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Patrick Criqui

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LEPII - EDDEN
BP 47 - 38040 Grenoble CEDEX 9 - France
1221 rue des Résidences - 38400 Saint Martin d'Hères
Tél.: + 33 (0)4 76 82 56 92 - Télécopie : + 33 (0)4 56 52 85 71
lepii@upmf-grenoble.fr - http://www.upmf-grenoble.fr/lepii

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Patrick Criqui[i]

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The debate over the prospect of a peak in oil production occurring in the near future radically divides oil experts. Some are convinced that the comparison of the total estimated recoverable resources with the quantities of oil already discovered and produced points to the inevitability of a slowdown in production growth, to be followed by a stabilization in the near future and a decrease over the following decades. Conversely other experts, often economists, consider the 'peak oil' prophecy to be a fallacy consistently undermined by empirical evidence, in particular by the slow but continuous increase in global proved oil reserves. Indeed, according to BP, these reserves amounted to 1380 Gbl in 2010 as against 670 in 1980.

According to Colin Campbell, one of the most prominent advocates of peak theory, 'the term peak oil refers to the maximum rate of the production of oil in any area under consideration, recognising that it is finite natural resources, subject to depletion'.[ii] The main objective of the Association for the Study of Peak Oil and Gas (ASPO), which he co-founded, is to expose to as many people as possible the '*objective phenomenon*' that 'the world's petroleum resources are becoming depleted, to marshal the empirical data that support the concept and probable imminence of a global oil peak and to attempt to understand and quantify the impact of an oil peak on society, the economy, and the lives of ordinary people' (Zhao, Fen & Hall 2009). The main message of the ASPO community is that the peak is here already – are at least coming very soon – and that the end of cheap oil is imminent.

Even if the exhaustible characteristic of oil and gas is an 'objective phenomenon', critics have put forward a series of strong arguments against the peak oil concept. They argue that the prophets of doom have been wrong for over 60 years and have overlooked the impact of increasing knowledge and improved technologies on the capability of the oil industry continuously to recreate the reserves that are destroyed in the hydrocarbon production process. Combined with this increase in knowledge – and also encouraging it – the rise in oil prices since the period of the oil shocks has strongly stimulated the continual economic renewal of this ultimately limited resource.

Two subjects are at thus the core of the controversies: the first one is, of course, when will the world face a levelling-off in oil production; the second one is what will be observed after production achieves its peak, will there be a rapid decrease or will a plateau be reached?

In this chapter we propose an 'agnostic' approach to the peak debate, while highlighting the complexities of determining the facts and the quantitative evidence. The often diverging empirical forecasts can only be reconciled when focusing on the dynamic aspects of the oil discovery and production process. This obliges one to consider the two sides of the 'tug-of-war between diminishing returns and increasing knowledge', which, according to Adelman (1993), is the very essence of the economics of natural resources. The outcome of the tug-of-war is never predetermined and our diagnosis is that although the peak oil theory may be wrong in its assessment of the timing of the peak and on the shape of the decline thereafter, one may expect a growing gap, as far as conventional oil is concerned, between the dynamics of production expansion and the growth in the demand for cheap liquid energy carriers, most notably for automotive transport. While it turns out to be more and more difficult to find and produce conventional oil outside the resource rich OPEC regions, the huge potential demand from the rapidly growing emerging regions of the world will impose strong pressures on the international oil market in a near future and encourage the development of non conventional oil with in most cases higher economic and environmental – both local and global – costs.

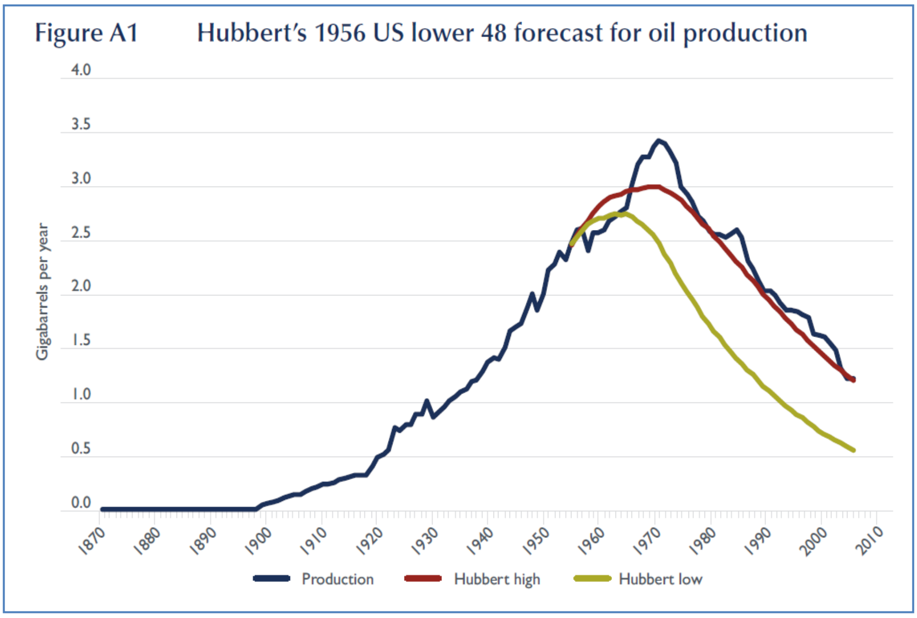
The purpose of this chapter is thus to review the concept of peak oil, critique its main propositions and assess the arguments advanced by oil optimists against those of peak oil. The paper is structured as follows. In the second section, we begin with a presentation of the Hubbert peak theory and of some recent applications of the theory at the global level. We then introduce a revised conceptual analysis and set of variables with a dynamic analytical framework. The third section assesses the issues behind the polarized debate between the peak community and the oil optimists. In particular, the methodological shortcomings that oil optimists consider as fundamental flaws of the peak theory are highlighted. In the fourth section, we examine the recent attempts by modellers and forecasters to overcome these shortcomings, which include more precise information about the different resources and particularly the taking into account of non-conventional resources. Finally, we examine these issues taking into consideration the potential impacts of international climate policies. In particular, we identify scenarios where sufficient implementation of mitigation policies at the global level would potentially change the very nature of the peak oil problem, turning it from a peak supply to a peak demand problem.

The Hubbert peak and the dynamics of the “creaming curve”

The Hubbert peak

Marion King Hubbert, a US geologist, was the founder of the ‘peak oil theory’ as he announced at an American Political Institute (API) meeting in 1956 that, given the bell shape curve of the production profile of individual oil regions, US production (lower 48)[iii] would reach its maximum by the early 1970s, when almost half of total resources will have been produced. The reasoning behind this was simple: the basic assumption is that the production profile of any oil producing region follows a bell-shaped curve; the maximum of production necessarily corresponds to the point when about half of the total recoverable resource has been produced. The original prophecy was indeed verified as US production peaked in 1972 and only the development of Alaskan fields allowed some rebound up until 1985, when a new decline followed. A recent study by the Australian government on the future of oil production confirms the validity of the Hubbert curve, at least for the US lower 48 region, from the start of production until 2010 (Figure 1).

Figure 1: Hubbert's 1956 curves and actual US lower 48 production (BITRE[iv])



NB: data does not capture the surge in US production after 2008 due to shale oil production

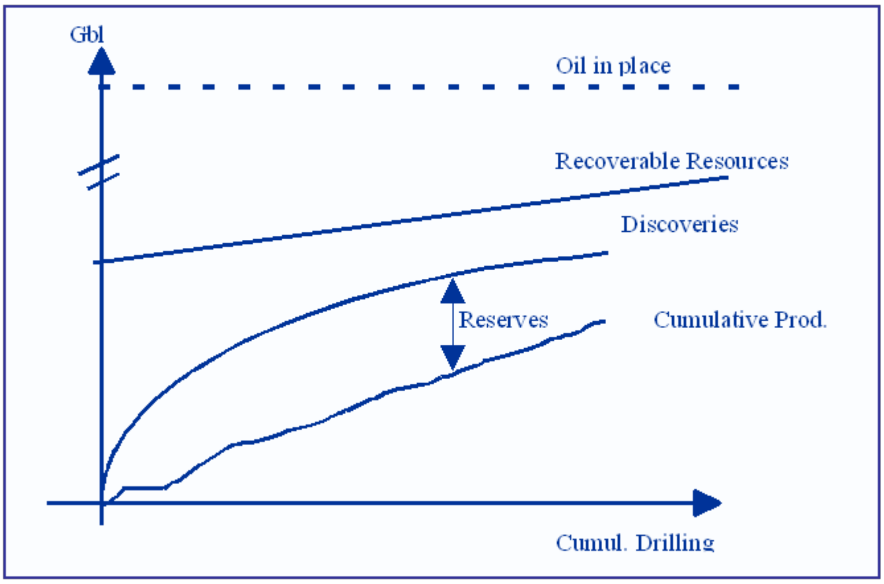
After preliminary extrapolation of Hubbert's theory to the global scale in the 1990s, ASPO was founded in 2000 by Colin Campbell in order to develop the approach for the analysis of oil production dynamics in different regions of the world and by aggregation, to provide a global assessment. The well-known principal conclusion and most striking statement of ASPO[v] is that peak oil is upon us and that the end of cheap oil is there, or almost there (Campbell & Laherrère 1998). Depending on different authors, members of the ASPO forecast that the peak is already here or that it will occur before 2020. One of the key argument set forward is that annual net real discoveries, to be clearly distinguished from existing fields' reappraisals, have become inferior to total yearly production since the beginning of the 1980s, which confirms the argument of the peak and the inevitable decrease of total oil production as the reservoir from which production is withdrawn necessarily shrinks.

The peak oil theory is a phenomenological approach to long term oil production profiles, with a simple mathematical basis and a limited number of variables, i.e. mostly resource stocks and production flows. However this simple theory should be replaced by a more complex description of a dynamic context, with causal relationships between different variables in the so-called oil discovery process models.

The dynamics of the 'creaming curve'

Many of the discovery process models are based on the use of 'creaming curves'. This is the key concept used by the oil industry to characterize the dynamic process of the development of an oil producing region through exploration. The creaming curve basically describes the decreasing returns between the exploration activity and the total discoveries for one given region. When expanded by including the limits imposed by the ultimate resources available and by the impact of technological progress in oil recovery technologies, it can provide a dynamic analytical framework. This framework organizes in a clear causal system the different concepts that are necessary to understand the dynamic development of oil or gas. Such a causal system is used for instance in the oil discovery process module of the POLES model.[vi]

Figure 2: Oil in Place, Recoverable Resources, Cumulative Production and Reserves (source: POLES model)



The key variables in the development of an oil producing region can be described as follows in a dynamic creaming curve (Figure 2 above):

- *Oil in place* represents the oil underground, the quantity of which will never be exactly measured.
- *Ultimate Recoverable Resources (URR)* are derived from oil in place as the quantity that can be extracted under current technological conditions. When changes in recovery technologies are taken into account it is more adequate to use the term recoverable resources, a quantity that is indeed increasing with technological progress (i.e. enhanced oil recovery (EOR)).
- *Cumulative discoveries* correspond to the oil that has been discovered since the very beginning of the oil exploration process in the region considered; by logical consequence, cumulative discoveries are inferior to the recoverable resources.
- *Reserves* are finally calculated as the difference between cumulative discoveries and cumulative production since the origin.

It is clear from Figure 2 that, given the different boundary conditions, the dynamics of reserve formation may allow for a full reproduction or even increase of reserves during a long period of activity, even for a mature region. However, it also shows that given the decreasing returns of the discovery process, reserve addition will eventually decline and become inferior to the annual production level. After that point, reserves and the reserve/production ratio will decline, resulting in the decrease in production. In that sense the dynamic creaming curve described above is fully compatible with the Hubbert curve for a producing region in that it describes similar production profiles in a series of causal relations. Furthermore, it provides a satisfactory answer to one of the most common critiques of the peak oil theory, as it takes into account technological progress in oil recovery technologies.

Cumulative production, reserves and discoveries: assessments and reassessments

At the time of the creation of the ASPO in 2000, the association estimated the URR at 2000 Gbl or a little bit less, while cumulative production was 870 Gbl and yearly production 27 Gbl/yr (see Table 1). At these production levels, the mid-point would be reached within five years and this led to the prediction of an imminent peak towards 2005. Ten years later, cumulative production was indeed 1160 Gbl with a yearly production of 30 Gbl, but the URR have been considerably revised upwards, at least by the International Energy Agency (IEA), which had a maximum estimate of 3500 Gbl. On the IEA assessment, with a slowly increasing annual production, the mid-point would be reached within twenty years, i.e. before 2030.

Table 1: Cumulative production, reserves, discoveries and resources, revisited

Gbl	2000	2010
Yearly Production	27	30
(1) Cumulative production	870	1 160
(2) Remaining reserves (BP)	1 100	1 380
(1) + (2) Discoveries	1 970	2 540
Ultimate Recoverable Resources	1 800-2 000*	3 000-3 500**
(1)/((1)+(2))	*44%*	*46%*

* ASPO estimate
** EIA estimate, conventional oil

Over ten years, the dominant view of the experts who consider the stocks and flows aspect of the oil problem, has shifted from the vision of an imminent peak to that of a pending problem that will have to be managed in the medium term. But not all experts consider this approach as valid, as most economists emphasise the role of economic and not physical variables in the changing picture of oil development.

Economists versus Geologists

The debate that opposes the peak oil community (a majority of geologists) and the oil optimists (a majority of economists) can be synthesised from the arguments found in papers by Adelman, Odell, Mabro, Yergin and Lynch (the oil optimists) and those by Campbell, Laherrère, Bauquis and Aleklett (the peak oil theorists). The application of the Hubbert curve at world level is the extension at a 'macro' level of a 'micro' level phenomenon and looks quite powerful. Nevertheless, Mabro points out that to move beyond the merely tautological – oil and gas are exhaustible and will therefore one day be exhausted – two questions must be carefully addressed (Mabro 2006). The first one is when will the world face a levelling-off in oil production and whether we are years or decades away from this point; the second one is what will happen after production reaches its peak - will there be a steady decrease or will a plateau be reached?

The peak: when and with what consequences?

The controversy is all about answering these two questions. Of course a set of major uncertainties are at the heart of this controversy and the arguments between the peak oil community and the oil optimists derive from these uncertainties. Beginning with the ASPO members, one can note different degrees of pessimism among them.[vii] For some, the global oil production has probably already passed its maximum. That implies that we have reached the peak of the oil age and of cheap and abundant oil (Aleklett 2010). Others consider that the peak is more likely to occur later, i.e. around 2020 (Laherrère, Babusiaux & Bauquis 2007). In contrast, the oil optimist institutions or economists, such as CERA, Odell or Lynch do not really consider that the limitation of oil underground will be the core of the problem during the next two decades. They argue that there will be no physical or 'underground' problem and that no decrease of production is likely to be observed at least in the medium term (CERA 2009, Odell 2003, IEA 2008, Lynch 2009).

Regarding the pattern of production that will be observed after production reaches its maximum, peak oil theorists believe that an absolute peak will occur, followed by a steep and irreversible decline. In contrast, the oil optimists see a succession of temporary peaks. As such, production would be able to recover after such temporary peaks and price hikes, when technology is improved and new fields are discovered. For most economists, the scenario of an 'undulating plateau', characterised by a succession of supply crunches, is the preferred image. One of the corollary implications of the 'undulating plateau' is that the peak will not necessarily imply a sharp and definitive price increase, but rather a regime of instability with price shocks followed by counter-shocks.

Beyond the differences in estimates of recoverable resources underlying these different visions[viii], one needs to analyse the main arguments of the peak oil community and of the oil optimists. The fact that the stories of doom articulated by the peak oil advocates have all proved to be wrong in the past underpins the scepticism of the economists. For most of them, the peak oil theory is at best a tautology and at worst shapes the debate in a wrong way. Adelman is a clear representative of this stance. He stresses that the exhaustible characteristics of oil and gas is actually a non-problem (Adelman 1990, 2004). The problem is not the question of the ultimate amount of oil in place that sooner or later will run out: oil is a commodity amongst others. Rather, it is all ultimately about demand, supply and prices. One day, there will be no demand at the price that will cover exploration costs and oil will be left in the ground. As Sheikh Zaki Yamani memorably stated, 'the stone age didn't end for lack of stones'.

From this perspective, the appropriate answer to the question of 'when will the last drop of oil be produced?' is: never. According to Adelman, the real oil problem lies with the cartel of OPEC, which involves a distortion of oil economic fundamentals and closes the door for exploration in the most resource rich regions of the world. Therefore, he considers the fact that new discoveries are inferior to current production level does not represent a convincing argument for the peak oil thesis.[ix] The fact that increases in reserves come mainly from new estimates of brown (i.e. existing) fields is not a surprise, as investment in the production stage is simply less expensive than investment in the exploration stage. Indeed, the Middle East countries that offer the best perspectives for new discoveries are also less extensively explored. For Adelman, this is another sign that, due to the OPEC oil cartel, the world oil industry is simply walking with its head down blind to what is going on around it.

For Mabro (2006) and the CERA (2009), the peak oil theory in its simplest form indeed appears as a mere tautology, which is undermined by several shortcomings in its methodology. The main one lies in the static perspective adopted. It does not capture the dynamic process of the development of reserves which is triggered by economic forces and the complex interaction between economic variables (Odell 2010, Lynch 1998, 2009). As one CERA report puts it, 'Hubbert's approach fails to account for fluctuation in demand, technological advances, and the discovery of new hydrocarbon physicals' (CERA 2009). Peak oil theorists are also accused of not taking into account the impact of higher oil prices that are triggered by temporary scarcities. Of course adjustment is imperfect and the response lag is an issue of critical importance but, according to optimists, adjustments are surely going to take place, in terms of reduced demand, technical progress and eventually a rebound in supply.

The role of technology

Technological progress, for which the peak oil community seems to have limited faith, is potentially the key issue. Technology is the 'great multiplier' and the oil industry has always demonstrated a great ability to develop and implement innovative technologies. According to Adelman, the history of any mineral industry reflects 'the endless struggle of nature versus knowledge' (Adelman 1993). So far 'knowledge' has won the battle. Progress in technology allows for both new discoveries and the increase in the recovery rate through improved technologies that turns non-recoverable or hypothetical resources into recoverable reserves. This is clearly sketched in the McKelvey diagram, which defines reserves as the part of total resources that is both sufficiently well identified and producible under current economic conditions, and which shows that price increases will both stimulate exploration and alleviate the economic constraints. This is why recoverable reserves is an ambiguous concept as it depends both on economic and technological variables. Also, one of the important subjects of debate is the potential contribution of non-conventional resources to future production (see below). Some works from the ASPO and from other institutions have indeed updated their forecasts of future oil production taking into account non-conventional oil and considering both crude oil and other liquid fuel production.[x]

The second major area for innovation in the oil industry, after seismic and exploration technologies, has been the increase in the recovery rates, region by region and globally. It is commonly considered that the average recovery rate is currently around 35 percent. Of course, this mean value hides large differences between oil fields and regions. But, in any case, what is striking is that even a small increase in the recovery rate adds considerably to accounted reserves even without real new discoveries. Optimists consider that the recovery rate could be as high as 60 percent fifty years from now. A more conservative view shared by ASPO members is that the recovery rate is unlikely to be higher than 45-47 percent in 2050. Interestingly enough, recent work by the IEA and Aleklett present a convergent view on the probable contribution of EOR to new production capacities with an extra 6 to 7 Mbd production by 2030.

A peak demand in place of a peak supply?

Forecasts regarding the dynamics of demand also face huge uncertainties. As noted by Porter, 'experts did poorly on estimating future supply potential and as bad or even worse on the demand side' (Porter 1995). The background to the uncertainties in forecasts and scenarios lie in the time lags for demand adjustments, technological progress for the development of substitutes, and the magnitude of environmental policies. This raises the prospect of a 'peak demand'. This idea is mainly proposed by those who believe that supply will permanently be in excess of demand (Odell 2003, CERA 2009, Shell 2008). From this perspective, 'oil's future seems likely to become demand-side limited so that potential supply-side (resources) limitation represents only a low probability prospect' (Odell, 2003).

When considering the demand side of the problem, one has to recognize that in most OECD countries oil demand peaked in 2005-2006 and, due to the combined effects of the economic crisis and high prices, has subsequently significantly decreased (-8 percent for total OECD demand in 2010 compared to 2005). This may accord some credibility to the thesis of peak demand. But this ignores the tremendous increase in oil consumption in the non-OECD and non-FSU regions in recent years, which has grown 46 percent from 2000 to 2010. This surge in oil demand is of course mostly explained by ongoing increases in car ownership. As argued by Dargay et al. (2007)[xi], these changes will only accelerate with rapid economic growth in the next twenty years. According to their model, between 2002 and 2030 the car equipment rate – currently at more than 800 vehicles for 1000 habitants in the US – may rise from 16 to 269 in China, 17 to 110 in India, and 121 to 377 in Brazil. One can easily imagine the consequences of such trends on gasoline demand in the emerging and developing regions of the world. Clearly, with this level of growth, the peak demand hypothesis does not hold at the global level over the next few decades unless stringent emission reduction policies are set in place (see below).

Despite these projections, the oil optimists maintain their faith in the necessary supply-side adjustments being made by increased investment and improved technologies as a response to price increases. Technological progress, investments in exploration and production, and demand side adjustments are the key issues. These are opposed to the static and determinist perspective of the peak theory. The reality of the complex and dynamic interconnections between economic variables makes the Hubbert method a poor tool for forecasting the timing of the peak. For some, this methodological flaw explains why the members of the peak community have been constantly forced to revise their forecasts for a peak and always to project it further into the future (Lynch, 1998).

Non-conventional resources: the new frontier?

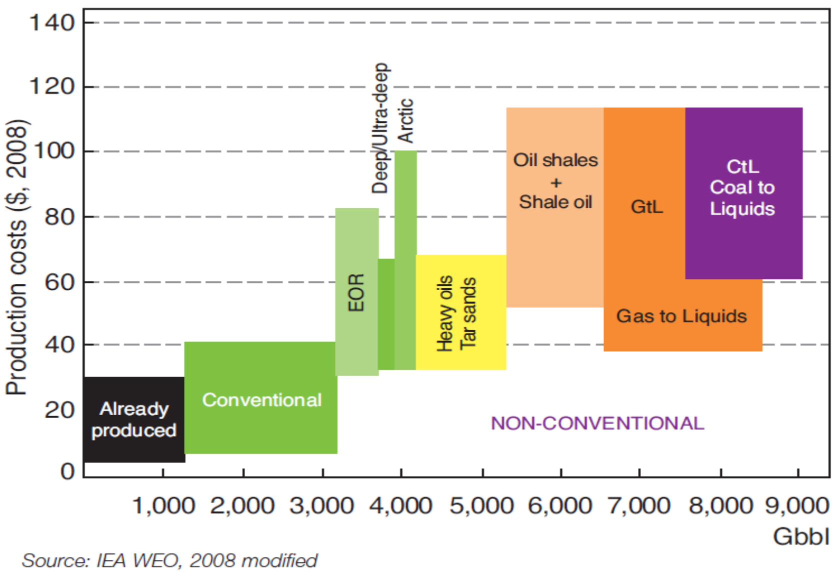
There is no strict definition of the concept of non-conventional hydrocarbons and the concept mostly relates to extraction method. According to Vially (IFPEN 2012), 'in the case of non-conventional hydrocarbons, the objective is to produce hydrocarbons that are very difficult to extract, either because they are located in beds of very low permeability or because their very nature makes them difficult or impossible to move'.[xii] For some authors the very notion of non-conventional oil should be questioned, as the frontier between conventional and non-conventional is not always clear-cut. This is particularly the case for offshore, deep offshore and ultra-deep offshore resources. However, beyond the differences in production costs, there is one clear reason for maintaining the distinction between conventional and non-conventional oil: it relates to the environmental impacts of the extraction methods for non-conventional oils, which are generally much more damaging both at the local and global level.

Non-conventional resources and anticipated production

Maintaining the essentially geological peak oil approach, some recent works propose updated and detailed analyses that take into account the assessment of non-conventional oil and gas resources, mostly extra-heavy oil, tar sands, oil shale and more recently shale oil, so as their potential contribution to future production.[xiii] For example, Masset (2009) provides an updated appraisal of conventional and non-conventional resources. He first identifies 2650 Gbl of recoverable conventional resources (including 300 through EOR and 350 yet to be discovered), i.e. two thirds of the 4 000 Gbl of oil in place. To these conventional resources, 600 Gbl of non-conventional oil should be added, representing only 20 percent of a total accumulation of about 3000 Gbl. The total 3200 Gbl of recoverable liquids are nearer to the conservative ASPO figures than to the IEA estimates that propose a similar amount for conventional resources alone.

The most recent estimates by the IEA (2008) and IFPEN (2012) of the different resource categories combine the geophysical approach with information on the expected production costs. Their results are much more optimistic. The IFPEN estimate in Figure 3 indeed points to global resources superior to 3000 Gbl at a cost inferior to 40 $/bl, 5000 Gbl at a cost of 80$/bl and finally 9000 Gbl at a cost of 120 $/bl (including Gas To Liquids and Coal To Liquids).

Figure 3: Conventional and non conventional liquid hydrocarbons (source IFPEN 2012)



As far as anticipated production is concerned, the IEA projects a non-conventional oil production increase from 1.7 Mbd in 2007 to 8.8 Mbd by 2030. On behalf of ASPO, Aleklett et al. (2010) forecast that non-conventional oil could contribute up to 6.5 Mbd by this date. Both IEA and Aleklett do not foresee a significant contribution from non-conventional oil compared with conventional oil. The POLES model Baseline projection in the FP7 SECURE project provides a projection for 2050, with total oil peaking in 2030 at 96 Mbd and non conventional oil adding 6 Mbd, and respectively 88 and 10 Mbd by 2050.[xiv]

Unsurprisingly, a more optimistic outlook is presented by CERA (2009), Odell (2003) and Aguilera *et al.* (2009). CERA indeed considers that unconventional liquids already contribute to approximately 14 percent of total global capacity and predicts that this share will grow to 23 percent by 2030. For Aguilera *et al.*, the most important conclusion to draw is that the potential of non-conventional oil undermines the idea that the peak of conventional oil will necessarily lead to a sharp and definitive increase in prices or to the 'the end of cheap oil'.

Replacing cheap and easy oil by dirty oil

The development of non-conventional oil may indeed modify the impact of the end of cheap and easy oil, while ensuring a revival in the production of liquid fossils. This is clearly the case in the US where, thanks to the development of shale oil, total oil production is again on the rise, from 4.95 Mbd in 2008 to 5.7 Mbd in the beginning of 2012. However, one key concern with the development of non-conventional resources is the importance of their environmental impacts, both at the local and global level. These include, first, the physical footprint of production and the impact on local ecosystems; second, the impact on the water cycle in terms of process water requirement and waste water disposal; and third, the increase in GES emissions due to the production process, treatment and refining of the primary products.

As far as the physical footprint is concerned, the impact on natural ecosystems can be highly visible and obvious as in the case of bitumen produced from tar sands in the Alberta province of Canada. Photographs of the Athabasca basin clearly illustrate the damaging impact on the neighbouring peat lands and boreal forests. Land reclamation might be undertaken by oil companies, but studies show that this reclamation does not prevent a massive loss of peat soils and the corresponding additional carbon losses from these soils.[xv] For shale oil however, the extensive use of horizontal drilling somewhat limits the aboveground impacts as one well can produce oil from a large underground surface.

The issue of water use and waste water or contaminant products disposal is closely associated to the hydrofracking technology that is common to shale oil and shale gas production. The United States Geological Survey (USGS) is currently conducting a comprehensive research program to analyze the environmental impacts of shale gas.[xvi] Recently, the European Parliament commissioned a study on the environmental impacts of shale gas and shale oil, drawing from the US experience but with a specific perspective on the potential development in Europe.[xvii]

Finally, the GHG content of non-conventional oil is a complex issue as it should be placed in a life-cycle analysis perspective. The results of different studies gathered by CERA[xviii] point to a Well To Retail pump (WTR) GHG content of the product from oil sands that is 40 to 70 percent higher than the average conventional fuel in the US. This however translates into a narrower gap of 5 to 15 percent higher emissions on a Well To Wheel (WTW) basis, as most of the emissions occur at the combustion stage.

As can be seen from the above, the question of the environmental impacts of non-conventional hydrocarbons is a complex and multidimensional issue as it incorporates both local and global impacts. One key issue for oil and gas policies over the next decade, and for different regions of the world, will be to decide whether it is worthwhile to engage in the development of non-conventional resources. This will require balancing the advantages in terms of energy independence and reduction in the cost of energy supply and the disadvantages and costs in terms of the local environment and a sustainable climate policy. The initial responses of different world regions are already diverging, with North America clearly on its way to ensuring greater energy independence through non-conventional resources, while Europe, where social acceptability problems appear to be more critical, is up to now on a more cautious path. The future of oil over the next decades will to a large extent depend on the policy pattern that will be set in North America and in Europe and, it goes without saying, also in emerging countries like China.

The future: supply crises or self-imposed sobriety through climate policies?

A common failure among both oil-optimists and pessimists is their tendency to focus just on 'underground' and/or economic variables. Both approaches leave aside questions of institutional barriers to investment or geopolitical constraints on the activities of the international oil companies. These factors are now the focus of new research dealing with a supply/investments crisis. This has mainly been developed by certain optimists who consider that resource exhaustion is only a fiction, at least for the next few decades (see IEA 2008, Stevens 2009, CERA 2009). The basic insight is that the evolution of supply is going to be mainly shaped by 'aboveground' institutional or political considerations. They argue that supply crunches will probably occur but that these crunches will not have anything to do with the underground availability of resources, but rather with a mix of political, institutional and financial barriers to investment.

Aboveground and underground constraints

In its 2008 report, the IEA argued that, 'capacity addition from current projects decreases after 2010…. The gap between what is currently being built and what will be needed to keep pace with demand is nonetheless set to widen sharply after 2010. The sheer scale of investment needed raises question about whether all of the additional capacity we project will be needed will actually occur. If actual capacity addition falls short of this amount, spare production capacity would be squeezed and oil prices would undoubtedly rise – possibly to new record high" (IEA 2008, see also Forbes 2010). The key insight here is that institutional barriers to investment and geopolitical issues may be more important for shaping the pattern of future production than the purely geological question of oil availability.

As far as the question of the ability of supply to meet future demand is concerned, this scenario points to some convergence in the forecasts by usually entrenched optimists and pessimists. First, it gives strength to the 'undulating plateau' approach. For example, Mathieu (IFPEN 2010) now gives credit to the prospect of an 'undulating plateau' during the next two decades mostly because of the inadequacy of global investment. From this perspective, the world is going to face some impeding supply crises but not due to lack of oil but because of the inability to convert underground resources into productive capacities. Second, these approaches stress that the world oil market is going to remain tight, giving strength to the idea that the inability of supply to meet demand may increase in a shorter term horizon than the timeframe usually adopted by oil-optimists. Whether peak or plateau, the expansion of oil supply will encounter limits over the next decades, thus posing the problem of adjustment in conditions of still powerful potential demand.

In this respect, the analysis provided by P. R. Wells in his twin 2005 articles on oil supply challenges for the *Oil and Gas Journal* still remain valid.[xix] He argues that 'the world faces challenges rather than impending doom with oil supply. The challenges include a sequence of supply crises likely to develop not when oil production peaks − the subject of much recent controversy − but earlier, when widening gaps appear between demand and sources of supply upon which the world has come to rely'. In his vision the challenges will be organized in a sequence of three stages: Stage 1 with the peak and decline in non-OPEC production; Stage 2 with the reduction in OPEC spare capacity; and Stage 3 with the incapacity of OPEC to meet incremental demand.

A close examination of oil production profiles in the main oil-producing regions indicates that Stage 1 might be already taking place: from 1965 to 2002, non-OPEC production (excluding US and the former Soviet Union) multiplied by seven, from 4 to 28 Mbd, i.e. a 5.4 percent per year increase; then production peaked and was 26 Mbd in 2010 in spite of the price hikes since 2002. With total OPEC capacity of about 38 Mbd, OPEC spare capacity has also been significantly reduced in recent years (Stage 2) and only the financial crisis starting in 2008 has allowed rebuilding some spare capacity margins. When the crisis ends, the key question will be the ability of the oil regime to facilitate the development of new capacities in the Middle East in order to meet the burgeoning demand of emerging countries. If the pace of this new capacity development is insufficient, then the world will enter into Stage 3 of Wells' analysis.

The problem is thus a combination of underground conditions, i.e. difficulties in developing new conventional oil provinces, and aboveground obstacles, i.e. the constraints imposed by political and institutional barriers to the development of new capacities in oil rich regions. Understanding that is important for policy purposes. However, the very nature of the oil problem over the next decades – whether constrained 'underground' or 'aboveground' – will mostly depend on the intensity of the climate policies that will be adopted through international negotiations on the climate change regime.

The impact of climate policies: a downstream solution to upstream problems?

The road towards an international climate agreement – from Rio-1992 and the UN Framework Convention on Climate Change to the roadmap for a global climate pact in 2015 agreed in Durban (2011) – has been a long and difficult one. Up until now, the attempts to define a global scheme for establishing national targets consistent with the goal of limiting climate change to an increase in average temperatures of +2°C compared to preindustrial situation have proven unsuccessful.[xx] However, the scientific analyses developed and organised in the framework of the four IPCC assessment reports currently available provide an increasingly convincing set of arguments for the reality of climate change, the anthropogenic nature of this phenomenon, and the necessity to curb emissions at world level. The 2°C target would in particular imply a reduction of world emissions by a factor of two in 2050 compared to 2000.

As CO_2 emissions from energy activities through fossil fuel consumption represent more than three fourths of global greenhouse gas emissions, it is clear that any international agreement nearing this target will have major impacts on the future of energy. Many scenarios exist to describe the impacts of carbon constrained energy futures, such as those produced by the IEA in its World Energy Outlook and Energy Technology Perspectives, or those developed in the academic community through different sessions of the Energy Modelling Forum.[xxi] Studies performed in the framework of European research framework programs have also explored these dimensions of the impact of carbon constraints on energy development.

The EU-funded SECURE and POLINARES projects[xxii] illustrate, based on simulations with the POLES world energy model, the energy consequences of different degrees of emission constraint. In terms of differing scenarios, in the 'No Policy' (or Baseline) case, the future oil development pattern is one of a strong demand from emerging regions and a resulting supply and demand balance that leads after 2030 to the 'undulating plateau'. As mentioned above, this plateau corresponds to a production level of about 96 Mbd for conventional oil, to which 6 Mbd of non conventional oil are added.[xxiii] In 2050, production is at 88 Mbd for conventional oil and 10 Mbd for non conventional.

By contrast, the scenario called 'Global Regime', where there is full global compliance with the 2°C target, offers a significantly different picture for the future of fossil fuels. Coal is of course most impacted with a major reduction in total consumption. The impact on oil is less pronounced but nevertheless the world production profile changes significantly: the peak comes sooner in time at 90 Mbd in conventional oil and 4 Mbd in non-conventional oil by 2020, and production is reduced to a level of 57 Mbd and 4 Mbd respectively in 2050; that is a 38 percent reduction from the no-constraint case. This means that the 'peak demand' concept, which as noted above is irrelevant in the absence of environmental constraints, fully applies in the case of the implementation of a strong climate regime. Furthermore, the lower demand profile heavily reduces the development of non-conventional oil resources (by 60 percent), because they represent the more costly marginal resources.

This does not imply a judgement on the probability of the establishment of such a severe regime, which is another debate. But it is necessary to point to the fact that if there were a regime, and an effective one, then the self-imposed sobriety in the oil consuming countries would profoundly impact the nature of the uncertainties pending on oil supply. While underground conditions will matter more in the 'No Policy' scenario, the 'Global Regime' would significantly reduce and even fully negate the underground risks for oil supply, leaving room only for aboveground and underinvestment risks. In that perspective, one can of course expect that oil exporting countries will adjust their investment policies in order to fit to the new demand pattern but the probability of severe and permanent price hikes would be significantly reduced.

One can also here identify the potential double dividend of climate policies: beyond the often mentioned and discussed macro-economic benefits of the recycling of the carbon tax (or emission permit auctions), strong climate policies would significantly reduce the energy vulnerability of the European energy system and, if shared by a sufficient number of countries, also significantly reduce the risks of oil shocks and price-hikes themselves, while preserving the earth's climate.

Conclusion

According to economists, the main shortcoming of the peak oil theory is its static methodology. It fails to recognize the dynamic process of reserves evolution that is triggered by economic forces and the capability of the oil industry to develop new resources in a competitive way. Contemporary forecasts try to take into account the dynamic links between economic variables and the impacts of new resources and technologies, thus introducing more refinement in the treatment of the problem.

However, the recognition of these new elements does not entail naive optimism. An 'agnostic' view to the problem of future oil production obliges one to recognise both the limits of the pure peak oil approach and the fact that, due to the nature and strategic importance of this natural resource, it would be unwise to consider that supply will meet demand in any future circumstance. If steep peak oil is no more the most probable hypothesis, there is still a high probability of some impending supply crises due to the expected relative dynamics of oil supply and demand. While the peak oil theory was supposed to identify the principal danger threatening the future of the world energy and economic system, it now appears, when taking into account of the climate change problem, that the promotion of a sustainable world energy systems is a much more complex issue than simply ensuring either the adequate level of investment in supply or, contrarily, the 'transition away from oil'.

First it appears that, at least for the short and medium term future, the 'aboveground' conditions for ensuring access to resources and adequate investment plans is of critical importance since, in many major oil-producing countries or regions, oil supply is constrained by political will or political instability more than by resource scarcity. Improving these conditions may significantly alleviate market tensions and permit a return to reasonable price levels, which would reduce the pressure on the world economy. The policy prescriptions promoted by the peak oil theory may thus be in contradiction with the need to focus on the financial, political or institutional barriers for access to conventional resources for IOCs and on the political depletion rate chosen by the producer states and consequently by NOCs (see similar conclusion in chapter 11).

Second, with current or future price levels near to $100 a barrell, huge resources of non- conventional oil become cost-effective if the cost of carbon is not accounted for: a doubling of total available resources seems a reasonable estimate. The possibility of mobilizing lower grade resources, as has been the case for most minerals in the past, may completely change the perspective of the future liquid hydrocarbon system. But this would be a move from Charybdis to Scylla as the environmental consequences of non-conventional hydrocarbons development are major, both at the local and global level. In the transition from the cheap and easy to dirty oil, the scarcity problem may thus only be solved at the cost of increased environmental damages.

In particular, and this is the third point, the climate impacts of a massive development of non-conventional resources are potentially huge. This is first because new sources of underground carbon would be made available. These sources require a high level of energy, and thus of CO_2 emissions, in their own transformation process, making them more similar to coal than to conventional crude oil from this perspective. These new resources may also provoke a shift in the energy strategies of many countries that benefit from important non-conventional resources, from the US to France, China or Poland. The shift would compound the temptation to solve the energy security problem not through more efficiency and low carbon sources such as renewable or nuclear energy, which would be consistent with climate policies, but through an increased reliance on domestic fossil sources.

In the near term, the particular characteristics of the international and domestic institutional framework governing relations between states and operators will mainly drive the future of oil production (see chapter 2). But from the medium to long term perspective, there should evolve a system of careful and long-term management of fossil fuel resource stocks and production flows to be discussed between the consuming and producing countries which also takes into account the global GHG atmospheric concentration constraint.

[i] The author wishes to thank Sylvain Rossiaud (EDDEN laboratory) for his contributions to an earlier version of the paper.

[ii] See ASPO's website: http://www.peakoil.net/

[iii] Lower 48 refers to all the territorially contiguous states in the US i.e all states except Alaska and Hawaii.

[iv] Bureau of Infrastructure, Transport and Regional Economics, *Transport energy futures: long-term oil supply trends and projections, Report 117,* Department of Infrastructure, Transport, Regional Development and Local Government, Canberra, Australia, 2009

[v] Or the 'Peak Oil brigade', as ironically set out by Dieter Helm in *Peak oil and energy policy – a critique,* Oxford Review of Economic Policy, Volume 27, Number 1, 2011, pp. 68–91

[vi] See for instance: Kitous, A., Criqui, P., Bellevrat, E., Chateau, B. (2010). Transformation Patterns of the Worldwide Energy System – Scenarios for the Century with the POLES Model. *Energy Journal*, vol. 31, Special Issue n° 1 on The Economics of Low Stabilization, pp. 57-90.

[vii] For a presentation of the different projected dates of the peak from several authors and organizations, see de Almeida & Silva (2009) and the thorough comparative work of most of the contemporary forecasts for global conventional oil production undertaken by UKERC (2009).

[viii] Recent estimates of ultimate recoverable resources for conventional oil vary within a wide range of 2000 to 4300 Gb. All methods and assumptions (especially the narrow/wide definition of conventional oil) have been criticized for underestimating/overstating the ultimate recoverable resources. See US Geological Survey (2000), IEA (2008), Aguilera *et al* (2009). One of the main conclusions of the UKERC's comparative study is the fact that most of the differences between the two groups of models, those displaying a peak before 2030 and those stressing a continued growth to 2030, ulitimately rest upon different assumptions for URR (see UKERC, 2009).

[ix] For the last decade, approximately 65 percent of new booked reserves come from new estimates of existing reserves in old fields. The amount of reserves is usually highly underestimated at the beginning of the development process.

[x] Bureau of Infrastructure, Transport and Regional Economics, 2009, ibidem

[xi] Joyce Dargay, Dermot Gately and Martin Sommer, Vehicle Ownership and Income Growth, Worldwide: 1960-2030, *Energy Journal*, 2007, Vol. 28, No. 4

[xii] R. Vially, in IFPEN, Panorama 2012, Non-conventional hydrocarbons: evolution or revolution?

[xiii] Once again the definition of non-conventional oil is a subject of debate, coal-to-liquid and gas-to-liquid being included or not. Therefore, a comparative perspective is not straightforward.

[xiv] Criqui, P., Mima, S. (2012). European Climate - Energy Security Nexus : a model based scenario analysis. *Energy Policy*, vol. 41, n° 1, pp. 827-842.

[xv] Rebecca C. Rooney, Suzanne E. Bayley, and David W. Schindlerl, Oil sands mining and reclamation cause massive loss of peatland and stored carbon, PNAS early edition, 2012

[xvi] Statement of David P. Russ Regional, U.S. Geological Survey, Before the Senate Energy and Natural Resources Committee Water and Power Subcommittee To Examine Shale Gas Production and Water Resources in the Eastern United States, October 20, 2011

[xvii] Directorate General for Internal Policies, Impacts of shale gas and shale oil extraction on the environment and on human health, IP/A/ENVI/ST/2011-07, june 2011

[xviii] IHS-CERA, Oil Sands, Greenhouse Gases, and US Oil Supply, Getting the Numbers Right, 2010

[xix] Wells Peter R. A. (2005), "Oil Supply Challenges -1: The non-OPEC Decline", *Oil & Gas Journal*, Feb. 21. "Oil Supply Challenges -2: What can OPEC Deliver?", *Oil & Gas Journal*, Mar. 7.

[xx] The only quantitative objective that came out of the fifteenth Conference Of the Parties in Copenhagen.

[xxi] Weyant John P. *et al.*, 2006 EMF-21 *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue.

[xxii] Security of energy considering its uncertainty, risk and economic implications, SECURE, project N°213744 under EU DG-Research FP7
http://cordis.europa.eu/search/index.cfm?fuseaction=proj.document&PJ_RCN=9905806
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[xxiii] Criqui, P., Mima, S. (2012). European Climate - Energy Security Nexus: a model based scenario analysis. *Energy Policy*, vol. 41, n° 1, pp. 827-842.