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Timing and future consequences of the peak of oil production

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ABSTRACT

Energy is fundamental for present societies. In particular, transportation systems depend on petroleum-based fuels whose production levels are unsustainable. The inevitability of a peak of oil production ("Peak Oil") is a now an accepted concept, although its date is still not consensual. In this work we discuss the peak of oil production and analyze the problems it will create. As much as can be inferred at this moment, the impact of the Peak Oil will certainly be significant but can still range from relatively benign to almost catastrophic scenarios. As a direct effect of Peak Oil, the increase in energy prices will be concentrated on the liquid fuels and the transportation sector will be specially affected. We believe that the cheap, wide-scale air transport that our present societies take for granted will revert to a more expensive and restrictive model closer to the selective commercial air transport of the early jet age. In our opinion the present road transportation systems will suffer an important transition that includes a reduced incidence of long distance road cargo movements, partially replaced by increased railway transportation, and, in terms of people commuting, a significant increase of mass transit and electrical vehicles. During this phase of forced adaptation, some countries will face greater challenges than others. However, the future of overall mankind and of particular countries, regions, or any groupings of people, is not yet fixed: it depends on decisions that are being taken at the present moment and on decisions that will still be taken in the future. As such, predicting the impact of the Peak Oil is something that must be done through a continuously refined process of information collection and analysis.

1. Introduction

By the end of the first decade of the 21st century, mankind is facing several challenges. Among others, they include the infamous climatic changes and the continuing financial and economic crisis. An issue that has been less discussed, but may be much harder to solve, is the need to change the development paradigm of the last few centuries, due to a progressive exhaustion of available Earth resources to supply the continued human growth. In fact, the continuous endeavor to improve the standard of living of an ever increasing number of human inhabitants is placing an escalating stress on several important Earth resources. Well known examples of overexploitation of resources, or destruction due to direct human pressure on habitats, include the severe decline of most fishing stocks, the unremitting reduction of the area of tropical forests, and the progressive extinction of several major animal species.

The stress on available resources has accelerated in the last few years since to the traditional tendencies of increasing world population and increasing per capita resource consumption was compounded by the fast development (and "westernization") of important economies as China and India.

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Naturally, if renewable resources that, with appropriate administration, could be managed at stable and healthy levels are being unreasonably depleted, we should expect greater problems in relation to heavily exploited non-renewable resources. This is the case of the main energy sources that have been feeding our growth. In fact, the fossil fuels (crude oil, coal and natural gas) – that are responsible for more than 80% of the commercial energy consumed in the world – are non-renewable in a human time scale, and are being depleted at a disquieting rate. In particular, crude oil is the fossil energy resource that is in a more advanced state of depletion and its depletion state is already noticeably affecting our societies.

In this paper we evaluate and discuss the evolution of this depletion and the way it will manifest itself in our societies, in the short to medium time frame.

2. Our dependence on fossil fuels

Our societies are totally dependent on commercial energy. A cut in the electricity supply of a city would stop all electric public transports, lifts, traffic and street lights, residential and commercial lighting, most of the refrigeration and heating systems, cooking devices, communication devices (from TV to fixed or cellular phones), most of the equipment of hospitals, shopping malls, etc. A lack of availability of liquid fossil fuels (mainly crude oil) would particularly affect the transportation systems. It would stop the cars, buses, trucks (both for long distance transportation and local distribution), airplanes, diesel trains and ships. As a very important side effect, in most countries, lack of fossil energy would also severely reduce electricity production. Naturally, the industrial activity, and even the modern agricultural production, is based on machinery powered by commercial energy, and mainly by fossil fuels.

To quantify our present dependency on commercial energy, we can consult the most recent yearly statistical data from OECD/IEA [13]. These data indicate that the proportion of fossil energy in the total commercial energy consumed in the world is 81.4%, and crude oil alone represents 34.0% of this total energy. The non-fossil sources of energy are nuclear (5.9%), hydro (2.2%), geothermal and solar (0.6%) and renewables and waste (9.8%).[1] These percentages show that the combined alternatives to fossil energy represent, at present, a very small proportion of the total consumed energy.

When we look at the transportation sector in isolation, the direct fossil fuels weight is even greater, reaching 97.5%. Crude oil clearly dominates, representing by itself 94.1% of the energy used in this sector, and reaching 100% in some specific transportation systems like airplanes.

These statistics illustrate quite well the vital importance of the fossil fuels and of crude oil in particular.

3. The Peak Oil concept

Although mankind has been using fossil fuels (and coal in particular) for millennia, human exploration of fossil fuels increased significantly some 250 years ago, with heavy use of coal in the Industrial Revolution. However, liquid fossil fuels (mainly crude oil) ended up proving to be more convenient. So, over the last 150 years, mankind has consistently developed the exploration and extraction of crude oil, turning it into the most important single energy source. During this period, its production has been consistently raised to match the growing demand generated by global population increase and economic development. The high efficiency and convenience of fossil oil can be gauged by the fact that the very significant technological developments that occurred over this period have consistently increased our dependency on this energy source, instead of creating effective alternatives.

Unfortunately, from a human perspective, the formation of the fossil fuels is extremely slow and so they may be regarded as non-renewable resources. At present, in the end of the first decade of the 21st century, the world crude oil production is very close to the maximum that it will ever reach, and afterwards availability constraints will force it to decline.

The analysis of the world oil production in the region of this maximum and also the study of the mitigation possibilities and of the consequences of the subsequent period of increasing oil scarcity, are the object of the new research area known as "Peak Oil" (PO).

It should be noted that, when talking about the "PO problem", the main concern is not the end of oil as an important energy source but only the peak of its production and the resulting reduced availability, price increases, and associated economic and social effects.

4. Peak Oil: a short history

The problem of the peak of oil production (PO) was first studied by Hubbert in 1949 [10]. Before that, several persons had expressed concerns about the future availability of crude oil, but those concerns were not scientifically addressed and in most cases were based on unrealistic early predictions of crude oil exhaustion. After that first presentation of the problem, Hubbert went on studying the subject and (in 1956) published a very important paper [11] in which he accurately predicted that the date for the peak of oil production in the continental USA (except Alaska) would be around 1970. This paper also presented the classical approach to the prediction of the natural (unconstrained) production profile for a sufficiently vast

[1] It should be noted that electricity is not an energy source—electricity production is based on the previously referenced sources with prominence of the fossil fuels.

Table 1
Peak oil predictions.

Date interval	Number of predictions
2007 or before	2
2008–2012	11
2013–2017	6
2018–2022	4
2023 or later	6

region (or for the world), and explained that the production should follow a bell-shaped curve. At first, this paper generated great controversy, since the USA was by then the biggest producer of crude in the world, and its production was rising without apparent problems (in fact, it had to be limited by regulator bodies, like the "Railroad Commission of Texas", to prevent the "flooding" of the markets). Eventually, however, that prediction proved correct, and that established Hubbert's prediction procedure. In 1971 Hubbert published a work in which he predicted that if the production and demand patterns were maintained, the world conventional crude production would peak around 2000 [12]. Considering the extraneous delaying effect of the political production constraints of the 1970s and 1980s, that prediction again seems pretty close to be correct.

Hubbert can rightly be considered the father of the research field concerned with the sustainability of the production of natural resources, and of the PO "theory". His prediction technique, based on the fitting of a bell-shaped curve to the historical production and to the Ultimately Recoverable Reserves (URR), remains the most common approach to predict future production of non-renewable natural resources and, in particular, of fossil resources.

Mainly using Hubbert's approach, in 1998, Campbell and Laherrère presented a very influential paper [7] discussing the peak of oil production, and predicting it to occur "before 2010". This paper influenced the "modern" discussion of the PO problem, and its global impact led Campbell and some others to create the ASPO,[2] the first and, at present, the most relevant international organization dedicated to the study of the PO problem.

5. PO date forecasts

Although it was considerably contested when first presented, the general idea of a peak of oil production is now well accepted. The time frame for that peak, however, is still contested. Table 1 shows the distribution of the date predictions for peak production of total fossil liquids[3] from a number of specialized institutions and individual experts. This distribution is a summarization of the list of predictions, made in 2000 or later, that is presented in [3].

This table shows that most predictions point to a PO date around the transition between the first and the second decades of the present century. Yet, a still significant number of predictions in Table 1 point to much later dates, namely 2023 or later. Regarding these later forecasts, we should note that, until recently, a limited number of analysts and institutions used to defend the theory that the peak of oil production is so far in time as to be irrelevant. Some of their predictions show up in Table 1 in the interval "2023 or later". However, these predictions were based on discredited models. As an example, two of the predictions listed for 2023 or later come from the IEA (International Energy Agency), an organization that has recently recognized that its long term projections for production were simply based on estimating demand and assuming that production would always be able to match it.

Anyway, disregarding any judgments related to the merits or demerits of the individual predictions, the distribution of forecasts illustrated in Table 1 constitutes a strong indication that the effective PO date should not be very distant.

Furthermore, we should note that the most recent PO evaluations that we are aware of, published in late 2009 or early 2010 and for that reason not incorporated in Table 1, also point to very near peak dates. These include [1,4,15]. In [1], Aleklett et al. present various scenarios. The farthest estimate for peak production that they propose, in the scenario with more urgent and extreme production efforts, is 2014. Document [4], the slides of a public presentation by the CEO of Petrobras (the national Brazilian oil company), shows a single scenario, with the world peak of production capacity in 2010. The report [15], presented in February 2010 by the UK Industry Taskforce on Peak Oil and Energy Security (ITPOES), describes several individual opinions on the PO. However, the formal synthesis opinion of the ITPOES report is for a world peak production in 2011, although with a plateau of very similar production values between 2010 and 2013.

Apart from the predictions of experts, another indication of a near-term date for the PO can be construed from the fact that, since the oil price drop of 2008, the prices of the futures contracts for more distant years have been systematically higher than the short-term futures contracts and spot prices—an inversion from the traditional historic behavior of those

[2] ASPO: Association for the Study of Peak Oil and gas (http://www.peakoil.net/).
[3] To simplify, the aggregate of all fossil liquids can be called petroleum. It includes crude oil, condensates, natural gas liquids, and also "non-conventional" forms of semi-liquid fossil energy sources (e.g., bitumen or oil sands).

contract prices. This new situation was reached through a slow but consistent (and predictable) process [2], and it can be argued that this is due to a recent recognition of future supply constraints from the part of the community of crude oil futures traders.[4] This generally conservative but very well-informed community no longer expects that in future years the price of crude oil will return to the lower "traditional" prices, but instead expects the prices to go on rising, and this can be construed as an objective validation of the arguments for a near-term PO [3].

Like the authors cited above and the community of futures traders, we are also convinced of a near proximity of the peak production of liquid fossil fuels. Our own predictions (the first one presented in the ASPO 2005 conference [2] and the last one appearing in [3]) also point to the 2008–2012 interval, precisely where Table 1 shows a greater concentration of predictions.

We know now that the reduced demand due to the economic crisis prevented the peak world production to be attained in 2009, and we believe that the record production of 2008 can be surpassed in the next few years (since the present world production capacity exceeds the 2008 value, and the demand is also picking up).

However, refreshing our bottom-up analysis with the same methodology we used before, we still obtain the same upper limit for the most probable interval for the PO date. That is, we still believe that it will occur in 2012 or before, with greater probability in 2012.

Our analysis of the future production of world liquid fossil fuels points to the present world production capacity (but not production itself) being close to the upper limit that will ever be achieved. Considering the present composition of the OPEC, we believe that the non-OPEC production[5] will remain fairly stable during the next few years, with production from new projects (mainly of "non-conventional" crude) matching almost exactly the predicted depletion effects – with increased production in countries like Brazil and Kazakhstan compensating for decreases in countries like Mexico, UK, or Norway. We expect that OPEC capacity (but not production) will also remain fairly stable – with expected increases in capacity in a small number of countries, like Algeria and above all Iraq, compensating for depletion effects in countries that are post-peak (e.g., Ecuador, Venezuela, Nigeria) or near it (most of the other OPEC countries including, in our perspective, Saudi Arabia, Kuwait, Angola, and others). However, in the case of OPEC, at present the production is being kept below the full capacity, resulting in a spare margin that we estimate to be in the region of 2.5 Mb/day, mainly concentrated in Saudi Arabia. In our perspective, this spare production capacity will be progressively exhausted by the predicted increased demand in 2011 and 2012 [14], leading to maximum world production around 2012. After that, our bottom-up country-by-country analysis points to a few years (perhaps 2, 3 or 4 years) of fairly stable production followed by a decay that will, at first, be rather slow but will tend to accelerate. It is important to emphasize that this analysis only concerns liquid fossil fuels and does not integrate biofuels or conversions like coal-to-liquids or gas-to-liquids. Biofuels, in particular, appear combined with the liquid fossil fuels in the most frequently watched statistics of global oil demand/production (e.g., in most IEA global statistics data). The increasing production of biofuels (at present in the region of 2 Mb/day) already tends to mask somewhat the effects of a limited fossil oil production and in a near future it will certainly contribute to cloak the PO occurrence in the next few years, to those less alert to actual fossil fuels production numbers. On the other hand, natural disasters like big hurricanes in production regions, wars that directly affect relevant producers or block important oil routes, and terrorist attacks or significant accidents on oil infrastructures, can cause unexpected constraints on future oil production or delivery, potentially accelerating the public noticing of the PO. A good example is the recent oil spill in the Gulf of Mexico. Apart from the immediate consequences, this accident caused 3 main longer term effects. The first one was a moratorium on oil exploration in US Gulf of Mexico. This moratorium and an associated virtual blocking of drilling permits are expected to reduce the oil production in the US Gulf of Mexico by some 100 kb/day in 2011 [14]. The second effect is an expected worldwide tightening of drilling regulations, especially in deep-water wells. This tightening will certainly contribute to increased production costs and to delays in new drilling permits. The third effect, potentially the most significant, is the blocking of oil exploration and production in areas that are considered sensitive due to environmental or other constraints (e.g., where economic activities, like fishing or tourism, could be directly impacted by new accidents) but that were under consideration for oil exploration. This effect is already being felt in the USA, but the present tendency is for it to spread all over the world.

6. The PO in the present context of economic crisis

Fig. 1 is a non-quantitative sketch that illustrates the approximate forms of the "natural" production curve of crude oil (constrained only by resource availability), the tendency of demand in absence of resource exhaustion or economic recession (i.e., constrained only by ordinary historic prices, technologic evolution and economic growth), and the behavior of the demand affected by the present economic crisis but in absence of future production constraints.

The separation between the "natural" evolution of the demand of liquid fossil fuels in a "non-constrained" supply scenario and of the actual production curve in the region of the peak must be resolved since, beyond very limited time frames, consumption cannot surpass production. In the last few years production could no longer grow as was usual in the

[4] This community includes some personal investors, but is mainly constituted by professionals representing specialized investment funds and oil consuming and producing companies.

[5] In non-OPEC countries, production equals the present available capacity since, in the last few decades, it has not been constrained by artificially-imposed reductions of production aiming to increase the oil prices.

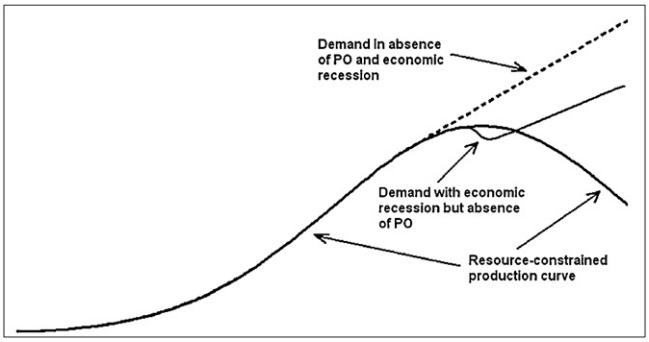

Fig. 1. Non-quantitative supply and demand curves for crude oil.

past, and so the desired consumption levels had to be lowered to match the production curve. As Fig. 1 illustrates, this occurred even before the date of the absolute peak of production. Due to the low elasticity of demand versus price, this forced demand compression could only be achieved by a very significant price increase and this culminated in 2008 with crude oil prices surpassing $140/barrel. Then the present economic crisis arrived. Through several mechanisms this crisis compressed the global oil demand, mainly because of a significant demand compression in most OECD countries. Also, 2008 and 2009 were exceptional years in regard to initial operation of new oil production projects. In particular, Saudi Arabia was able to bring online several very large projects, adding important new production capacity.[6]

The demand reduction and the significant new production coming online in the last two years created the transient excess of production capacity that exists at present. Unfortunately, this excess capacity (something that used to be the norm up to 2004 but that disappeared between 2005 and early 2008) cannot last very long. This is so because of two main factors. The first one, already discussed above, is that everything leads to believe that the PO date is now very near. As such, during the next few years the depletion of the present producing fields will force a greater reduction in production than the addition of new projects can compensate. The second factor is that the demand is already recovering. Indeed, although the demand is now rising from a departure level depressed by the economic crisis, every estimate points to significantly growing demand from countries and areas like China, India and the Middle East. One must remember that in China, in 2009, 13.6 million new cars were sold (against just over 10 million in the US) and that, in India, industry sources expect the sales of new cars to evolve from a growth of around 5–6% in 2009 to a growth of 10–12% in 2010. As such, in 2010 and in the next few years this effect is expected to easily compensate a probable continued weakness in many OECD countries. Tellingly, the International Energy Agency's most recent predictions[7] point to an average world demand of 86.6 Mb/day in 2010 and 87.9 Mb/day in 2011, against 86.2 Mb/day in 2008 and only 85.0 Mb/day in 2009.

Overall, from the PO point of view, the present economic crisis had a small positive effect of reducing demand, and of slightly delaying the peak date. However, one must also remember that it had effects over the crude oil price, lowering it enough to send a very wrong price signal to the uninformed consumers, and enough to force the delaying of several exploration and extraction projects. These delays will inevitably have some impact in the production capacity of the next few years—which, we believe, will precisely be the Peak years.

7. Energy alternatives

As discussed above, we are probably very close to the world historical maximum for the production of liquid fossil fuels. As such, our societies will have to adapt to a new paradigm: Instead of the comfortable situation of the last century, in which petroleum production was able to grow without significant constraints to match the gradually increasing demand, we will have to adjust to a progressively decreasing production. This new reality will have an important impact on the availability and prices of the commercial energy used in every activity sector.

Excluding the transportation sector, the dependence on liquid fuels is more limited and, although with inevitable transition difficulties, our societies will probably be able to mitigate the ensuing problems, for example relying in a greater use of renewable technologies for electricity production (such as wind farms, hydroelectric dams, geothermic plants and solar energy conversion).

However, in the transportation sector, the dependence on crude oil is so overwhelming that it is difficult to imagine a relatively painless transition. Naturally, electricity use can be intensified in several classes of transports, and that can help solve environmental and sustainability problems. For instance, modern electrical train-like mass transportation systems can

[6] The important "Megaprojects" collaborative effort keeps a continuously updated listing of new oil supply projects. The results are available at: http://en.wikipedia.org/wiki/Oil_megaprojects.

[7] The values appear in the Oil Market Report from September 2010, available at: http://omrpublic.iea.org/.

be very efficient and attractive to the users both in intercity travel and in city transportation networks. Also, most of the uses of today's cars (e.g., daily commuting to work) could also be performed by electrical vehicles. However, there are classes of transports that cannot realistically convert to that solution, such as airplanes, long distance cargo trucks, and ships. For these classes, liquid fuels are by far more convenient than any other available alternative, although it can be argued that compressed gaseous fuels, or even coal in case of ships, can be used if the need arises.

In the last few years, hydrogen has been the most discussed gaseous solution to replace liquid fossil fuels. However, hydrogen is only an energy carrier, not an energy source like crude oil. Besides, the path to the much touted "hydrogen economy" is blocked by several very important technologic and economic problems. Moreover, it even presents a long-term sustainability problem since a massive production and utilization of a gas as volatile as hydrogen would inevitably result in some escaping to the atmosphere before recombination with oxygen. This hydrogen in the atmosphere rises and escapes to space, and since this important new source of atmospheric hydrogen would easily surpass the present sources, this would aggravate significantly the continuing "hydrogen loss" from our planet.

Other gaseous fuels alternatives presently under consideration are mainly based on liquefied petroleum gas (LPG) or on natural gas (NG). For many applications, these gaseous fuels can be directly used. The most important example is the growing use of compressed natural gas (CNG) in transport applications. Natural gas can also be liquefied and can be a fairly convenient short to medium term alternative to the conventional petroleum derivatives. Although the world NG resources have not been as intensively studied as the crude oil resources, they are still relatively plentiful and point to the peak of gas production occurring significantly later than the Peak Oil. The tendency for an increased importance of NG in the world energy mix has been reinforced with the recent strong increase in NG extraction from shale formations in USA. It can be expected that the technological developments that allowed this increase in the USA can also be applied to shale formations through the world. However, at present, the shale gas reserves outside the USA and Canada are still in an initial evaluation phase. A recent study financed by the USA gas industry, points to an increase of the NG role in the USA total energy mix from today's values of 24% to an optimistic value of 40% by 2040 [17]. This 40% percentage can be contextualized with the present relevance of crude oil and coal in the world energy mix, respectively 34% and 27% [13]. However, the use of fossil gaseous fuels is not a long term solution for a progressively declining oil production, since they are also non-renewable. The possible dates for the peak of gas production are not as extensively studied as the PO dates, but one can find predictions pointing to 2020 [16] and to 2030 or later [17]. From the moment of peak of gas production onward, both the oil and gas production will be declining simultaneously, increasing the need to find long term alternatives.

Getting back to liquid fuels, besides those of fossil origin there is a significant possibility of using renewable biologic fuels. Presently, those "biofuels" represent only about 1.5% of the energy used in the transportation sector [13]. Ethanol produced from sugar cane in semi-tropical climates, for example in Brazil, is already close to be price-competitive with conventional fossil fuels, although this is far from true in the case of ethanol production from corn, beet, and other agricultural products used on temperate climates. However, due to direct constraints in soil availability, biofuel productions based on present technologies will always be severely limited.

Finally, it is possible to produce fuels that are liquid at ordinary atmospheric pressures and temperatures through the industrial transformation of gaseous (e.g., natural gas) or solid (e.g., coal) fossil energy sources, although those transformations present some economic and ecological problems. In particular, industrial coal-to-liquids conversion dates back to World War II, and since then has seen limited use in countries like South Africa. However these liquid alternatives to conventional petroleum have similar future availability problems as petroleum itself and as gaseous fossil fuels, since they are also based on the consumption of limited, virtually irreplaceable, fossil resources and may also be subjected to political supply constraints [5]. During the last century, conventional crude oil proved to be the most precious and convenient of the fossil fuels, and as such it was the most actively extracted and consumed, and so it is now in a more advanced state of depletion. However, several authors are already expressing serious concerns about a "peak gas" [21] and about a somewhat more distant "peak coal" [22].

8. Effects of the Peak Oil

Our societies should regard the fossil resources (oil, coal and natural gas) as a precious gift from nature. They required many millions of years to create, but we are now consuming them fast—they will basically be exhausted in some 4 centuries (only 2 centuries for crude oil), a short time frame even in the context of the history of mankind. Since the beginning of the 20th century, the swift development of our civilization (in terms of number of inhabitants, standard of living, technological progress, ability to travel and to transport goods to long distances, etc.) has depended on a relatively unconstrained supply of cheap energy. Crude oil has indubitably been the greater component of this ever growing supply of convenient energy. Excluding limited periods during wars and during the politically based energy crisis of the seventies and eighties, until recently (arguably until 2004) our societies only had to spend a very limited proportion of their resources to pay for this absolutely vital energy supply. In fact, since the beginning of commercial oil extraction, around 150 years ago, a number of factors[8] allowed us to increase oil production at a rate that was able both to match the ever growing demand and to maintain

[8] Such as the vast initial base of fossil resources, the early discovery of the best production provinces, the very attractive return on most production investments, and the continued technical progress in the exploration and extraction techniques.

Table 2
Oil production and price.

Year	2002	2003	2004	2005	2006	2007	2008
Production [Mb/day]	77.0	79.6	83.1	84.6	84.5	84.4	85.4
Price [$/barrel]	26.18	31.08	41.51	56.64	66.05	72.34	99.67
Price [2002 $/barrel]	26.18	30.40	39.46	51.96	58.71	62.37	82.93

enough extra capacity to cover for occasional production problems. This has allowed the long-term relative cost of energy to drop significantly [9]. A near-term peak of oil production will dramatically change this comfortable state of affairs. In our opinion, the first effects of the Peak Oil already made themselves felt. However, it seems indisputable that the most relevant consequences will be suffered in the future, as a result of the progressive decrease of oil production that will follow the occurrence of the peak.

8.1. Up to the present

The unbalanced relation between the extreme usefulness and convenience of the fossil fuels (in particular of liquid fossil fuels) and their low relative cost has molded our societies and our behavior. This seems obvious when we compare our present way of life with the realities from a couple of centuries ago. Apart from their relevance in the production activities (agriculture, mining and manufacturing), the fossil fuels enabled us to travel in cars and planes in everyday commuting and in business and leisure traveling. They also enabled us to transport commodities and goods both locally and globally. We got used to this convenient way of life to such a degree that it can be seen as an addiction. This is clearly true in developed countries but, perhaps more surprisingly, it also tends to be true in many of the less developed countries. In fact, many of them have experienced fast urbanization trends, depend on the international shipment of natural resources, food, and manufactured products, and have an internal transportation system even more dependent on liquid fossil fuels than most of the developed countries. These development models created rigid demand patterns that make it difficult for our societies to reduce significantly the consumption of fossil fuels even in the face of important price increases. This means demand has low price elasticity. As a consequence of this low price elasticity, in a situation where production cannot fulfill the desired demand and the only possible matching mechanism is demand compression, the prices have to rise very significantly to create the required reduction of consumption. This is precisely what has been happening since 2003.

In the last few years we have been experiencing the first significant global signs of crude oil exhaustion. The price of oil (and, naturally, of the refined products) has risen to record highs as a result of lack of ability to go on increasing the world production to match the continued increase in demand. This was particularly noteworthy during 2005, 2006 and 2007, when the prices increased very significantly, reaching values well above the ceiling desired by the oil producers. This ceiling, apparently contrary to the producer's direct interests, resulted from concerns about a possible demand reduction due to excessively high oil prices.[9] During this phase, from 2005 up to July 2008, with the very high prices acting as a very strong incentive to maximum production and also in face of very significant political pressures from the importing countries, all the producers attempted to increase oil supply to the markets. However, in spite of their best efforts, the world production could not be increased to match the desired demand. Table 2 illustrates this reality, showing averaged, annual, world oil production values in million barrels per day and averaged annual spot oil prices in US dollars per barrel.[10] The third line in this table presents the same prices but corrected to 2002 dollars so as to discount the inflation effect. As can be seen, even when the prices are corrected for inflation, the price increase presents the same behavior.

Basically, this inability to increase the world oil production, even in the face of very high prices and of the international pressures of the importing countries, was not due to wars or political decisions but rather to physical constraints on available oil resources and on the associated production infrastructure. As such, the high fuel prices of last few years can be regarded as the first effective consequence of Peak Oil that mankind had to face.

It is interesting to analyze the impact of these significant higher fuel prices in our societies.

Due to the lack of flexibility of the individual consumption patterns (i.e., due to the low price elasticity of demand) even significant price increases tend to have relatively limited direct effect on demand. However, through one mechanism or another, demand really has to be compressed to match the available supply. As it happens, a significant rise in fuel prices tends to trigger secondary effects that have ulterior reflections on demand. Sadly, instead of relying on voluntary behavior changes, these secondary effects are invariably related to a depression of the economic activity.

[9] OPEC, the only world body that officially tries to control the world oil prices, had since March 2000 until January 2005 an official price ceiling of $28 for its crude basket. This ceiling was largely surpassed by the averaged oil prices in 2003 and 2004 and was officially abandoned in 30 January 2005. From that point on, several ceilings were discussed only to be successively surpassed by the continued rise of the oil prices.

[10] The values shown in Table 2 were obtained from the US Energy Information Agency website (http://www.eia.doe.gov/). The production values are for all fossil liquids. The quoted prices are based on the WTI spot, one of the most important world references for oil price.

Table 3
Federal funds rate – USA, and ECB refinancing rate – EU.

Year	2002	2003	2004	2005	2006	2007	2008
Federal funds rate [%]	1.25	1.00	2.25	4.25	5.25	4.25	0.0–0.25
ECB refinancing rate [%]	2.75	2.00	2.00	2.25	3.50	4.00	2.50

The recent increase in fuel prices has affected directly a number of activities (e.g., airline industries, road transportation, fisheries) reducing some operations and resulting in financial losses and even bankruptcies. Besides having a direct effect in fuel demand, this reduced business activity also tends to diminish overall wealth, and the tax income of the governments, and to increase unemployment—with additional secondary consequences in fuel demand. Naturally, it is possible to identify additional mechanisms that contribute to a reduction of oil demand. As an example, increased spending at the fuel pump by individuals and families usually forces a compression in other expenses, mainly affecting less essential discretionary activities and the associated businesses (e.g., restaurants, tourist resorts, other leisure-related businesses), again reducing overall economic activity, with secondary reduction of oil demand.

However, since 2008, the worst and most visible consequences of this kind of effects directly traceable to oil scarcity were effaced by the occurrence of a major global economic crisis. This crisis induced a significant fuel demand compression and created a temporary excess of production capacity that lead to a major oil price decrease. Yet, in our opinion, the crisis itself cannot be isolated from the Peak Oil production plateau that we have been experiencing since 2004.

It is uncontroversial that the main cause for the recent financial and economic crisis was the bursting of a major credit bubble. However, we believe that the increased costs incurred by the families, by the companies, and even by the importing countries, due to the increase in crude oil and fuel prices between 2004 and 2008, were one of the triggers for this crisis.

There are several links that connect the oil price raise and the present economic crisis. Clearly, the very significant increase of the fuel prices between 2003 and 2008 generated a cascade of other price increases (mainly in energy, agriculture products and another commodities) creating inflationary pressures. To fight these pressures several central banks had to increase their lending rates. These rate increases contributed to the bursting of the vast debt bubble that had been growing in most developed economies. In Table 3 we present the evolution of the major lending rates of the two most important central banks. The rates shown for each year were in effect at the end of December. One must note that the values for 2008 resulted from aggressive rate reductions that occurred during that year, already in response to the beginning of the financial and economic crisis.

Besides the induction of inflation, it is possible to identify other more or less direct connections between the PO-induced increases in the fuel prices and the causes of the economic crisis. Naturally, the effects of increased fuel prices on some particularly vulnerable economic activities, already referenced, also had some influence in the beginning of the crisis. However, we can propose a more direct effect of high fuel prices that can be associated to the bursting of the credit bubble. One must remember that this rupture started with a significant correction in the overheated USA housing market, and then affected the directly connected economic activities (e.g., the building industry) and propagated to the financial institutions that had assumed excessive risk through mortgage-related leveraged financial instruments. In our opinion, the increase in commuting costs, stemming from the higher fuel prices, suddenly reduced the appeal of the more remote suburban housing projects, and this was one of the initial drivers of the housing market crash (this was particularly noticeable in some projects in California, one of the first regions of the USA where the housing crash was felt).

Considering this combination of factors, we believe that it can be argued that this crisis is already, in part, an effect of the Peak Oil.

8.2. The future

As discussed, some of the first effects of the Peak Oil already manifested themselves in the recent past and, since even in the difficult context of the economic crisis the prices of crude oil remain very high in relation to the historic average, they keep being felt at present. However, it seems clear that those effects will be significantly stronger in the future. As those effects become more salient, they will undoubtedly be easier to trace to the root cause—the depletion and resulting increased scarcity of valuable, non-renewable, fossil liquids resources.

In the future, the supply/demand tightening that will result first from absence of oil production growth and later from an actual production decrease, will again force significant fuel price increases. This fact will lead to an increased effort to improve the energy efficiency of the overall societies and, in particular, of cars and other transport systems. This should result in a compression of world demand growth that, in mature developed countries, will translate into actual demand decrease. However, even in the face of higher fuel prices, a continued demand growth can be expected in rapidly developing countries (among whom the most important are China and India), and in oil producers like Saudi Arabia, reinforcing the expected supply/demand stress that would always result from a peak in oil production.

As could be expected, most of the future problems related to the occurrence of the Peak Oil can be viewed as "economic", and will simply be an extension of the effects felt up until now, already summarily described. Besides the direct increase in fuel prices, these effects include:

Table 4
Cost of oil imports for several countries in 2008.

Country	Net oil imports [kb/day]	Average oil price [$/barrel]	Oil cost deficit [$\$ \times 10^9$]	Balance of payments [$\$ \times 10^9$]
Germany	2418	98.98	87.4	+241.5
Greece	429	98.98	15.5	−50.9
Portugal	284	98.98	10.3	−29.5
Spain	1534	98.98	55.4	−152.7
USA	10,984	98.98	396.8	−706.1

(a) An increase in the prices of base materials or products that require significant use of liquid fossil fuels in their extraction, production and transport. Those include many commodities, among them minerals and agricultural products.
(b) A secondary increase in the prices of products affected by higher prices in the more directly impacted base materials cited in (a), or by transportation costs. These include almost all final physical products, such as processed food, clothing and appliances. Naturally, this effect can be delayed by temporary deflationary pressures resulting from the ongoing economic and financial crisis.
(c) Damage to the activities and industries more dependent of fuel prices. These include agriculture, fisheries, activities related to tourism or traveling, the auto industry, road transportation, etc. A secondary effect of this is an increase in unemployment.
(d) Reduced mobility for most people and merchandises, directly resulting from increased mobility and transport costs [18]. This effect is compounded by reduced overall wealth stemming from the debt-induced economic and financial crisis and, indirectly, from the effects of the Peak Oil itself.

Other effects, also easy to predict on the basis of what has already occurred in the recent past, relate to the social impact of rising fuel prices. This impact differs according to the realities of each country, but some main issues can be identified:

(a) Difficulties in imposing fuel price increases, in particular in countries where the fuel prices are viewed as set by the governments. This tends to be an even bigger problem in countries where the prices are subsidized. In these countries the populations are used to consume fuels at prices below the effective market values, and to regard that as their right. Since, in these circumstances, crude oil price increases tend to, sooner or later, translate into sudden large increases in final fuel prices, it is easy to understand the social impact that this can cause.
(b) Since some specific industries will be affected earlier and more strongly by fuel price increases than the society at large, and will suffer disproportionaly, in the limit these industries may fail to assure the services they usually fulfill. The social impact of these problems depends on the relevance for the normal working of the overall society of each affected activity. Also, industries whose stopping can cause more severe and more immediate problems, can easily feel that they may gain from strikes and other demonstrations of discontent. The widespread trucking strikes that occurred in Europe in early 2008 present a good example of the problems that can be created by these industry actions.
(c) Difficulty, in the face of significant crude oil price increases, in maintaining the important tax revenues associated to the consumption of liquid fossil fuels—particularly in countries where these taxes are presently higher (e.g., most European countries). This difficulty results both from consumer protests due to the increasing effort level of fuel purchases and from an inevitable consumption reduction, even if limited by the initial low price elasticity. For some governments, the fuel taxes are a significant revenue source and so this reduction in tax collection will cause increased difficulties in their financing, creating additional problems in the present background of large deficits and very high public debt.

A very relevant problem of international economic balance that has been gaining impact, and will be a source of increasing international stresses as the Peak Oil forces higher crude oil prices, is the relative impoverishment of most of the countries that depend on crude oil imports. Apart from the other components of the international trade balance of each country, the need to import crude oil (or its refined products)[11] represents a permanent and unidirectional financial drain. Naturally, if this continued financial expense could be avoided, those values could be used to import other commodities or goods, or could simply not be spent, with significant advantages to the trade balance of those countries. Table 4 shows, for a

[11] A marginal effect that is being felt at this moment and will certainly aggravate itself, is the tendency of some important exporting countries (e.g., Saudi Arabia and other Middle East exporters) to process their own crude oil production. This way, these countries also capture the economic benefits of the refining industrial activity, an important diversification to countries were agriculture and industrial activities are scarce and that depend almost exclusively of crude oil production—an activity that creates little employment and that generates social imbalances. Important consumers like China and India have also increased very significantly their refining capacity. Conversely, partially due to these refinery additions elsewhere and partially due to excess refining capacity installed to cover higher previous consumption levels, many OECD refining companies are having successive losses due to a prolonged phase of very low refining margins [19]. This is true to refiners with old equipment that only can process light sweet crude but also, although to lesser degree, to newer refineries able to process heavy sour grades [20].

sample of some oil importing countries, the evaluation of the import costs during 2008—the most recent year for which there is publicly available data for oil imports and balance of payments.[12] The net oil imports include crude and refined products. The oil price refers to the average, during 2008, of the price of the Brent blend, the most used referential for European countries, and very close in price to the WTI and New York referentials used in the USA. The oil cost deficit was estimated as a simple product of the annual net oil imports and the average oil price. As can be noted, for all the countries in Table 4, in 2008 the cost of the imports of liquid fossil fuels represented a very significant fraction of the balance of payments. Greece, Portugal and Spain have been referenced as countries with severe public accounts deficits but also present high external trade deficits that represent an important part of their economic and financial problems. The USA presents similar public accounts and trade deficits. As Table 4 illustrates, if the oil imports could be avoided the trade balance for these countries would be significantly improved. This is particularly true for the USA, where the net oil imports represent more than half of the deficit of the balance of payments. Even in the case of Germany, until recently the world largest exporter, avoiding the cost of oil imports would still have a significant impact in the balance of payments, increasing it by over a third.

It is interesting to consider the results of the same level of oil imports but at the average, historic, inflation-corrected oil prices of approximately a quarter of the 2008 values. As an example, the impact of those lower prices in the US balance of payments would be a reduction in the deficit from about 700 to 400 billion dollars. This would happen with exactly the same physical imports and exports of the 2008 balance. We should note that these lower prices were still occurring as recently as 2002, before the first Peak Oil effects. From this basis, one can easily project the impact of future increasing oil prices in the balance of payments of the importing countries. Again using the USA as an example, the same level of imports at double crude oil prices would raise the deficit of the balance of payments from about 700 to 1100 billion dollars. This kind of effect in the trade balance is also noteworthy in countries that are forced to change from oil exporters to importers (e.g., Indonesia and UK in the recent past, Mexico in the near future). On the other hand, oil exporting countries have the converse benefit of a significant positive effect in the trade balances, and this effect can be expected to increase with higher crude oil prices—if those countries manage to remain significant exporters on the face of the depletion of their fossil resources. Unfortunately, in some of those exporting countries this wealth influx has limited impact in the prosperity of the general population.

As discussed in the previous section, the very first Peak Oil effects already had a role in the occurrence of the present economic crisis. This resulted from a simple difficulty in increasing crude oil production to match the growing demand, still before the actual peak production date. In the future, with the start of an actual decrease in oil production, we will inevitably experience progressive effects on the price and availability of liquid fuels, with important negative impacts in the economies of most countries. Considering this, it can be expected that the peak and posterior decline of oil production will trigger and aggravate new global economic hardships. Depending on the dynamics of global economy and of the efforts taken by the governments to fight the present and the future crises, the result can be a succession of cycles of crises, followed by weak recoveries, followed by new crises, or it can take the form of a more continuous "long crisis" characterized, at the very least, by very slow world economic growth. It is important to notice that, as discussed before, the present relatively weak world economic recovery is occurring at a time when the oil production still can grow to match the (recovering) demand. In the present societal and technologic context, it will be extremely hard to achieve any world economic growth in a situation of progressively decreasing oil production.

However, in spite of the partial influence of the Peak Oil, the present international crisis was mainly due to a credit bubble linked to very high levels of debt on the part of many governments and families. These debt levels are being compounded by the expenses incurred by many governments to limit the effects of the crisis itself. The result is that many countries are running very high public deficits that add to the already high public debts. This course will have to be corrected, and that will require a very significant contraction of spending levels. Unfortunately, the necessary tightening of government (and individual) expenditures will overlap with the time frame when our societies should be dedicating their best efforts to the difficult problem of creating viable alternatives to the present energy paradigm based on fossil fuels. Naturally, the necessity of compressing national expenses at this very moment creates an additional obstacle to the achievement of a benign transition to the new reality of decreasing availability of liquid fossil fuels.

Nevertheless, the crises themselves result in a compression of demand for liquid fuels—in fact, we believe that in the present conditions, economic crises are the main effectively available mechanism for demand compression. This is a rare positive effect of these (present and future) crises although, unfortunately, this form of unplanned and involuntary demand compression inevitably involves important hardships.

Naturally, even in this difficult context, the adjustments to respond to the progressively decreasing availability of liquid fuels will have to be made. These adjustments will include improving general energy efficiency (in particular when related to transportation), bringing to the market more competitive electric cars, developing the renewable forms of electricity production (and increasing the actual use of those that are or become viable), researching better electricity storage devices, increasing the production of biofuels, etc. These efforts, and the resulting progresses, are positive in themselves, since they tend to reduce pollution (in particular CO_2 atmospheric emissions) and to improve the sustainability of our societies [6], but

[12] The net oil imports and price data was obtained from the Energy Information Agency web site (http://tonto.eia.doe.gov/). The balance of payments data was obtained from the statistical OECD web site (http://stats.oecd.org/).

they will also result in several direct positive economic and social developments. Among them, it is easy to predict an increase in some classes of jobs (in several areas of research, in biofuels production, etc.) and the emergence and growth of several industrial activities.

Overall, however, it is impossible to expect that the beneficial effects of Peak Oil will be able to balance its negative effects. The peak of oil production is not a voluntary option that we have chosen for its benefits. It is an involuntary result of the physical impossibility to go on increasing the extraction of a non-renewable natural resource—a precious resource that, during the last 150 years, has contributed significantly to allow our growth in numbers and the global improvement of our standards of living.

9. Conclusions

Near the end of 2010, with the present (relatively) lower fuel prices and the overwhelming concerns about the ongoing economic recession, the mainstream media have totally forgotten the worries related to a near term PO that had begun to surface with the high fuel prices of early 2008. However, as sketched in Fig. 1, in a near future the desired consumption will again tend to exceed the world production capacity. Due to the predictable absence of effective large-scale alternative energy solutions, this will result in a renewed strong price increase for crude oil, and for its refined products. Moreover, after the moment when the crisis-depressed demand hits the post-PO production capacity, everything points to an irreversible situation of progressively reduced world oil production. That new situation, with lower production and tendentially higher prices year after year, will inevitably be more difficult to accommodate by our addicted societies than the relative benign pre-peak tightening of 2004–2008.

A significant increase in energy prices will affect the whole society by several mechanisms, one of which will be the induction of economic recessions. However, as a direct effect of Peak Oil, the increase in energy prices will be concentrated on the liquid fuels. As such, the transportation sector will be specially affected. In this sector, a strong fuel price increase will have a particularly negative impact in the air transport, both of passengers and cargo [8]. We believe that the cheap, wide-scale air transport that our present societies take for granted will be replaced by a more expensive and restrictive model, closer to the selective commercial air transport of the early jet age. In contrast, high-speed electric rail transport will inevitably grow, and will partially replace air travel. This transition, by itself, will strongly affect specific industries like the intercontinental mass tourism that flourished with the recent emergence of low cost air travel, or the production of fresh agricultural products very far from the consumption locations.

The present road transportation systems will also suffer important consequences from significantly higher liquid fuel costs. Predictable transitions include a reduced incidence of long distance road cargo movements, partially replaced by increased railway transportation and, in terms of people commuting, a significant increase of mass transit and electrical vehicles. During this phase of forced adaptation, some countries will face greater challenges than others. These include oil importing countries with greater dependence on oil in terms of their energy-mix, and countries that got used to oil production surplus, but due to increased populations and to the peaking of their own oil production will have to adapt from exporters to importers.

The impact of the Peak Oil will be felt at worldwide level, at regional level (i.e., integrated groups of countries with similar societal and energetic issues like the European Union), at the level of individual countries and their sub-regions, at the level of municipalities, and at the level of companies and families. However, the future of overall mankind and of particular countries, regions, or any groupings of people, is not yet fixed: it depends on decisions that are being taken at the present moment and of decisions that will still be taken in the future. As such, predicting the impact of the Peak Oil is something that must be done through a continuously refined process of information collection and analysis.

As much as can be inferred at this moment, the impact of the Peak Oil, at each of the levels discussed above, will inevitably be significant but can still range from relatively benign to really catastrophic scenarios.

Unfortunately, we believe that most of the decision makers at all levels (international organizations, individual countries, municipalities, commercial companies and even at family level) still need to improve significantly their knowledge about this very important problem. The present lack of knowledge is illustrated by many decisions being taken at all levels that seem to be totally inappropriate in face of this new reality and that do not point to an effective mitigation of the Peak Oil problem.

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