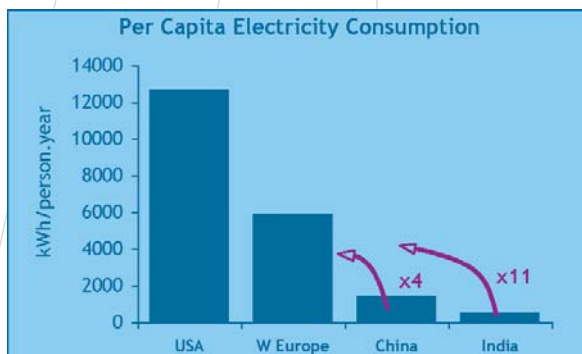


Figure 27. Per capita electricity consumption

China and India's growing demand, unrestrained by the lack of internationally binding emissions targets, is widely recognised in most forecasts. However, in western

countries the environmental issues associated with coal are containing its development, because of formal emissions targets or the fear of future restrictions and carbon taxing schemes. Nevertheless the rise of two technologies could steer a transition to a new coal era, boosted by the scarcity of oil and gas, the resulting high energy prices and growing concerns of energy security and independence. These are 'clean coal' technologies and coal-to-liquids.

6.3 Alternative technologies

'Clean coal' refers to a series of new technologies that aim at reducing the specific emissions of coal-fired power plants and ultimately eliminating them. The first step in this strategy is reducing emissions by improving thermal efficiency. On average, currently installed coal power plants have an efficiency of around 30%⁹ and emit about 1 kg of CO₂ per kWh generated, compared to 45-50% efficiency and 0.5kg CO₂/kWh for Combined Cycle Gas Turbines (CCGTs). However, recently a new generation of high efficiency coal plants have begun to be installed worldwide.

Supercritical steam cycle plants work at higher pressures and temperatures, reaching efficiencies of 40-45%. Ultrasupercritical cycles, under development, will take efficiency beyond 50%, further reducing emissions. However, it should be noted that these advances can only aspire to approach the emissions levels of natural gas (Figure 28).

On the other hand, the recently developed Integrated Gasification Combined Cycle (IGCC) achieves efficiencies 5% higher than supercritical cycles through a different and promising technology. Coal reacts with steam to produce a synthetic gas ('syngas') formed of hydrogen, carbon monoxide, and some methane, that is burnt in a specially designed gas turbine fitted in a combined cycle. Thereby, the syngas can be cleaned before it ever goes through the turbine and SO_x and NO_x emissions are greatly reduced.

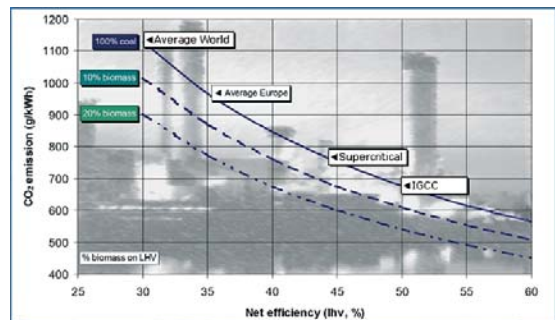


Figure 28. CO₂ emissions and thermal efficiency

What is more, IGCC paves the way for the final step towards zero emissions: Carbon Capture and Storage (CCS) (also sometimes referred to as carbon sequestration). Indeed, carbon concentration in syngas is significantly higher than in the flue gases, which makes it easier to capture by first reacting the syngas with steam to transform CO into CO₂. This way, carbon is separated before combustion (pre-combustion capture) and the input of the turbine is only hydrogen. (Figure 29). Other capture schemes have been devised, such as oxyfuel combustion and post-combustion, but the former is less developed and the latter less efficient than the pre-combustion process.

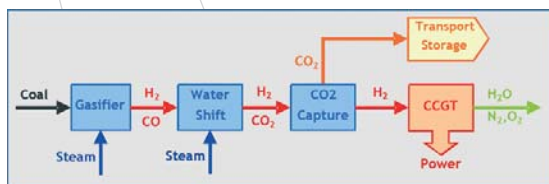


Figure 29. IGCC with pre-combustion carbon capture

Once CO₂ has been captured, it must be transported through pipelines and safely stored underground so that it does not reach the atmosphere. Three storage options are considered:

- *Depleted oil and gas reservoirs:* this option is being used in the US as part of an Enhanced Oil Recovery (EOR) operation
- *Deep saline aquifers:* a pilot project is running in the North Sea
- *Unmineable coal seams:* still at research stage

It must be stressed that CCS is currently at an R&D stage and uncertainties persist as to the potential chemical and physical interactions of CO₂ with the storage medium. No mature technology exists for CCS today, but coal-rich countries like the US are investing heavily to develop it and aim at having a demonstration project in the coming years.

According to a DTI (UK) study [20], CCS costs for a new IGCC plant are estimated at 97 €/tonne of abated CO₂, including the cost of the energy used in the process. In terms of electricity cost, a carbon-free kWh generated in such plant would cost 3.9c€ more than one produced by a modern CCGT. Clearly, CCS will not develop without incentives but a support scheme will not be easily established, as nuclear generators could probably claim for similar premiums. However, costs are expected to be reduced as capture technology improves. Financial returns from EOR could further ease the burden.

The second technology that is likely to boost coal use is

coal-to-liquids (CTL). Actually, CTL is not a new process. Hydrocarbons have been produced from coal in the past when special circumstances interrupting the oil supply justified the extra cost. Germany used CTL during World War Two to provide for 90% of its oil needs. So did South Africa during the apartheid embargo and it remains today the leader in this technology with a production of 0.16 Mb/day. CTL relies on the very same gasification technique described above, followed by the Fischer-Tropsch process to transform syngas into gasoline, diesel and other light hydrocarbons. The process is capital and energy intensive (40% of the energy is spent in the conversion), so costs are high: the US DOE estimates around \$30/b. Potentially, CTL has the great advantage of providing medium-term energy security to coal-rich countries currently dependent on Middle East oil.

CTL's contribution to the world oil supply will not be significant in the near future and it will by no means replace the decline of oil production, but it is still a promising long term option because it can be combined with electricity production in IGCC plants. Indeed, the polygeneration concept envisions a coal gasification plant producing electricity, liquid fuels and hydrogen with no emissions using CCS. At present, the South African CTL plant is the largest single greenhouse gas emitter in the world, so CTL would face important environmental barriers elsewhere without carbon sequestration.

9: Coal power plants in the OECD average 38% efficiency, but developing countries have older, less advanced technologies. China in particular, with 27% efficiency, affects the global average [19].

7.0 NUCLEAR FUEL

Nuclear energy currently provides 16% of the world's electricity and is a major electricity source in Europe. It stands today at the centre of an intense debate over its future, with environmental and cost concerns leading to a phase out in many countries and talks of a renaissance in support of emissions targets and energy security in others. However, the adequacy of nuclear fuel resources to cope with the expected demand or resurging growth is an issue generally ignored in the discussion.

7.1 An unusual market

Following the present trend, fuel consumption of conventional nuclear reactors is not expected to change significantly, as higher capacity factors counteract efficiency gains. Thus, global fuel requirements will depend primarily on the nuclear installed capacity. As building nuclear power plants is essentially a political decision, any fuel demand forecast bears a great deal of uncertainty. However, available forecasts [1][21] generally agree on the following trends, which balance each other resulting in a flat or slowly growing demand:

- Western Europe is phasing out its nuclear programmes, except for France which will maintain its pro-nuclear policy, and the UK which is currently debating whether to replace its ageing fleet of reactors
- North America has extended plant life cycles considerably and will maintain its capacity
- East Asia (Japan, South Korea, China, India) will build new reactors to cope with soaring electricity demand, as gas is not a realistic option

Figure 30 compares the IEA's nuclear capacity forecast with that of the OECD Nuclear Energy Agency ([21], known as the 'Red Book').

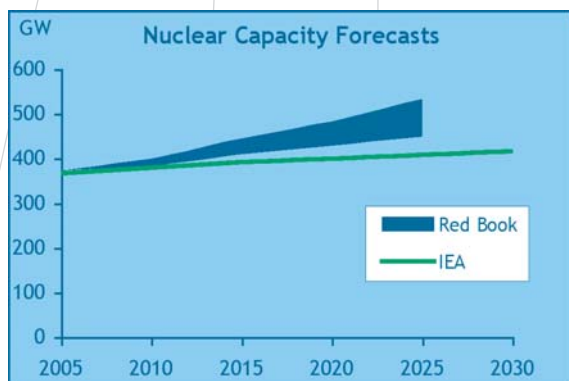


Figure 30. Nuclear installed capacity forecasts

Although such a demand range would not a priori seem to put much pressure on the supply side, the uranium market has developed in a peculiar way that now threatens the availability of supplies in the medium term. Indeed, only 60% of the 67,000 tons of uranium consumed in 2004 came from mines; the remaining 40% was supplied by military stockpiles (from nuclear weapons programmes), civil inventories (from privatised utilities mainly) and re-enriched spent fuel. The availability of these secondary uranium sources in the market has kept production and prices at a low level for the last 15 years, deferring investments in new mining capacity (Figure 31).

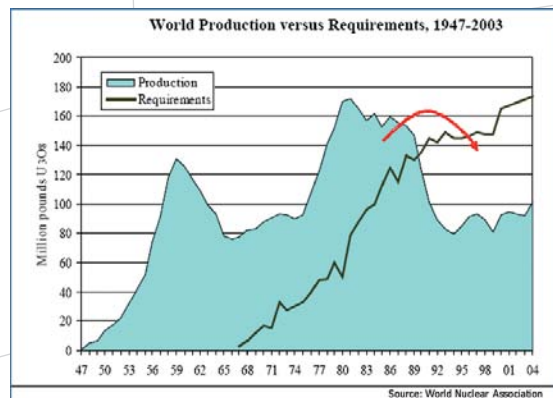


Figure 31. Uranium historical production vs. requirements [22]

Unsurprisingly, information about stockpiles is scarce because both military and civilian stockholders consider it confidential, but they are believed to run out before 2020 [21]. On the other hand, new mining projects usually have a lead time of 10-25 years between the concession of an area and the beginning of production, as shown in Figure 32. The combined effect of insufficient production capacity (Figure 33), long lead times and dwindling stockpiles points to a probable medium-term shortage.

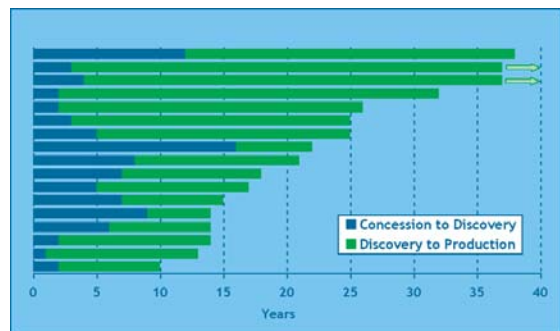


Figure 32. Lead times in the largest uranium mining projects

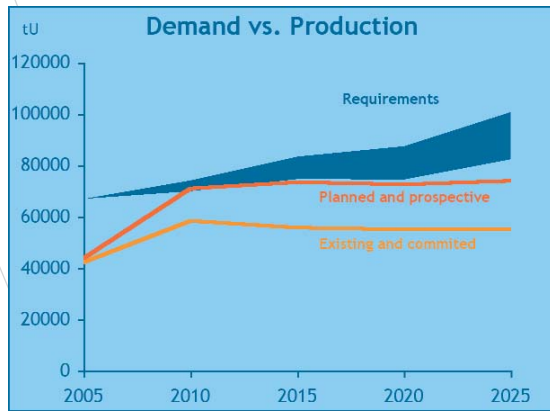


Figure 33. Uranium requirements and effective production capacity (85% of nominal)

As the market has started to realise the possibility of a shortage, the uranium price has increased 5-fold in the last 2 years after more than a decade of relative stability (Figure 34). With the late news that some countries (UK, Germany) might reconsider the nuclear option and recurrent mine floods, spot prices have soared. The market is already reacting and exploration expenses have resumed. Producers are now expecting to expand capacity by 30% by 2010. Whether this challenging schedule will be met remains to be seen.

However, it is important to understand that the cost of uranium makes up for less than 5% of the generation cost of a nuclear power plant, so prices still have room for further excursions. Still, if the shortage materialises, it could advance the decommissioning of the older power plants.

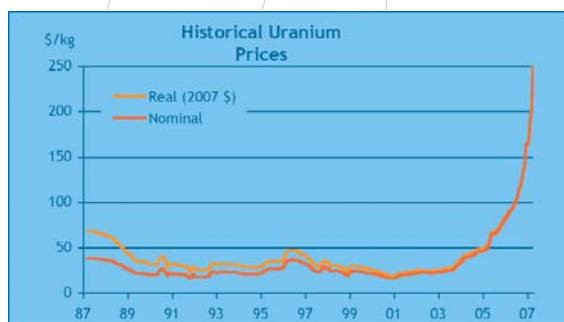


Figure 34. Uranium price

Needless to say, the market fundamentals will end up balancing supply and demand, but a period of extremely high uranium prices and physical shortage could undermine an incipient nuclear renaissance, by eroding its political and public support.

7.2 Uranium resources

Like most minerals, uranium occurs naturally in a range of concentrations with an associated range of extraction costs. Thus, resources are generally classified in cost categories. As the nuclear industry is made up of only a few players, the only comprehensive information source on uranium resources is the Red Book [21], that relies on information submitted by governments. Table 4 summarises its findings.

Cost Category	Million tonnes
<130\$/kgU	4.74
<80\$/kgU	3.80
<40\$/kgU	>2.75

Table 4. Known conventional uranium resources

Given the current price level, all of these categories must be considered to assess future availability. Hence, in the highest of the demand scenarios presented above (Red Book's high end), current reserves would last about 60 years, which is the lifetime of a new generation of nuclear reactors. This 'high case' scenario should not be confused with a nuclear renaissance; in fact, the share of nuclear power in the electricity mix drops continually even in this forecast.

Although reserves are expected to grow in the coming years as high prices revitalise exploration, alternative sources would clearly have to follow in the long-term, especially if a new generation of reactors is built.

7.3 Alternative resources

The first technology to be deployed in order to secure the future supply of uranium will most probably be enhanced fuel recycling. Technology improvements have already been identified to extend the reutilisation beyond the current point of one single recycling (if any at all), allowing multiplication of the existing resource base.

Next, uranium can be recovered from phosphates, of which substantial resources, believed to total 22 million tonnes, exist. The technology is now mature but development has not kicked off because the extraction costs, around 100 \$/kg, could not be justified in the recent background of abundant cheap uranium.

In addition, thorium might also be used as a nuclear fuel in fast reactors. Countries holding significant thorium resources but no uranium, such as India, are considering developing this fuel cycle. Global resources are estimated to match those of conventional uranium at least.

Intense R&D efforts have been carried out for many years to develop fast breeder reactors, which would decrease uranium requirements by up to 60 times, but no success was met at a commercial level and research programmes are being abandoned in many countries, in the midst of

safety concerns over decommissioning and proliferation. In any case, a new generation of fast breeders would certainly not come online before 2030.

Finally, seawater has been widely publicized as an alternative source. The world's oceans hold about 4000 million tonnes of uranium in very low concentrations. While laboratory tests have successfully recovered very small amounts through adsorbing tissues, large scale extraction plans involve massive offshore structures covering immense areas [23]. The chances of this technology being developed are extremely low, considering that the sea surface will have more attractive uses in terms of revenue density, including energy production by offshore wind power, tidal and wave power.

In brief, unconventional uranium resources seem adequate to cope with demand in the long term, although substantial R&D and capital investments are required for them to reach the market.

8.0 IMPLICATIONS

The assessment presented above shows that the expected energy demand for oil and gas cannot be supported by the resource base. A growing gap between supply and demand emerges in each of these two sources that the IEA suggests will provide more than half of the world's energy in 2030. If a crisis is defined as 'a crucial stage or turning point in the course of something'¹⁰, then there is certainly one looming. Clearly the energy mix will need to change drastically in the coming decades. But as in every crisis, many opportunities will arise, and wind energy has the potential to provide an important part of the solution.

8.1 Supply-demand gaps

Figure 35 merges the supply-demand projections of the different energy sources. The gaps in oil and gas supply become evident after 2010. Combined, they represent 8% of the primary energy demand in 2020 and 15% by 2030.

In the case of nuclear fuel, the supply gap cannot be calculated because no reliable information exists about the remaining stocks. For the same reason, it is unclear whether market fundamentals will encourage the needed expansion of production capacity in time. Hence, a thorough review of the exploitable nuclear fuel from stocks would be of great value in keeping policy makers from making the wrong choice in the nuclear debate.

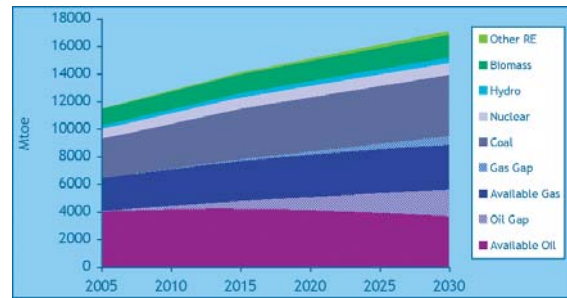


Figure 35. Primary energy: oil and gas supply gaps in IEA's projected demand

The oil gap is the most urgent and certainly the hardest to fill because no alternative liquid fuels have been developed on a large scale so far and the time to do so is running out. As demonstrated in a study sponsored by the US DOE [24], only a crash programme starting now could prevent a major global economic blow caused by oil peaking, but the issue has so far failed to gather the necessary political momentum. Eventually, the oil gap will be filled by a mix of:

- demand destruction and vehicle efficiency (a minimum 10-year lag is needed for the latter)
- liquids from coal (CTL) with or without CCS, depending on environmental policy
- biofuels
- natural gas through liquids (GTL), Natural Gas Vehicles (NGV) or hydrogen fuel cells from gas reforming

Figure 36 illustrates by how much the per capita oil consumption should be reduced if no alternative sources were developed beyond the scope forecasted in this paper and demand reduction absorbs the gap completely. This also suggests that developing countries like China and India will be the most affected because they are the ones who are still climbing the 'energy ladder' and are responsible for the expected rise in the global average consumption rate.

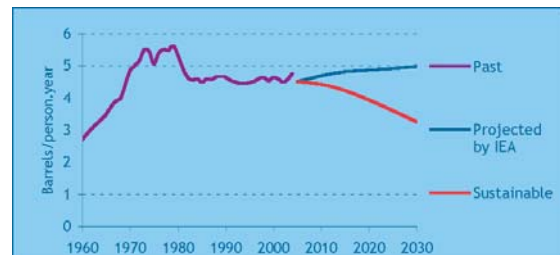


Figure 36. Per capita oil consumption

¹⁰: definition from WordReference.com English dictionary

Although gas production does not peak until 2030, the gas gap opens up as soon as 2015 and already accounts for 16% of the demand in 2030. In time, it will be filled inevitably with a mix of:

- Demand destruction and efficiency
- Coal with or without CCS, depending on environmental policy
- Power generation from all renewable energies
- Heat generation from biomass and solar thermal
- Nuclear power

In any case, the immediate consequence of these gaps is a new, higher base level for all energy prices. That will indeed be the mechanism by which some of these alternatives (including demand destruction) will prevail over the others, although regulatory policies will also play a decisive role. Forecasting energy prices beyond the short term is extremely complex and exceeds the scope of this report. However, exposing the potential scale of the role of wind energy in helping meet these imbalances would be a useful starting point for policy making and business planning.

For further analysis, and as a helpful follow-up to this work, the author recommends devising future energy mix scenarios with the alternatives described above.

8.2 Opportunities for wind energy

Wind energy has been the fastest growing energy source of the last decade, at an annual rate of 28%. Today, the installed capacity has reached 75GW, nearly two thirds of which is located in Europe. Developing countries are virtually untouched markets, except for India (1840 new MW in 2006). As wind power is still marginally more expensive than coal and gas-fired generation in most countries, its impressive development had to rely on incentives that acknowledged its advantages over conventional power sources in terms of environmental impact, and energy security to a lesser extent. These incentive schemes, in all their diverse forms, are ultimately paid for by electricity consumers.

As successful as the incentive mechanisms have been in countries like Germany, Denmark and Spain, the lack of similar support has prevented or slowed down the development of wind energy almost everywhere outside Europe. The IEA is not very optimistic about overcoming the barriers against wind energy, predicting a cumulative installed capacity of 430 GW by 2030. The Global Wind Energy Council (GWEC) believes support schemes will be maintained in the future and will spread gradually to new markets in and outside Europe. In its Moderate scenario described in "Global Wind Energy Outlook 2006"

[25], the installed capacity reaches 1129 GW in 2030. This sustained growth projection is based on the assumption that targets set by many countries for wind energy are successfully met by replicating the European policies globally. In the Advanced scenario (similar to GWEC's Wind Force 12 study [26]), they assess how far wind energy could penetrate in the energy mix if radical policy reforms such as legally binding targets and internalisation of environmental costs are implemented worldwide. As a result, installed capacity grows to 2107 GW in 2030.

An important point should be made here: none of these scenarios take into account the supply gaps described above. The potential for wind power development relies mainly on the deployment of favourable regulatory policies. But the premature scarcity of fuel resources could pave the way for a rapid and market-driven deployment of wind power.

According to the IEA, electricity generated by gas-fired power plants will double in the next 25 years, as CCGTs will be the production unit of choice. Indeed, more than half of the total increase in gas demand during that period will come from power plants. But as this paper shows, gas resources are not sufficient for such an increase. If final consumers (residential, commercial and industrial) are to be addressed first, there would not be enough gas to fuel the projected gas-fired power plants (Figure 37). In fact, out of the 1300 GW of new capacity additions planned to 2030, the supply base could only support 350 GW, leaving a gap of 950 GW for other power sources (Figure 38).

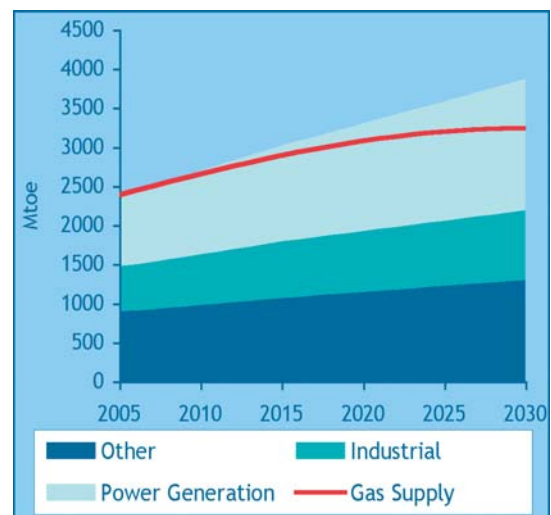


Figure 37. Gas demand by sector vs. available supply

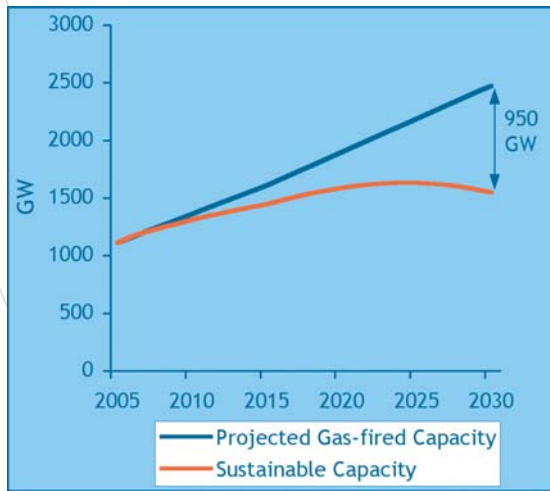


Figure 38. Gas-fired power generation capacity, projected vs. sustainable

Thus, the gas gap offers an enormous additional potential for wind power that is not accounted for in the traditional wind capacity forecasts. This potential is technically realisable, as GWEC's studies show. Eventually market dynamics would end up raising gas prices in a way that would make wind energy cost-competitive because fuel costs account for around 70% of the generation cost of CCGTs. Although wind power would have to vie against other alternatives for this new market, it clearly stands in a privileged position as one of the most cost-effective. Figure 39 compares the extra potential arising from the gas gap with GWEC's Moderate and Advanced scenarios¹¹.

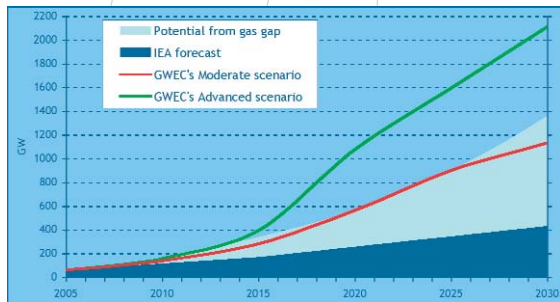


Figure 39. Wind energy capacity projections and potential extra capacity due to gas unavailability

Indeed, most of the policy measures required to boost wind energy development from the IEA's scenario to GWEC's, while needed in the short to medium term to build industrial capacity, will in time be made redundant by high fuel costs. This is especially true for policy reforms aiming at levelling the playing field in the electricity market and improving wind power competitiveness, but not so much for measures targeting the effectiveness of practical implementation, such as improving grid access procedures and grid integration management. However, as wind power becomes a mainstream electricity source, eliminating these

constraints will be in the interest of a greater number of key players in the energy market, including those who compete with wind power today. This interesting shift in balance is already being observed in Europe and the US as big utilities are starting to invest heavily in wind energy and to work for the operational mitigation of its large scale integration. Yet, whether this same dynamic will help to attract the necessary investments into new grid capacity for the expected offshore wind power development remains to be seen.

By comparing forecasts at a global level, Figure 39 suggests wind energy has the potential to supply up to 950 GW of extra capacity arising from the gas gap, on top of IEA's expectations. But, will the opportunities created by gas unavailability occur in markets with limited wind power potential? This does not appear to be the case. The regions with greatest imbalance between gas demand and indigenous resources will be North America and Europe. These are also the regions that show the best potential for wind energy and renewables in general, in terms of resource, investment capacity and political momentum. In GWEC's Advanced scenario, 45% of the achievable capacity corresponds to North America and Europe. Thus, regional distribution will not limit the ability of wind power to benefit from the gas gap opportunities.

In contrast with gas, there will be more limited implications in the case of the oil gap. Although oil still provides 7% of the world's electricity, its share is expected to fall to 3% by 2030. Judging by the size of the oil gap and the consequent price increase, this share will drop much faster and might disappear. However, oil-fired generation is frequently used in isolated networks and self-generating industrial facilities and this may lead to increased take up of wind in such situations. In addition, the oil gap will certainly affect wind energy in a more indirect way by absorbing part of the gas supply as a substitute for heating oil for example or in the form of GTL products, thus further increasing gas and electricity prices. A quantitative analysis of these fuel substitution interactions in a subsequent study would be helpful.

¹¹ In fact, the potential for wind power could be even greater because in these calculations the capacity factor of gas-fired power plants is around 37%, which is the actual factor today and in IEA's projections. As the average capacity factor of wind farms is slightly lower than that, more MW would be needed to replace the gas power plants.

9.0 CONCLUSIONS

- The world's energy resources are not sufficient to sustain the expected growth trends. The current fuel mix will change significantly in the medium term future as a growing gap develops between the expected demand and the available supply of hydrocarbons.
- Energy prices have reached a new peak from which they can only recede temporarily.
- Unless oil demand growth recedes swiftly, production will peak in the next decade and decline ever after. Unconventional sources will not compensate for the massive supply gap.
- Natural gas production will peak 15 years later and will not be able to supply the necessary additions of power generation capacity.
- Coal is seen as a cheap and safe option by most energy-hungry countries. If CCS is successfully developed, coal could become a clean multifunctional fuel and might take over as the main energy source in the future.
- Nuclear power faces a potential but transitory medium-term shortage that could threaten its further development. A nuclear renaissance would require substantial investments to tap alternative fuel sources or enhance fuel recycling.
- Energy efficiency will be critical, as the world is late in developing fuel substitutes and sustainable alternatives.
- There will be no such thing as a 'business as usual' future. An unforeseen potential will become available to wind energy as a result of gas supply limitations. Up to 950 GW of extra capacity could potentially be installed by 2030.

10.0 REFERENCES

- [1] International Energy Agency, "World Energy Outlook 2006" (WEO2006), OECD/IEA, 2006.
- [2] Energy Information Administration, 'International Energy Outlook 2005' (IEO2006), Report #:DOE/EIA-0484(2005), July 2006.
- [3] European Commission, 'World energy, technology and climate policy outlook 2030 - WETO', European Communities, 2003.
- [4] K. Aleklett, C. Campbell, 'The Peak and Decline of World Oil and Gas Production'. Uppsala University, Sweden, ASPO web site, 2003.
- [5] C. Campbell, J. Laherrère, 'The End of Cheap Oil', Scientific American, March 1998.
- [6] E.M. Khalimov, 'Classification of Oil Reserves and Resources in the Former Soviet Union', AAPG Bulletin 77/9, 1993.
- [7] C. Campbell, 'The End of the First Half of the Age of Oil', 4th International Workshop on Oil & Gas Depletion, ASPO, Lisbon, May 2005.
- [8] J. Laherrère, 'Forecasting Discovery from Production', 4th International Workshop on Oil & Gas Depletion, ASPO, Lisbon, May 2005.
- [9] J. Laherrère, 'Future of oil supplies', Seminar Center of Energy Conversion Zurich, May 2003.
- [10] J. Laherrère, 'Peak oil and other peaks', ASPO, October 2005
- [11] K. Chew, IHS Energy, 'Global Oil Supply Issues: Global Oil Supply Issues: Recent Trends and Future Possibilities', APPEX London Global Perspectives Forum, March 2005.
- [12] P. Stark, K. Chew, IHS Energy, 'Global Oil & Gas Resources: A View from the Bottom Up', May 2004.
- [13] P. Stark, K. Chew, I. Cross, IHS Energy, 'Global Exploration Trends & Outlook', Second International Petroleum conference & Exhibition, Cairo, May 2005.
- [14] US Geological Survey, 'World Petroleum Assessment 2000 – description and results', 2000.
- [15] Royal Dutch/Shell Group, 'Shell Global Scenarios to 2025', Shell International Limited, 2005.
- [16] J. Laherrère, 'Future of Natural Gas Supply', 3rd International Workshop on Oil & Gas Depletion, ASPO, Berlin, May 2004.
- [17] BP, 'BP Statistical Review of World Energy June 2006', June 2006.
- [18] World Energy Council, '2004 Survey of Energy Resources', World Energy Council, 2004.
- [19] World Coal Institute, 'The Coal Resource: A Comprehensive Overview of Coal', May 2005.
- [20] UK Department of Trade and Industry (DTI), 'Review of the Feasibility of Carbon Dioxide Capture and Storage in the UK', September 2003.
- [21] OECD Nuclear Energy Agency and International Atomic Energy Agency, 'Uranium 2005: Resources, Production and Demand', OECD Publications, 2005.
- [22] Combs J., 'Fueling the Future, A New Paradigm – Assuring Uranium Supplies in an Abnormal Market', WNA, Sep. 2004.
- [23] T. Sugo, M. Tamada, T. Seguchi, T. Shimizu, M. Uotani, R. Kashima, 'Recovery System for Uranium from Seawater with Fibrous Adsorbent and Its Preliminary Cost Estimation', Nihon Genshiryoku Gakkaishi- Journal of the Atomic Energy Society of Japan, Vol. 43, No. 10, 2001.
- [24] R. Hirsch, R. Bezdek, R. Wendling, 'Peaking of Oil Production: Impacts, Mitigation and Risk Management', February 2005.
- [25] Global Wind Energy Council (GWEC), 'Global Wind Energy Outlook 2006', September 2006.
- [26] Greenpeace, EWEA, 'Wind Force 12', May 2004.
- [27] Petróleos de Venezuela S.A.(PDVSA), 'Planes Estratégicos: Faja Petrolera del Orinoco', August 2005.
- [28] Alberta Energy and Utilities Board, 'Alberta's Reserves 2004 and Supply/Demand Outlook 2005-2014', ST98-2005, September 2005.
- [29] National Energy Board, 'Canada's Oil Sands Opportunities and Challenges to 2015. An Energy Market Assessment', ISBN 0-662-36880-0, May 2004.
- [30] Alberta Chamber of Resources, 'Oil Sands Technology Roadmap: Unlocking the Potential', January 2004.
- [31] B. Söderbergh, 'Canada's Oil Sands Resources and

Its Future Impact on Global Oil Supply', Uppsala University, 2005.

- [32] J.W. Bungler, P.M Crawford, H.R. Johnson, 'Is oil shale America's answer to peak-oil challenge?', Oil & Gas Journal, August 2004
- [33] J. Laherrère, A. Perrodon, C. Campbell, 'The world's gas potential', Petroconsultants report, 200p, CD-ROM, July 1996 (Conclusions confirmed in and quoted from [16])
- [34] A.V. Milkov, 'Global estimates of hydrate-bound gas in marine sediments: how much is really out there?', Earth-Science Review 66 (3-4) pp. 183-197, 2004.
- [35] C.P. Thomas, 'Methane Hydrates: A Major Energy Source for the Future or Wishful Thinking?', SPE Distinguished Lecture Series 2001-2002.

GLOSSARY OF TERMS

All Liquids – All the refinery feeds used to make petroleum-derived products, which add up to the figure widely quoted as ‘oil production’. It includes conventional crude oil, natural gas liquids, refinery processing gains, biomass additives (ETBE, MTBE, ethanol) and synthetic crude from unconventional oil, CTL and GTL.

ASPO – Association for the Study of Peak Oil & Gas

boe – barrels of oil equivalent

Carbon sequestration – capture and secure storage of CO₂ that would otherwise be emitted to or remain in the atmosphere. This could be achieved through CCS, to capture CO₂ before it is released in the atmosphere, or by enhancing the natural uptake of atmospheric CO₂ of terrestrial ecosystems (forests, microbes, oceanic plankton).

CCGT – Combined Cycle Gas Turbine

CCS – Carbon Capture and Storage – capture and secure storage of CO₂ that would otherwise be emitted to the atmosphere. CO₂ is separated from exhaust gases of chemical, industrial or power generation plants and pumped into underground geological reservoirs for its long term storage. CCS is also referred to as carbon sequestration.

Clean coal – refers to a series of new technologies that aim to reduce and ultimately eliminate the specific emissions of coal-fired power plants

Coalbed methane – methane trapped in coal seams that can be extracted for use

Creaming curve – a parabolic-shaped curve plotting the cumulative amount of oil or gas discovered as a function of the exploratory wells drilled. It allows the URR to be estimated.

Crude oil – petroleum in its unrefined state

CTL – coal-to-liquids – a process that transforms coal through gasification to syngas and then to gasoline, diesel and other light hydrocarbons

DOE – United States Department of Energy

Drilling logs – geological records and assessments of oil resources compiled by the industry

Early toppers – in the open debate about the peaking of world oil production, the participants who believe the peak will occur before 2020 at less than 100Mb/day

EHO - extra-heavy oil – found in the Orinoco belt in Venezuela, a heavy hydrocarbon recovered by cold extraction and needing to be pre-treated (to form syncrude) before it can be fed to refineries

EIA – DOE’s Energy Information Administration

EOR – enhanced oil recovery - the stimulation of oil wells beyond conventional recovery methods by injecting steam, gases, or solvents to improve production rates

EWEA – European Wind Energy Association

Fast breeder reactors – a nuclear reactor using fast neutrons which produces at least as much fissionable material as it uses.

FSU – Former Soviet Union

Gas shale – shale reservoirs that contain natural gas as a free gas within rock pores adsorbed on organic material or as free gas within the system of natural fractures

Gb – gigabarrels, or billion barrels

GTL – gas-to-liquids – a process that transforms natural gas to synthetic petroleum

GW – gigawatt

Hubbert’s curve – A logistics curve (bell-shaped) used to model the production of an oil well or region over its lifecycle, first postulated by geologist Dr. King Hubbert

IEA – International Energy Agency (part of the OECD)

IGCC – Integrated Gasification Combined Cycle

Late toppers – in the open debate about the peaking of world oil production, the participants who believe the peak will not happen before 2030 and production will exceed 120Mb/day

LNG – liquefied natural gas

Mb – million barrels

Methane hydrates – A solid compound of methane and water found under some sub-sea continental shelves and arctic permafrost. It has been postulated as a future source of natural gas.

MW – megawatt

NGL – Natural Gas Liquids

Oil and gas resource terms:

- **Technical discoveries** - the history of resource discoveries, taking the mean (mathematical expectancy) recoverable amounts and backdating subsequent revisions to the original discovery date
- **Discovered** - the cumulative amount of technical discoveries
- **Produced** - cumulative amount produced up to now, including losses and resources used in the process
- **Known reserves** – the difference between the discovered and produced amounts
- **Yet-to-find** – the difference between the URR and the discovered amount

Oil sands – a mix of sand and bitumen, at the end of the heavy oil spectrum, extracted by mining or in situ thermal recovery

Oil shale – a solid fine-grained sedimentary rock containing organic matter, similar to coal, which is processed to extract a viscous heavy oil

OPEC – Organisation of Petroleum-Exporting Countries

Orimulsion – a mix of EHO and a solvent.

Syngas – synthetic gas, formed of hydrogen, carbon monoxide and methane. When burnt in a specially designed gas turbine fitted in a combined cycle, it generates electricity with fewer SO_x and NO_x emissions and aids capture of carbon.

Tcf – trillion cubic feet

Tight gas – natural gas found in sandstones or carbonates of low permeability and porosity, from which the gas can be extracted through natural fractures or hydraulic fracturing

Thorium – chemical element of atomic number 90. As a naturally occurring, slightly radioactive metal, it has been considered as an alternative nuclear fuel to uranium

toe – tonnes of oil equivalent

Unconventional sources – in this report, refers to other forms of oil, gas and nuclear fuel other than crude oil, natural gas and mined uranium, eg extra heavy oil, tight gas, thorium.

URR – Ultimate Recoverable Resource – the total amount of a resource that can be recovered from a field/deposit/region throughout its exploitation lifecycle, from the first extraction to its complete depletion

Uranium phosphates – a family of uranium-bearing minerals. The uranium currently extracted in mines comes from uranium oxides, which is easier to transform into nuclear fuel

USGS – United States Geological Survey

WF12 – Wind Force 12, report by Greenpeace and EWEA, 2004

ANNEX A – UNCONVENTIONAL OIL

Oil exists in a wide range of forms other than the sweet crude gushing out of the Middle East's super giant fields. Several non-conventional sources of oil have been identified long ago but remained underdeveloped while the 'lowest hanging fruits' were picked first. Ranked by increasing viscosity, extra heavy oil, oil sands and oil shale are the most abundant of these well-known and fairly concentrated sources. Interest in heavy, viscous oil ($\leq 20^\circ\text{API}$) intensified with the oil shocks of the 70s that resulted in high prices and concerns over security of supply. The pilot projects running since then suffered different destinies: the Canadian oil sands industry slowly developed and reached the market whereas most oil shale projects in the US were abandoned.

This annex concentrates on the three major unconventional oil deposits, which altogether account for more than 80% of the total:

- Extra heavy oil of the Orinoco belt (Venezuela)
- West Canada's oil sands
- US oil shale

Although the total non conventional resource in place is thought to exceed 6000 Gb (3 times the conventional resource), the recoverable amount is significantly less. A sizeable and profitable production is already under way, but what can be expected of these resources, often quoted as the solution to oil scarcity?

A.1 Extra Heavy Oil (EHO)

The main characteristic that differentiates EHO from the other unconventional sources is that it is mobile at reservoir conditions. Hence, it can be pumped to the surface without thermal stimulation, just like conventional oil. This process is called cold extraction.

Like all of these heavy hydrocarbons, EHO needs to be pre-treated before it can be fed to refineries, to improve its H:C ratio and reduce its sulphur content. This process, called upgrading, increases production costs but yields high quality synthetic sweet crude (syncrude). There are currently 4 projects producing syncrude in Venezuela, with a combined output of 0.6 Mb/day (0.8% of world demand). All of these projects started in the past 5 years and plans to further develop the area are under way. The national company's blueprint expects production to reach 1.2 Mb/day by 2012 [27].

Alternatively, the Orinoco EHO is also marketed as 'Orimulsion'. A mix of EHO and a solvent, Orimulsion was developed in the past by the national oil company (PDVSA) as a substitute to fuel oil suitable for burning in

power plants. At the time when upgrading technologies weren't perfected, it was a fair solution to a stranded resource, but today its future looks very uncertain as environmental issues constrain its use. Indeed, in view of the success of syncrude operations, which have a bigger market, Orimulsion doesn't seem to make much sense anymore.

PDVSA's studies estimated the total EHO resource in place at 1200 Gb, of which only 240 Gb could eventually be recovered. Current production costs are around 10\$/b ($\approx 18\$/b$ with royalties) for cold-extracted syncrude. In some cases higher recovery factors could be achieved through thermal recovery, but with increasing energy costs and greenhouse gas emissions. According to the pace of government plans and the URR (240 Gb), a Hubbert-type curve can be modelled, predicting a production of 6-8 Mb/day at most in 2030. Hence, even if the resource is vast and the progress promising, EHO's contribution is important but does not constitute a solution in itself.

A.2 Oil Sands

Oil sands are basically a mix of sand and bitumen, the end of the heavy oil spectrum. As bitumen is not mobile at reservoir conditions, there are two options for extraction: mining or in situ thermal recovery.

Mining is only possible in low depth deposits, with overburdens of up to 50-75m. Huge open cast installations process the oil sands to separate the bitumen (10%) from the sand (90%). The bulk of the present and planned operations are mines, since it is the easier and cheaper extraction method, perfected for almost 40 years now. Unfortunately, the great majority of Canada's oil sands lie too deep for mining.

In the case of deep deposits, in situ thermal recovery is required, which involves drilling and then injecting steam to make the oil flow to the surface¹². Needless to say, this is a highly energetic process, fed by large volumes of natural gas. A variety of in situ technologies are being tested to improve recovery rates and save on energy needs.

Whatever the extraction method, bitumen needs to be upgraded before refining to remove carbon, sulphur and nitrogen and add hydrogen. The process uses natural gas to produce heat and hydrogen and delivers synthetic crude oil (syncrude).

According to official reports [28], the original oil in place might amount to 1600 Gb, of which around 315 Gb could be ultimately recovered, 20% by mining and 80% by in situ recovery. This average recovery factor of 20% is based on detailed studies of bitumen concentration, reservoir characteristics, land availability and other technical parameters, which are being constantly

¹²: Cold drilling in situ production is actually possible in a few favourable sites, though recovery rates are lower.

¹³: Natural gas production corresponds to the Supply Push scenario (optimistic) from [29]. Exports to the US are from EIA's Annual Energy Review 2005. Demand from the oil sands industry is the business as usual case from the "Oil Sands Technology Roadmap" [30].

perfected. Development of Western Canada's oil sands resource began in the 1960s and has slowly progressed to become an important industry producing 1Mb/day. With the current and expected high oil prices, the future looks very promising for oil sands operations.

However, the critical role of natural gas as an input to the extraction and upgrading processes threatens the planned expansion. In a business as usual scenario, the oil sands industry would consume more than 40% of Canada's annual natural gas production by 2025. What is worst, almost half of Canada's gas output is exported to the US, meaning that the oil sands would require 90% of the remaining production (Figure 40). To compete for gas supplies with the North American market would be impossible for the industry, considering that natural gas accounts for as much as 60% of the costs of in-situ production. According to the Alberta Chamber of Resources [30], 'The 'business as usual' case is clearly unsustainable and uneconomical (...) perhaps as early as 2015. The solution is energy and hydrogen self-sufficiency, either through the use of residues, or external energy alternatives, such as coal or nuclear energy'. Gasifying bitumen residues (or coal) could indeed overcome the natural gas barrier, as similar technologies exist and the energy balance remains beneficial. But the technology switch would leave the Kyoto Protocol targets well out of reach for Canada, as Figure 41 shows.

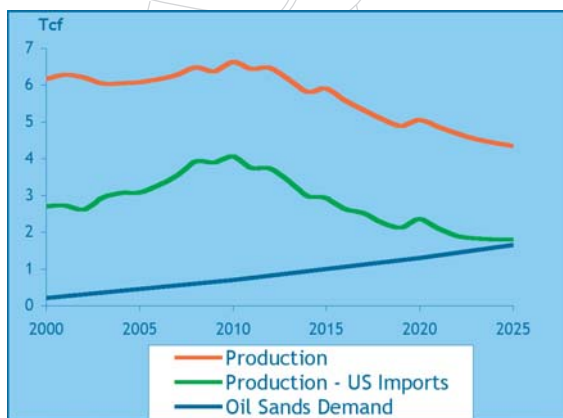


Figure 40. Projected Canadian natural gas supply vs. oil sands demand¹³

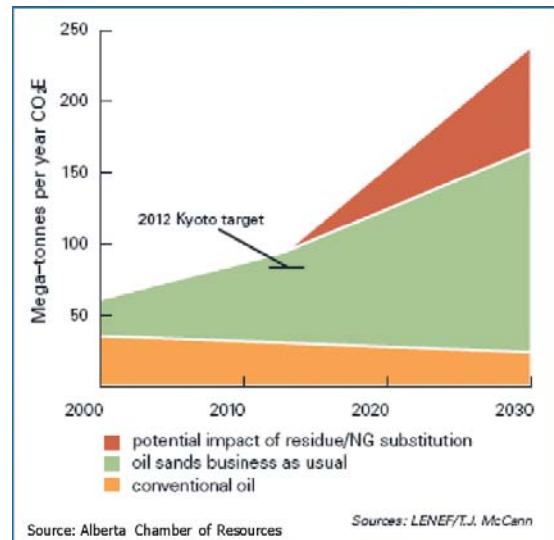


Figure 41. Greenhouse gas emissions from the oil industry [30]

If the oil sands industry managed to replace natural gas by new energy sources, sustained growth would turn Canada into a major oil source in the future. However, the contribution oil sands can make to the declining world oil supply does not seem to be enough. Even if every planned and prospective project were actually built, a very optimistic hypothesis, the output would reach 5.3 Mb/day by 2030. In fact, in that case the rise of oil sands production would not even compensate for the decline of the combined conventional oil production of Canada and the North Sea [31].

A.3 Oil Shale

Oil shale is a solid fine-grained sedimentary rock containing organic matter, completely non mobile at reservoir conditions. In fact, it does not differ greatly from coal, except that it has a lower organic/mineral ratio and a higher hydrogen/carbon ratio. Hence, it is generally extracted by mining. The shale fresh from the mine is of no great use; to extract the oil it must go through retorting, a process similar to pyrolysis that heats it to 500°C in absence of air. The product obtained is viscous heavy oil that needs to be upgraded before refining.

Oil shale was mined in the past for a variety of uses before conventional oil was found in large amounts. Limited extraction continued throughout this century, mainly in Estonia to fuel power stations, but has now been abandoned for cost and environmental reasons. As the US holds about 80% of the world's oil shale resources, great interest arose after the oil shocks of the 70s to develop it as an almost infinite indigenous source of oil. Deposits were leased to oil companies and large investments were made to set up pilot mining and retorting facilities. After 20 years of efforts and minimal production, the last production facilities closed.

The total resource in place is estimated to exceed 3000 Gb, 80% of which are in the US, surrounding the border

between Utah, Colorado and Wyoming. According to different assessments of US resources, about 750 Gb occur in concentrations similar or richer than currently produced Canadian oil sands (Figure 42). This means the US would then hold 3 times as much oil as Saudi Arabia in its own land.

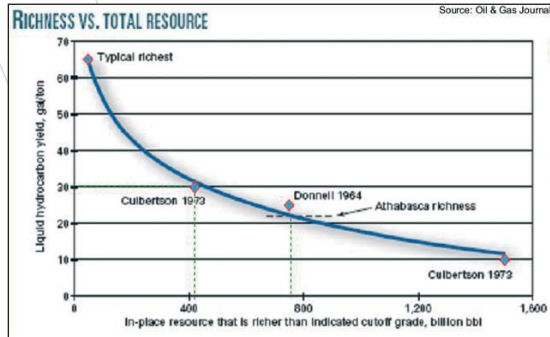


Figure 42. US oil shale resource: richness vs. amount in place [32]

However, prospects for bringing the oil shale industry back to life are not very promising, even with a high oil price background. Technological and environmental problems extend beyond a mere relative cost barrier. Indeed, a mature benchmark technology does not exist for the sustained exploitation of oil shale on a large scale. Previous operations were small and generated large amounts of waste as a result of the mining and retorting process. In fact, a facility producing 200,000 b/day, like the large Canadian oil sands mines, would produce 4 times more waste than the largest iron mine in the world. Energy is not necessarily a critical input as the heat for the retorting process can be obtained from burning the residues (though with high emissions). But the massive volumes of water required would certainly restrict the development of the industry. At 1000 liters per barrel of oil, process-water needs are 4 times greater than for oil sands processing. In fact, an industry producing 5Mb/day ($\frac{1}{4}$ of the current US demand) would consume 4 times as much water as the city of London. Such large volumes would hardly be available in the deserted area where the deposits lie.

A research project has been conducted for some time by Shell to develop in situ production from oil shale. The shale is retorted underground by heating it for several months with electric resistances and then pumped to the surface. Little progress has been reported with this technology and the energy balance so far is largely unfavourable.

In brief, given the technological and environmental constraints and the poor past experiences, oil shale resources are not likely to be developed in the foreseeable future. More mature and flexible technologies, such as coal-to-liquids, are much closer to replacing conventional oil. Hence, the eventual contribution of oil shale to the world oil supply is not considered in this report.

14: Coalmine methane is the gas accumulated in seam fractures that is spontaneously released or purposely drained in mines, as opposed to CBM which is embedded in the coal's internal surface. CMM is originated in CBM, but its resources are negligible as compared to CBM.

ANNEX B – UNCONVENTIONAL GAS

Conventional natural gas is found either associated with oil in the form of gas and condensate at the top of oil reservoirs or 'free' in independent gas reservoirs. But gas is also present in other unconventional sources that need to be considered in a resource assessment, namely:

- Coal seams
- Tight sands
- Gas shale
- Geo-pressurized aquifers
- Methane hydrates

This annex briefly reviews each one of these sources. Although some are already being tapped successfully, knowledge on global unconventional resources is poor, mainly because conventional resources are still abundant and often closer to consumer markets. The US pioneered the exploitation of unconventional sources to offset the decline of its gas fields, supporting it through tax credits. Close to 1/3 of their domestic gas production now comes from coalbed methane, tight gas and gas shales. But in a global scale resources are largely untouched and information is vague. This report therefore relies on a global estimate of 2500 Tcf for all unconventional recoverable resources from a specialised study by Laherrère, Campbell and Perrodon [33]. This estimate should be considered as an educated guess and might suffer significant revision when deeper research and exploration are carried out.

B.1 Coalbed Methane

A coal seam can act as a source rock by trapping gas in its internal surface, just like the source rocks that form the conventional gas reservoirs. This stranded gas, that was usually considered a nuisance to mining and an important source of greenhouse gas emissions, can be retrieved by extracting the water that is also contained within the coal. By 'de-watering' the coal seam, the internal pressure drops and coalbed methane (CBM) is released.

Environmental problems are attached to CBM production, related to the disposal of the vast amounts of saline water extracted from the coal deposits and the potential drying up of aquifers vital to human activities.

The US produces 1.6 Tcf/year of CBM and Canada recently started production. Most countries with large coal resources, like China, Australia and Russia, are currently exploiting coalmine methane (CMM)¹⁴ to power their mines and avoid methane emissions, but are expected to develop CBM at some point.

The resource in place and the recoverable fraction are

both uncertain and estimates vary in wide ranges. Laherrère [16] calculates the US ultimate recoverable resource from the production record and extrapolates the value (100 Tcf) to the rest of the world using the ratio of coal resources. His approximation results in 300-400 Tcf globally.

B.2 Tight Gas and Gas Shale

Tight gas sources are gas-bearing sandstones or carbonates of low permeability and porosity. These resources can be exploited in areas where natural fractures abound, or by hydraulically fracturing the source rock to allow the trapped gas to flow. Although tight gas wells have very low productivity, they provide 20% of the domestic gas production in the US.

Recoverable resources in the US are estimated at 135 Tcf by USGS. Tight gas formations are also thought to exist in Canada, the Middle East, the FSU and China, but little is known about their potential.

Similarly, shale reservoirs can contain natural gas as free gas within the rock pores, adsorbed on organic material or as free gas within the system of natural fractures. Because of the low permeability, stimulation (some type of fracturing) is generally required to achieve commercial production rates.

The US produces about 0.6 Tcf of shale gas a year and its recoverable resource estimates range from 31 to 76 Tcf (Gas Technology Institute). Knowledge on a global scale is scarce; according to Laherrère [16], 'the world gas shale resources are badly estimated, but could amount to 1000 Tcf.'

B.3 Gas in geo-pressured aquifers

The solubility of methane in saline water greatly improves with pressure. Hence, deep subterranean geo-pressured aquifers can hold large amounts of methane dissolved in brine. This resource attracted US researchers eager to find alternative energy sources after the oil shocks and pilot projects managed to extract some gas successfully. Ideally, gas can be recovered in hybrid plants along with geothermal power production. The technology soon proved uneconomical and research was abandoned.

The amount of gas dissolved in water depends mainly on pressure, salinity and temperature. Recoverable resource estimates in the US vary greatly, 250 Tcf being an often quoted value. Studies show Russia's resources could be much larger than that. However, a great deal of research into resource characterisation and recovery methods needs to be undertaken before this resource can be considered as an energy source. This will certainly not happen before the sources previously discussed are fully developed.

B.4 Methane Hydrates

In high pressure and low temperature conditions, water molecules can surround and trap methane molecules in a network, creating what is known as methane hydrate. This solid compound has a structure and appearance similar to ice. Methane hydrates have long been known for obstructing gas pipelines, as a drilling hazard in arctic and offshore fields and, more recently, as a potential trigger of climate change. However, great expectations have been raised by the possibility of developing the vast resources of methane hydrates as an unconventional source of natural gas for energy use.

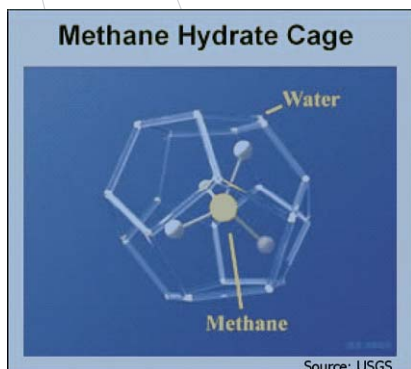


Figure 43. Methane hydrate structure, drilling core samples and combustion experiment

Stability conditions entail that hydrates are found in sediments of the sub-sea continental slopes and in the subsurface of Arctic permafrost regions. Indeed, the first samples were recovered in unrelated drilling projects. A myriad of studies have tried to quantify hydrate resources, based generally on seismic reflection assessments. But methane hydrate is at an early stage in

R&D and its properties and behaviour are not fully understood. So simulation models designed for oil and gas exploration do not necessarily apply, as confirmed by some pilot drilling projects failing to find any hydrates. Knowledge has been progressing though, and resource estimates have been decreasing steadily, as Milkov [34] showed by compiling previous studies (Figure 44, note the logarithmic scale). His paper gives a range of 35,000-175,000 Tcf, which is still an enormous amount in relation to conventional resources (10,000 Tcf). What portion can be recovered, if any, is an open question.

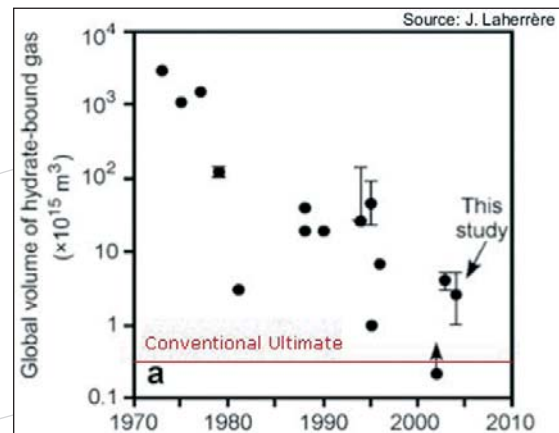


Figure 44. Evolution of resource estimates from past studies, compiled by Milkov

Laherrère summarises [16] the results of the latest research activities on hydrates, namely Japanese offshore drilling in Nankai (1999), offshore drilling off the Carolina coast (US), the international joint effort in the Canadian permafrost (Mallik well) and the DOE-funded Hot Ice project in Alaska. Very few test wells have found hydrate deposits. The Mallik project tested gas production methods and succeeded in producing a very small amount of gas through depressurisation and thermal stimulation, though far from commercial-scale volumes.

Although the possibility of methane hydrates contributing to the world energy supply at some point in the long term cannot be ruled out completely, the resource characteristics, remoteness and dispersion imply it cannot be considered as a plausible energy source in this report.



Renewable Energy Systems Ltd (RES)
Beaufort Court
Egg Farm Lane
Kings Langley
Herts WD4 8LR
United Kingdom
Tel: +44 (0)1923 299200
Fax: +44 (0)1923 299299
Web: www.res-group.com
Email: info@res-group.com

Report written by Francisco Varela of RES (varela@eoleres.com) in co-operation with the
Global Wind Energy Council and
EUREC Agency's European Master in Renewable Energy

This is an update of the original version of the report published in September 2006

Date of publication: May 2007

© Renewable Energy Systems Ltd