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Fossil resource depletion and climate change emissions: the role of physical constrictions

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Abstract

In terms of global warming, early peak forecasts in oil and natural gas seem reasonably good news because most emissions arise from fossil fuel burning. However, this can be misleading if coal resources are as enormous as some estimations report because a switch between low carbon content fossil fuels (oil and natural gas) and high carbon content (coal) can be envisaged. Following this hypothesis we develop peak oil and natural gas scenarios where coal supplies what is needed for levelling off fossil fuel energy as soon as oil and natural gas reach their joint peak. We estimate the implications in terms of greenhouse gas emissions and we compare them with the most pessimistic IPCC scenario. Our conclusion is, despite this IPCC scenario probably being unrealistic, the limitation of fossil fuel resources is not quite sufficient to avoid very dangerous emission future evolutions. CO_2 concentrations well above 450 ppm at the end of the century are derived and, in addition, no sign of stabilization is observed.

Resumen

En lo que concierne al cambio climático, los pronósticos de cercanos picos de combustible fósiles parecen buenas noticias pues la mayoría de las emisiones proceden de la quema de combustibles fósiles. Sin embargo, esto podría resultar engañoso de confirmarse las enormes estimaciones de reservas de carbón pues puede divisarse un intercambio de combustible fósiles con baja concentración de carbono (petróleo y gas) por otros de mayor (carbón). Ciñéndonos a esta hipótesis desarrollamos escenarios donde tan pronto el petróleo y el gas natural alcanzan su cénit la extracción de carbón crece lo necesario para compensar el descenso de los primeros. Estimamos las emisiones que se deriva de tales supuestos y las comparamos con el peor escenario del IPCC. Si bien dicho escenario parece improbable concluimos que los picos de petróleo y gas no son suficientes para evitar peligrosas sendas de gases de efecto invernadero. Las concentraciones de CO2 halladas superan con creces las 450 ppm sin signos de remisión.

Keywords: peak oil, global warming, non renewable resource models.

JEL: C6, Q3, Q4.

1. A short introduction

Global warming and energy from fossil fuels are both sides of the same coin. Last decades –and especially after the UNCC 1992 convention- public concern about massive fossil fuels use has mostly been focused on its climate effects. The anthropogenic Greenhouse Gas (GHG) emissions arise from different activities but have only become significant since "industrial revolution" with its huge increase in fossil fuel burning. Nowadays, approximately 70% of CO_2-eq emissions (IEA, 2007: p253) come from energy sector, so its key role in climate change. This carbon is emitted in the combustion of fossil fuels, a process that provides 80% of energy supply (IPCC, 2007: p256; IEA, 2008a: p38). Even though there are experimental "Carbon Capture and Storage" (CCS) technologies and some optimists expect that in the future these technologies will be used at a great scale, future GHG emissions will very probably be strongly associated with.

On the other hand, in the 1970s and 1980s public worry was not for the environmental impacts of fossil fuels burning but for the natural scarcity of fossil fuels –and, especially, of oil, the key energy source. It was the time of price oil "shocks". Latter decrease in oil prices left this concern to one side, at least up to first years of XXIst century. However, several authors have been defending the importance that fossil fuels reserves are, in historical terms, very limited and, therefore, the massive availability of concentrated and accessible energy characterising last world history period will not last forever.

As soon as 1956, geologist M. King Hubbert predicted (and he was correct!) a decline in US oil output from 1969, following the extraction a bell curve path. Hubbert and his followers –represented now by the ASPO (Association for the Study of Peak Oil)- have been pointing out that –as oil in USA- the world increasing historical use of oil and natural gas will be followed by an opposite trend in the near future (Campbell y Laherrère, 1998). When in the period between 2004 and mid 2008 oil barrel prices stepped up to 50$, 100$ and nearly 150$ (before financial crisis affected dramatically economic activity and world oil demand) the “peak oil” (and “gas peak”) model began to be considered more seriously.

Thus, different worries about climate change and fossil fuel depletion have dominated different historical moments. Nevertheless, both problems have not been often analysed together in an explicit way (Kharecha & Hansen (2007), Brecha (2008) and Nell and Cooper (2008) are three exceptions); for instance, IPCC scenarios do not make any reference about limits in fossil fuel geological availability. This article aim to analyse the consequences on emissions of different patterns of fossil fuel use along XXIst century considering resources are limited.

2. Depletion of non-renewable resources: non-economic and economic models

As we have pointed out in previous section, the “peak oil” model (Hubbert, 1956) is nowadays an essential reference point in the debate on energy resource future.

The peak oil model is a type of S-shape model. In this kind of models the curve describing the accumulated extraction process is characterised by a slow beginning followed by a fast development until the extraction rate decreases and the function tend asymptotically to the final accumulated extraction. This final extraction is a key variable: the Ultimate Recoverable Resources (URR). Obviously nobody thinks that complex reality can be reflected in a simple mathematical model but it is postulated that the resource will not exhaust suddenly: the phase of increasing extraction rate is followed by a similar (or equal, depending on the specific model) phase of decreasing extraction rate.

To model the extraction of a non-renewable resource in an S-shape model, we need the historical extraction data, to speculate about the value of URR which it is not known (and in fact it depends not only on geological realities but also on technological, economic and political ones) and to decide the specific mathematical model to apply. Logistic curve, usually called Hubbert's Curve in this context, was the first Hubbert's proposal for an S shape curve, and it is, probably, the most used. However, other symmetric curves can and have been suggested: Deffeyes fits a Cauchy curve (quoted in Caithamer, 2008: p656), Caithamer tries LSD densities relying on the fact that world oil production grows faster than polynomially but slower than exponentially (p664), other authors prefer t-Student density and different logistic curves modifications (Brecha, 2008). In fact, any distribution function (in the probability theory sense) is a potential candidate because of its S shape. Moreover, there is not any reason to consider only symmetrical extraction patterns and we can introduce asymmetrical extraction models (Mohr & Evans, 2007; Feng et al., 2008). Table 1 is a collection of "peak oil style" functions proposed by several authors in which we distinguish whether they are characterised by a symmetrical or not symmetrical pattern.

The most striking characteristic of these mathematical models is not only their simplicity but also the fact that they do not consider any economic variable. However, we cannot claim these models are purely "geological" because geology is key in determining the depletion rate in a specific oil field but it can hardly explain the world resources exhaustion rate which relies on the investment rate in the extractive industry. Moreover, every model could be compatible with very different economic scenarios; specifically, a phase of decreasing rate of extraction could be compatible with many different processes (for instance the demand could step down as a result of a planned transition to other energy sources or sparked off by a dramatic increase in prices).

Table 1. Extraction functions.

Name	Extraction[1,2,3]	Accumulated extraction[4,5]	Symmetrical	References
Logistic	$\dot{P} = rP\left(1 - \frac{P}{P_\infty}\right)$	$P(t) = \frac{P_\infty}{1 + \left(\frac{P_\infty - P(0)}{P(0)}\right)e^{-rt}}$	Yes	Hubbert (1956), Deffeyes (2005), Caithamer (2008), Brecha (2008)
Logistic-Brecha	$\dot{P} = rP\left(1 - \frac{P}{P_\infty(1+rt)}\right)$		No	Brecha (2008)
HCZ	$\dot{P}(t) = aP_\infty e^{-\left(\frac{a}{b}\right)e^{-bt} - bt}$	$P(t) = P_\infty e^{-\left(\frac{a}{b}\right)e^{-bt}}$	No	Feng, Li & Pang (2008)
Gaussian	$\dot{P}(t) = P_\infty \frac{e^{\frac{-(t-\tau_{peak})^2}{2\sigma^2}}}{\sqrt{2\pi}\sigma}$		Yes	
LSD	$\dot{P}(t) = \frac{P_\infty}{\sigma LSD(\alpha,\beta,\gamma)} e^{\left(\frac{-\gamma\left\|\frac{t-\mu}{\sigma}\right\|^{\beta}}{\left\|\frac{t-\mu}{\sigma}\right\|^{\beta-\alpha}+1}\right)}$		Yes	Caithamer (2008)
Cauchy	$\dot{P}(t) = \frac{P_\infty}{\pi(1+t^2)}$	$P(t) = \frac{P_\infty}{\pi}\tan^{-1}(t)$	Yes	Caithamer (2008)

1 P_∞ stands for the Ultimate Recoverable Resources (URR).
2 In Brecha, P_∞ does not represent a fix UUR. The resources are assumed to be continuously growing and expressed by $P_\infty(1+kt)$.
3 Kaufmann & Shiers represent extraction in a discrete fashion, so we choose Q instead of P' to represent “discrete”extraction.
4 When an analytic expression exists.
5 Initial time is considered to be 0.

Kaufmann & Shiers	$Q_t = \begin{cases} Q_{t-1}\left(1+R\left(1-\frac{1}{((\tau_{peak}+1)-2004)(t-2004)}\right)\right) & t \le \tau_{peak} \\ Q_{t-1}\left(1-S\left(1-\frac{1}{((\tau_{peak}+1)-2004)(t-2004)}\right)\right) & t > \tau_{peak} \end{cases}$		Yes	Kaufmann & Shiers (2008)
Pointy peak	$\dot{P}(t) = \begin{cases} rP(t) & t \le \tau_{peak} \\ k(P_\infty - P(t)) & t > \tau_{peak} \end{cases}$	$P(t) = \begin{cases} P(0)e^{rt} & t \le \tau_{peak} \\ P_\infty\left(1-e^{-k(t-\tau_{peak})}\right) + P(0)e^{-k(t-\tau_{peak})+r\tau_{peak}} & t > \tau_{peak} \end{cases}$	No	Wood et al. (2003)
Mohr-Evans[6,7] algorithm				

6 Mohr-Evans algorithm (Mohr & Evans, 2007) is a more complex procedure for achieving a better adjustment of forecast extraction to historical data.

$$\dot{P}(t) = \begin{cases} IBC(t) & t < t_{a_0} \\ SP_i(t) & t_{a_{i-1}} \le t < t_{a_i}, 1 \le i \le m \\ p(t) & t_{a_m} \le t < t_1 \\ IBC(t + t_2 - t_1) & t \ge t_1 \end{cases}$$

(I) Find τ_{peak} and $IBC(\tau_{peak})$ in $IBC(t) = \frac{2IBC(\tau_{peak})}{1+\cosh(R(t-\tau_{peak}))}$ using a P_∞ estimate.

(II) Select a period of anomalies $t_{a0}<t_{a1}<\ldots<t_{am}$ and adjust small grade polynomials (grade 1 or 2) for every subinterval $[t_{ai-1}, t_{ai}]$.

(III) Find t_q such that $\int_{t_{a_0}}^{t_q} IBC(t) = \sum_{i=1}^{m} \int_{t_{a_{i-1}}}^{t_{a_i}} SP_i(t)$

(IV) Estimate a high degree polynomial for the last years $Q(t)$.

(V) Select a grade n and find an n-polynomial, t_1 and t_2 such that $p^{(i}(t_{am}))=Q^{(i}(t_{am})$ for 0≤i≤n-1, $p(t_1)=IBC(t_2)$ and $\int_{t_{a_m}}^{t_1} p(t) = \int_{t_q}^{t_2} IBC(t)$.

7 The Mohr-Evans function is not symmetrical.

How could we select the most suitable models? We should make use of some "economic intuition" and avoid economically strange results. For instance, as Kaufmann and Shiers (2008) say, a model characterised by a very large reduction in extraction after a yearly peak is not very probable because it would imply investments in extraction and transport infrastructures that would become rapidly obsolete and owing to, in the authors' own words, "the large reduction in output after the peak also is inconsistent with the most rudimentary forms of forward-looking behaviour that is required to maximize the net present value of a non renewable resource. A large reduction in global production (…) seems to imply a significant jump in prices following the peak (specially after many decades of steadily increasing production prior to the peak)" (Kaufmann and Shiers, 2008: p406).

In spite of the absence of explicit economic variables, the Hubbert and other similar models have an important and desirable feature: they respect the constraint that the total accumulated extraction must be lesser than the (unknown but certainly finite) total URR. It might seem of little importance but we should remember that neither usual theoretical growth economic models nor many economic projections satisfy this minimal requirement. To adapt economic projections to geological restrictions is more or less important depending on the situation of the resources and the period of projection. When we analyse the future of oil and gas in the XXIst century we are faced with a lot of extraction paths apparently plausible in economic terms but impossible –or very improbable- taking into account the geological restrictions. By contrast, this might not be valid for coal because a great deal of feasible economic scenarios can be considered geologically feasible as well. We will further return to this question.

The economic theory of non renewable resources has been based in the Hotelling's 1931 *Journal of Political Economy* article; in the words of Devarajan and Fisher: “There are only a few fields in economics whose antecedents can be traced to a single, seminal article. One such fields is natural resource economics (…); its origin is widely recognised as Harold Hotelling’s 1931 paper” (1987, p. 670). According to the Hotelling's rule the prices (nets of extraction costs) of a non-renewable resource should build up at a pace equalling interest rate and resource should run out exactly when demand become null. This rule should give the only “equilibrium” price path compatible with the intertemporal (and discounted) profit maximization of economic agents in a competitive market. Hotelling's rule does not directly say anything about the evolution of extraction along time. Were the demand function to be invariable (a very implausible assumption) and the extraction cost constant, the extraction would monotonously decrease but, with other assumptions, it would be consistent with a “peak” in extraction (for example in the case of increasing demand or in the case of an initial phase of decreasing extraction costs brought about by technological change); nevertheless, peak could be situated in any point of accumulated extraction depending on the particular demand and cost evolution (Holland, 2008).

Despite its historical significance and merits, Hotelling's model shows a lot of problems when it is applied to explain the effective prices of non-renewable commodities. The economic agents do not make their decisions based upon actual and future prices but in function of actual prices and expectations about future prices; in other words, the opportunity cost of not selling the commodity today is not known. Even in the simplest model this fact will provoke prices to be defined more by instability than by very foreseeable paths (Mishan, 1981; Roca, 1991). Moreover, we cannot consider that resources are immediately available for being used now or in the future in any quantity only relying on actual and expected prices; actually, the extraction of non-renewable resources is constrained by previous investment in extraction capacity (Thompson, 2001; Cairns, 2001; Banks, 2004). Investors decide how much to invest in the industry when the future conditions of the market are very uncertain; so, past decisions determine the maximum commodity amount which can be sold at any moment and, usually, how much will effectively be sold taking into consideration sunk costs, possibly resulting in cyclical patterns in prices.

Accounting that non-renewable market is, in many cases, very far from perfect competitive markets (e.g. the OPEC relevant role in some periods in oil market) (Slade, 1991) it is not surprising that the “Hotelling's rule” is not able to explain the historical trends in non-renewable prices (Krautkramer, 1998). The great geographic concentration of resources such as oil and gas will cause strategic decisions of some key actors to become more and more relevant in the future (and also political conflicts in some areas will become more relevant).

As we have said, the Hubbert-type models do not consider explicitly the interactions between economy and non-renewable extraction. Some models, notwithstanding, have taken into account these interactions. The most famous is World3, used in Meadows et al. (1974) and –with few minor changes- in Meadows et al. (2004). Relationship between Hubbert's model and Meadows' team model seems deep. In fact, in the non-renewable resource sector description in Meadows et al. (1974) we can read “the following discussion is based on material in M.King Hubbert's “Energy resources” ” (Meadows et al., 1974: p381). However, the dynamical system proposed in World3 for dealing with non-renewable resources appears to be far more complicated than logistic model. And indeed, it is. It considers feedbacks between economy and non-renewable resource use: when industrial production increases, the use of non-renewable resource increases but –at the same time- an increasing fraction of industrial output has to be derived to extracting this resources (extractive capital non disposable for industrial capital) because of the major difficulties to obtain resources as they are being depleted.

The system can be described in a mathematical form as

$$\dot{R} = -rN \qquad (1)$$
$$r = f(y), with\ f' > 0 \qquad (2)$$
$$y = \frac{Y}{N} \qquad (3)$$
$$Y = \left(1 - g\left(\frac{R}{R_0}\right)\right)\frac{K}{\beta}, with\ g' < 0 \qquad (4)$$
$$\dot{K} = sY - \delta K \qquad (5)$$

being R non-renewable resource remaining, N population, Y industrial output free of extraction tasks, K industrial capital, s savings, δ the depreciation rate, β the capital to output ratio, $f(y)$ resource per capita needs for an industrial output per capita y, $g\left(\frac{R}{R_0}\right)$ the share of industrial output needed when the fraction of remaining resources equates $\frac{R}{R_0}$. As expected, the resource production P equals rN. Putting together some of the above equations the system reduces to

$$\dot{R} = -f\left(\left(1 - g\left(\frac{R}{R_0}\right)\right)\frac{K}{N\beta}\right)N \qquad (7)$$
$$\dot{K} = K\left(\left(1 - g\left(\frac{R}{R_0}\right)\right)\frac{s}{\beta} - \delta\right) \qquad (8)$$

Now, Hubbert model can be obtained from World3 model choosing $\delta = 0$, $f(x)=a\cdot x$ being a constant, $g(x)=1-x$ and $K_0=0$. It can be easily proved that

$$\dot{R} = -\frac{s}{\beta R_0}R(R_0 - R) \qquad (10)$$

Or

$$\dot{P} = cP\left(1 - \frac{P}{R_0}\right), with\ c = \frac{s}{\beta}, \qquad (11)$$

closing this way the link between both model classes.

The dynamics of the whole system –with demographic, economic and environmental subsystems connected between them- depends on many equations but, in most scenarios considered in these works, non- renewable resource extraction decrease and the system collapses in the XXIst century. World3 model is so general that all non-renewable resources are treated as a single resource without any distinction between different fossil fuels nor even between fossil fuels and other mineral resources. Several world models, notably the International Futures saga by Barry Hughes, have been designed to overcome this limitation and even consider unconventional sources (IF, RIVM (DeVries, 2001), G-Cubed (McKibbin & Wilcoxen (1995)), MESSAGE (IIASA, 2005), GEM-E3, WEM (IEA, 2008b)).

Nel and Cooper (2008) in a recent paper consider an economy-energy model without prices where future energy supply is limited –in the fossil fuel case using Hubbert-type curves- and global production is a function of total energy (corrected by energy efficiency coefficients for every fuel and by the increasing energy cost for obtaining energy commodities). They add an *adhoc* assumption consisting of, when total production decreases, equally dividing production decrease between declining consumption and declining capital formation. Their model generates futures scenarios where primary energy consumption is lower – due to insufficient investment- than energy availability.

3. Future scenarios of fossil fuel extraction[8]

As pointed out previously, we think geological constraints must be seriously regarded if we are interested in long term possible fossil fuels extraction paths. In this section we limit ourselves to consider XXIst century scenarios. Despite the fact in every case scenarios must be compatible with geological restrictions

[8] Most non-renewable resource models choose the term “production” instead of extraction. However, in conventional economic terms “production” is almost synonymous with “added value generation” and, from another viewpoint, we can stand fossil fuels are “produced” by very long term geological processes and just extracted by man.

as a whole, we think it is useful to distinguish between two fossil fuels resources: on one hand, oil and gas, on the other hand, coal. The oil URR are unknown but we can be sure –also under very optimistic expectation- that even if a great economic investment could make up for physical exhaustion and allow the world to sustain or increase the extraction rate for several years or even some decades it would be followed by a decline in extraction rate; the same is true for natural gas although one can bet decrease will be delayed in comparison with oil. Obviously geological constrictions imply the following trade off: if peak is reached later and/or the recoverable resources quantity is higher, then fall will be more dramatic and probably social and economic problems will be harder. (Of course, geological constraints do not let laying aside the possibility of complex paths with oscillating decreasing and increasing extraction periods). By contrast, in the coal case, geological constraints are much more weaker and we are allowed to assume resources are abundant enough for regarding the extraction rate during the XXIst century as unconstrained by geological availability and essentially determined by economics and politics, including environmental policy.

In the following scenarios we do not develop explicitly any economic model. Our purpose –more modest- is to consider the implication of several different and feasible extraction paths and to analyse their implications in terms of CO_2 emissions. Realise the different scenarios are opened futures –what could be an advantage- because they are compatible with many social and economic evolutions: for instance, a decline in fossil fuel use for next decades could be associated to (and perhaps be the cause of) a global economic recession or with a delinking between economic activity and fossil fuel burning thanks to more energy efficiency, alternative energies deployment and/or changes in the relative weight of different economic activities in favour of less energy intensive ones. Moreover, economic growth or degrowth could have various social impacts depending on how many and what countries and social groups are affected: one can even imagine a possible economic degrowth in rich countries without a decrease in most population welfare.

Oil and gas URR Assumptions: Low and High scenarios

Oil and gas extraction paths can be forecast by former models on condition that certain values are fixed and others deduced. Probably, the most important is the Ultimate Recoverable Resource which we are going to take as the defining concept of two different scenarios classes: *low* and *high*. In the oil case we only refer to "conventional oil"[9].

Low scenarios

These scenarios could have been termed ASPO (Association for the Study of Peak Oil) scenarios because the proposals are going to be based on authors' estimations who are ASPO members or with a strong relationship with the association. Inspired by the following conventional oil recoverable resource list –and taken into account that we use conventional oil in a no very restrictive sense- we have chosen 2,100 Gbo as a good measure for the oil ultimate: Campbell & Laherrère (1998, p81) suggested 1,800 Gbo, Ehrlich et al. in 1977 spoke of 1,900 Gbo (Bentley & Boyle, 2008: p610), Hubbert in 1977 and Ivanhoe in 1996 (Bentley & Boyle, 2008: p610) estimated 2,000 Gbo, IEA in 1998 (Bentley & Boyle, 2008: p610) 2,300 Gbo, Campbell (2002: p3) 1,925 Gbo and (2002: p8) 1900 Gbo.

Natural gas resources has been less analysed. [10]Nel & Cooper chose 2,038 Gboe

[9] We follow IEA in considering that conventional oil stands for crude oil and NGL, including deep sea wells (IEA, 2006 : p91). Synthetic crude oil, oil shale, tar sands, heavy oils (<20º API, BGR, 2006: p31) are considered unconventional oil. Moreover, liquids derived from coal (CTL) or gas (GTL) are not included in conventional oil. This definition changes between institutions and authors (e.g. Campbell does not consider conventional oil from deep water wells, polar oilfields, NGL either).

[10] The gas resources are usually expressed in unites different of Gboe. For the translation in terms of Gboe we have sued the following conversion factors: 6,29

(p169). Brecha suggested three scenarios: first, URR equal to BP reserves (1,116 Gboe), second a 50% higher and third doubling BP reserves (p3498).Cumulative production is read in BGR (2006: p62), 527 Gboe. It also seems there is agreement in the fact that natural gas resources are significantly lower than oil resources. Considering the uncertainties we finally suggest 1,700 Gboe.

Fossil fuel	***URR(Gboe)***
Oil	2,100
Natural gas	1,700

High scenarios

These scenarios have been called high scenarios because they are based on the biggest estimates we have found in broad diffusion literature on recoverable resources

US Geological Survey (2000) provides a high estimate of 3,900 and a mean estimate of 3,000 Gbo for URR oil (Cleveland & al., 2003: p321). As the biggest number seems too unlikely but we are interested in high proposals we choose to move estimate a third the distance between the high and the mean values: 3,300 Gboe. Other high –but more moderate estimation- are BGR (2006: p51) 2,304 Gbo, Mohr & Evans (2007) between 2,234 and 2,734 Gbo.

With regard to natural gas BGR (2006) gives the value of 2,968 Gboe, the biggest we have found: we round up 3,000 Gboe (Table 2). Estimates of IEA (2008a: p42) 2,516 Gboe and IPCC (2007: p264), speaking of 2,356 Gboe, are lower.

Gboe/tcm; 1 bcm (billion cubic meter) equals 6,29 Mbo (Megabarrel oil) (from BP (2007); 1 toe equals 42 GJ.

Extraction functions

We try three different mathematical functions for describing oil and natural gas extraction paths. This is intended to extend the scope of our results to a broader set of feasible behaviours. We look at three "styles" of exhaustion: a symmetrical curve with a peak; a symmetrical curve with a plateau lasting several years; an asymmetrical curve with a peak and a decreasing phase faster than the increasing one.

Symmetrical peak curve (in particular, *Logistic or Hubbert's Curve*)

These kind of functions are suitable for a path characterised by a peak and symmetrical up and down extraction rates. As explained before (see Table 1) there are multiple functions with this propriety and we have experimented with many symmetrical curves (Gaussians, for instance) but not meaningful differences in results have been found so we restrict ourselves to logistic ones. We are looking for two logistic curves being the solution of the next two differential equations:

$$\dot{P}_i = k_i P_i (P_\infty - P_i), where\ i \in \{1(oil), 2(natural\ gas)\} \qquad (12)$$

Thus, our problem is to determine k_i values minimizing the sums of the square differences between the values given by the solutions of the equations and those supply by historical data. Once optimal k_i are calculated, peak years can be easily found.

Plateau curve

It can be economically argued that for a period fossil fuel extraction could follow a plateau curve, an extraction pattern in which a maximum is reached and sustained for a period [$\tau_{peak\ up}$, $\tau_{peak\ down}$] (while investment capital offsets deposits geological exhaustion) before starting a decline (Kaufmann, 2008; p406). Notwithstanding, we have not found a specification of a plateau curve in the literature, so we propose the following based upon two Gaussian curves enclosing the plateau. The graph is chosen to be symmetric fixing the same deviation (σ). Eventually, a faster or slower decline could have been selected breaking the symmetry.

$$\pi(t) = \begin{cases} \dfrac{e^{\frac{-(t-\tau_{peak\ up})^2}{2\sigma^2}}}{\sqrt{2\pi}\sigma} & t \leq \tau_{peak\ up} \\ \dfrac{1}{\sqrt{2\pi}\sigma} & \tau_{peak\ up} \leq t < \tau_{peak\ down} \\ \dfrac{e^{\frac{-(t-\tau_{peak\ down})^2}{2\sigma^2}}}{\sqrt{2\pi}\sigma} & t \geq \tau_{peak\ down} \end{cases} \qquad (13)$$

$$\dot{P}(t) = \frac{P_\infty}{\left(\frac{\tau_{peak\ down}-\tau_{peak\ up}}{\sqrt{2\pi}\sigma}\right)+1}\pi(t)$$

Asymmetrical curve

As commented previously there is no reason for ruling out the possibility of an asymmetrical extraction curve. This is also suggested by IEA (2008a: p17) which reports the graph of a fast extraction trend followed by a long and soft slope. We suggest joining two Gaussian Bells characterised by different deviations (σ_1 and σ_2) and demanding continuity in peak year (τ_{peak}). In Table 1 other kinds of assymetrical curves are included. However, we construct this one because of the easiness in the parameter interpretation.

$$\pi(t) = \begin{cases} \dfrac{e^{\frac{-(t-\tau_{peak})^2}{2\sigma_1^2}}}{\sqrt{2\pi}\sigma_1} & t \leq \tau_{peak} \\ \dfrac{e^{\frac{-(t-\tau_{peak})^2}{2\sigma_2^2}}}{\sqrt{2\pi}\sigma_2} & t \geq \tau_{peak} \end{cases} \qquad (14)$$

$$\dot{P}(t) = \frac{P_\infty}{\frac{1}{2}\left(1+\frac{\sigma_1}{\sigma_2}\right)}\pi(t)$$

A spike, a not derivable point, is allowed at τ_{peak}. Usually softer coupling (equality of first derivatives) is demanded. Nonetheless, we do not see neither the need nor the convenience of adding a new parameter for meeting the additional condition.

Table 3 sums up the scenarios.

Extraction function | URR	*Oil=2,100 Gas=1,700 (Gboe)* **Low**	*Oil=3,300 Gas=3,000 (Gboe)* **high**
Symmetrical	Symmetrical low	Symmetrical high
Plateau	Plateau low	Plateau high
Asymmetrical	Asymmetrical low	Asymmetrical high

<u>The coal question: will XXIst century be the century of coal?</u>

In the second part of XXth century oil became clearly the first primary energy source. Last years, coal extraction has increased more than oil extraction. Our scenarios imply oil and gas extraction will decrease next decades; these scenarios are not predictions and the effective extraction path is sure to be more complex; nonetheless, taking into account the limited available amount of these resources and the present accumulated extraction we think that real future extraction will likely be situated in –or near- the range of our scenarios; in other words, we believe total energy from oil and natural gas will peak –as we will see in next section- between present and 2036.

Thus, the key question regarding CO_2 emissions along this century is coal consumption. Rich countries are used to step up fossil fuel burning and this energy model is being adopted by an increasing number of countries. When oil and natural gas supply will decrease there will be a lot of pressure to extract more and more coal (and also non conventional oil) to make up for the other fossil fuels in order to obtain heat, to produce electricity and even liquid fuels (via Coal-To-Liquid conversion). This substitution will cause huge environmental (and economic) costs but, likely, resource geological availability will not be an insuperable obstacle, at least during most part of XXIst century.

As said by Laherrère "estimates for coal resources are very uncommon" (Laherrère, 2004: p6): IEA(2006: p126) 2,961 Gboe[11], IPCC (2007: p264) speaks of more than 17,452 Gboe for coal and BGR gives the astonishing estimates of 46,686 Gboe for hard coal and 8,204 Gboe for lignite, adding both we get an approximate 55,000 Gboe resource stock. Last numbers are very speculative, have not received the same attention as oil and are enormous in comparison with accumulated extraction calculated from BP (2007): 1,189 Gboe[512]. Recently, several studies have put the reliability of coal reserves and URR in doubt (Zittel & Schindler, Dave Routledge) clashing directly against explicit or implicit statements held by international institutions as IEA or expert groups as IPCC. Even though we think former estimations could be excessive, coal is a resource more abundant than oil and natural gas. This fact justify the consideration of a scenario where coal supplies what is needed for levelling off fossil fuel energy[13] when oil and natural gas sum reach their joint peak. Formally stated,

$$\dot{P}_{coal}(t) = \dot{P}_{coal}(\tau_{oil+gas\,peak}) + \dot{P}_{oil}(\tau_{oil+gas\,peak}) + \dot{P}_{gas}(\tau_{oil+gas\,peak}) - \left(\dot{P}_{oil}(t) + \dot{P}_{gas}(t)\right) \quad t > \tau_{oil+gas\,peak}$$

Observe that this assumption represents a huge increase in coal burning but also represents to stop the trend defining humankind since Industrial Revolution: an increasing use of fossil fuels. Were our scenarios to happen, total use of the

[11] 909 bt (billion tonnes), assuming from BP (2007) that 1 toe equals 2.25 carbon tonnes which is an average between hard coal (1.5) and brown coal (3): (3+1.5)/2

[12] The consumption is added from 1965 to 2007, 646 Gboe. Then a linear trend from a 0 consumption in 1865 to a 1,482 Mtoe in 1965 is considered: 544 Gboe.

[13] We also need to make some assumption about the use of coal before oil and gas joint peak. In all the scenarios we suggest a logistic extraction curve tending to a peak when half of the resources have being extracted (URR equaling BGR resources).

three fossil fuels would stabilize. Moreover, this stabilisation in terms of primary energy would suppose a step down in available energy for final uses if we realize that future Energy Return On Investement (EROI) –energy gained by unit of total energy invested- will be reduced as a consequence of the extraction of fossil fuels in more and more difficult and remote sites; EROI could even suffer a more steep reduction if an increasing part of fossil fuels are devoted to energetically costly transformation processes such as transform coal or gas to liquid.

Our scenarios want to emphasize future coal extraction could follow a very distinct pattern from oil and natural gas. We focus on understanding the possible implications of a more and more intensive coal consumption to relieve oil and natural gas depletion. It is just a possibility, not the most probable but, for climate change and other environmental impacts, possibly the worst. We expect the world will transit to a more efficient energy model based in renewable energies. Energy and environmental policies and lifestyle evolution –not geology– will determine what will be the coal future.

The so-called non conventional oil have not being included in our scenarios. The exhaustion of conventional oil and natural gas will also press to use non conventional oil: oil from coal through the Fischer-Tropsch reaction, oil shales, bitumen extra-heavy oil (World Energy Council: p54), tar sands from Alberta and deep offshore wells. Controversy around the size and the development pace of this type of resources is a fact although most authors believe their relative weight in total energy will be limited at least for the next decades. This type of oils are characterised by a lower EROI than conventional ones and the (environmental and economic) costs of their extraction and transformation are high. If we integrated non conventional resources in our assumption of preserving total fuel oil primary energy after conventional oil and natural gas joint peak the coal curve should be interpreted as coal plus non conventional oil. Alternatively, we could model the increasing use of non conventional oil as a delay in the oil and gas joint peak.

4. Main results

To elaborate our results we have developed the previously brought up six scenarios combined with the explained assumption about future coal extraction. We have ajusted the functions taking into account historical data: oil data source is Caithamer up to 2003, following years are calculated substracting IEA (2005: p94) unconventional data to BP (2008) production and through interpolation; coal and natural gas data comes from BP(2008).

In what remains of this section we describe the main outcomes. The annex show the parameter values for every estimated functions.

Symmetrical peak curve

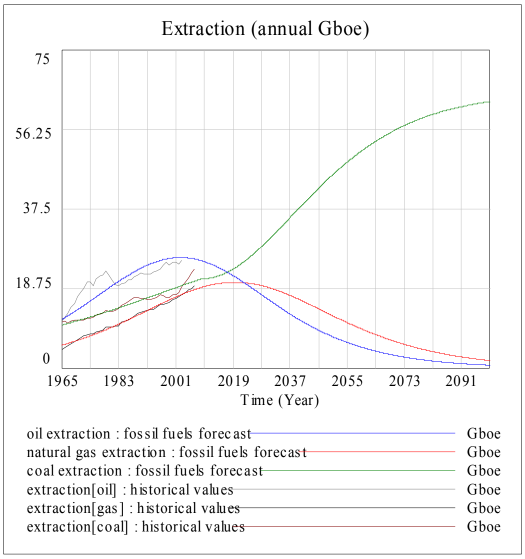
Graphs 1 and 2 give the results of these scenarios depending on the resource levels. Peak year estimations found are

Fossil fuel	***Low scenario Peak***	***High scenario Peak***
Oil	2004	2022
Natural gas	2019	2041
Oil + gas	2010	2030

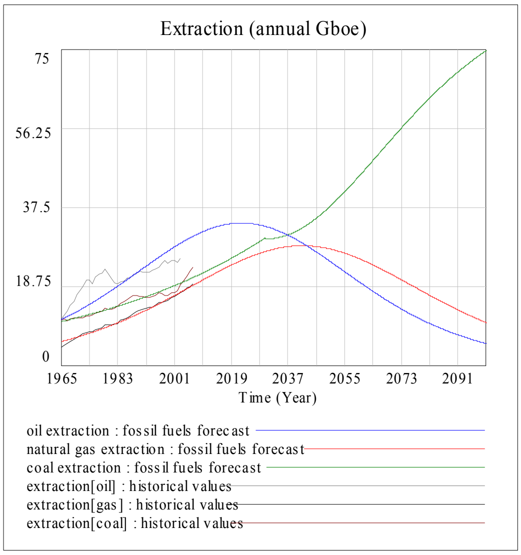
In low scenario, peak oil year is comparable to Hubbert 2000, Deffeyes 2005 or Bakhtiari 2006 (Bentley & Boyle, p610). Peak gas follows just after 17 years, a period of almost a couple of decades commented by Goodstein, Deffeyes or Kunstler (Porter, 2006: p190). Joint peak arrives in 2010. High scenario draws a similar picture with a 20-years delay in reaching peaks. Joint peak is reached in 2030.

There is no too many differences among accumulated coal extractions: 5,207

Gboe versus 5,238 Gboe in low and high scenarios respectively. Huge numbers but lower than the possible resource exploitable if there was no restriction and a lot of economic resources were invest in coal mining.



Graph 1. Fossil fuel extractions in Symmetrical low scenario.



Graph 2. Fossil fuel extractions in Symmetrical high scenario.

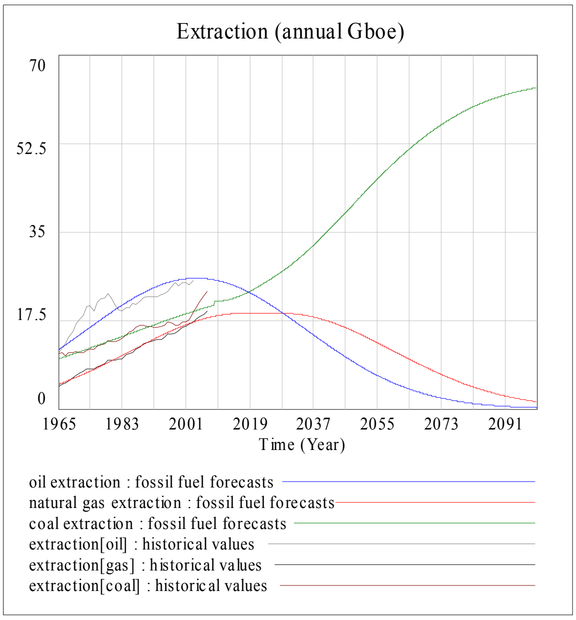
Plateau curve

Realizing data has not sufficiently evolved to see a plateau one of the parameters, $\tau_{peak\ up}$, $\tau_{peak\ down}$ or $\tau_{peak\ down}$ - $\tau_{peak\ up}$ must be fixed. If not, the system will choose both being equals. We think of a plateau beginning as soon as possible and lasting for 20 years. However, this is not always possible if consistency with data must be conserved. In the low scenario, there is no possibility to adjust a Plateau curve to oil extraction because a too large share of oil has already been consumed. In the natural gas case the better results are obtained fixing $\tau_{peak\ up}$ as 2017. The plateau lasts for 11 years before starting to decline (see Graph 3). In the high scenario, we found no problem in defining a plateau lasting for 20 years. Notwithstanding, the declining phase is meaningfully delayed (see Graph 4).

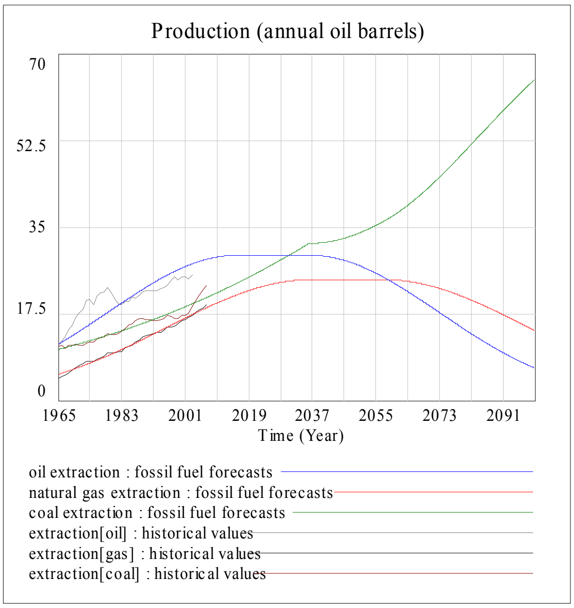
	Low scenario		***High scenario***	
Fossil fuel	***Peak up***	***Peak down***	***Peak up***	***Peak down***
Oil	2004	2004	2016	2036

Natural gas	2017	2028	2037	2057
	Peak		***Peak***	
Oil + gas	2009		2036	

Joint peaks are reached in and 2009 and 2036 respectively, with fossil fuel yearly extractions of 65.53 and 95.37 Gboe. Accumulated coal extractions are equal to 4,986 and 4,688 Gboe. Surprisingly, the quantity is lower in high scenario than in low although a fast look to the graphs reveals the conundrum: a lesser abrupt decline in oil and gas reserves implies delaying coal extraction.



Graph 3. Fossil fuel extractions in Plateau low scenario.



Graph 4. Fossil fuel extractions in Plateau low scenario.

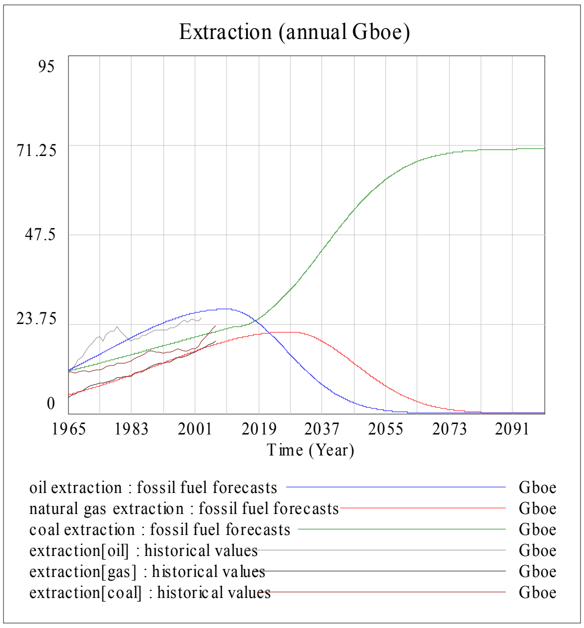
Asymmetrical curve

In this case, we want to study a scenario in which fall is more abrupt than stepping up; specifically we have set $\sigma_2=0.5\sigma_1$. This idea can also be tracked down in Wood pointy peak (2003) although our choice is sensitively softer as recommended by the previous economic explanations given in the Plateau curve. In some sense it can be seen as a complementary view respect the Plateau one.

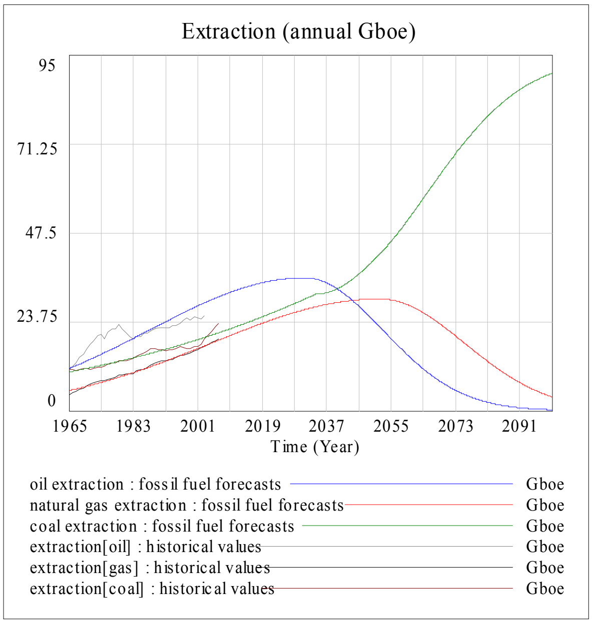
Fossil fuel	***Low scenario Peak***	***High scenario Peak***

Oil	2011	2031
Natural gas	2031	2032
Oil + gas	2013	2034

Joint peaks are reached in 2013 and 2034 respectively, with fossil fuel extractions accounting for 70.86 and 93.96 Gboe/yearly (see Graphs 5 and 6). The accumulated coal extraction is a huge 6,159 Gboe in low scenario and 5,886 Gboe in high scenario. Again, high scenario accumulated coal extraction is lesser than low scenario one, again for the same reasons as those explained in the Plateau curve.



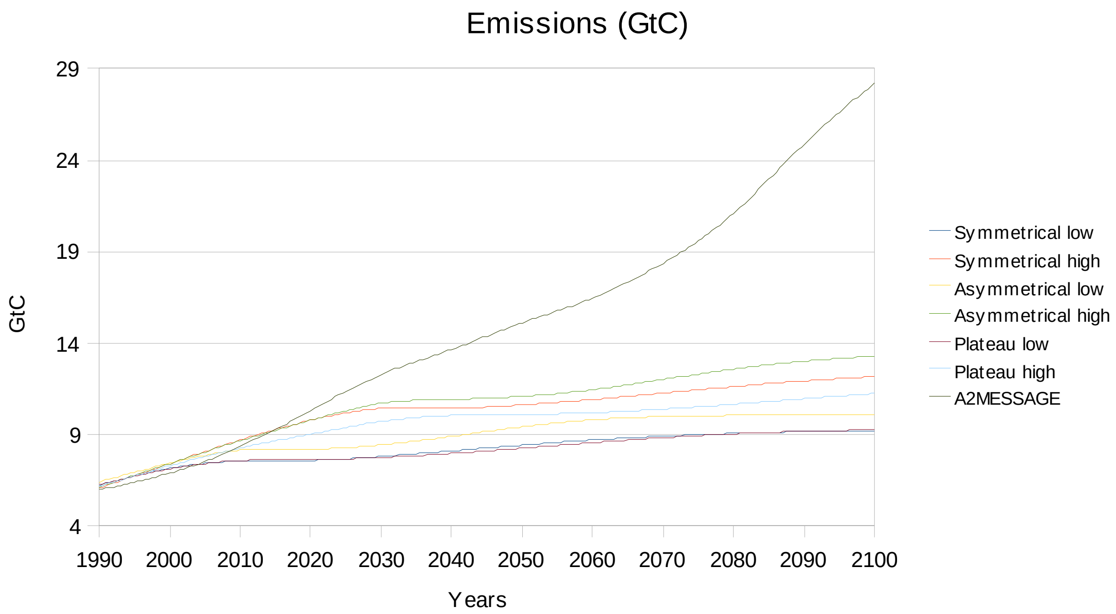
Graph 5. Fossil fuel extractions in Asymmetrical low scenario.



Graph 6. Fossil fuel extractions in Asymmetrical high scenario.

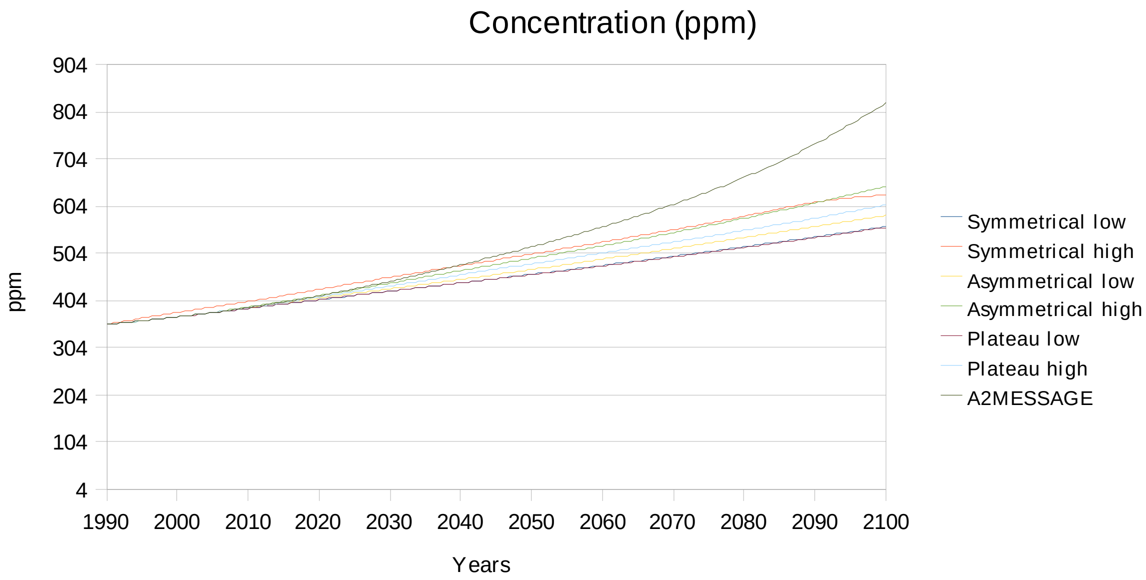
5. Implications for CO_2 emissions and climate change

Fossil fuel extraction paths allow to calculate the corresponding CO_2 emissions. As it is known, IPCC develops different scenarios of future emissions when it models their implications for climate change. The IPCC A2 is the worst of the scenarios in terms of expected concentrations and the temperature and sea level increase. We confront our results to IPCC A2 scenario keeping other climatic parameters and other greenhouse gases (different than CO_2) emissions projections unchanged. We select A2 storyline because we are interested in analysing if some of the IPCC assumptions can be thought to be "unrealistic" taking into account the limited reserves of oil and natural gas. As we have said, this question has not a clear answer because it depends basically on the future consumption of coal. Moreover, we are assuming that all the CO_2 emissions produced in the fossil fuel burning will go into the atmosphere without no Coal Capture and Storage (CSS). The massive use of CSS technologies are considered in Kharecha and Jansen (2007) and in Brecha (2008) pointing out that, taking into account what really matters are emissions from coal and not coal extraction, the use of these technologies would have analogous implications to a reduction in coal consumption (but we could ask for the risks and the energy cost of this technologies (Page, S.C., et al., 2008)); for Brecha (2008), coal availability seems to be the keystone when dealing with climate change and the related issue of which technology should receive most support considering the investment and time finiteness: in their opinion a superabundance would suggest substituting for oil and gas and CSS development, fewer resources would imply huge investments in renewable energies.

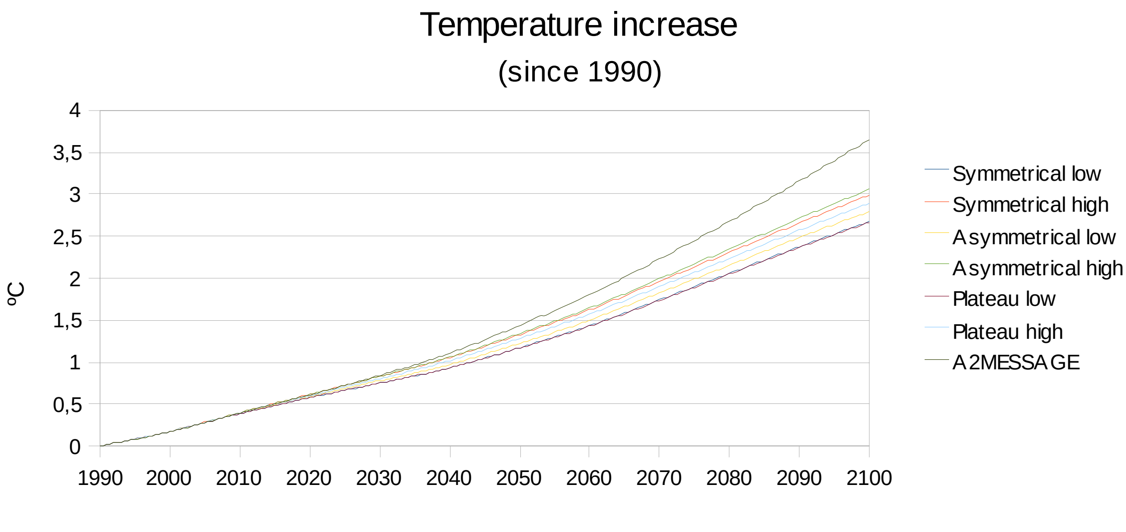


As it can be observed, emissions in our scenarios are significantly lower than A2 ones, with high scenarios accounting for the maximums, especially in combination with the Asymmetrical Curve. However, they are higher than those in Kharecha and Hansen (2007), what is more, they are still increasing in 2100.

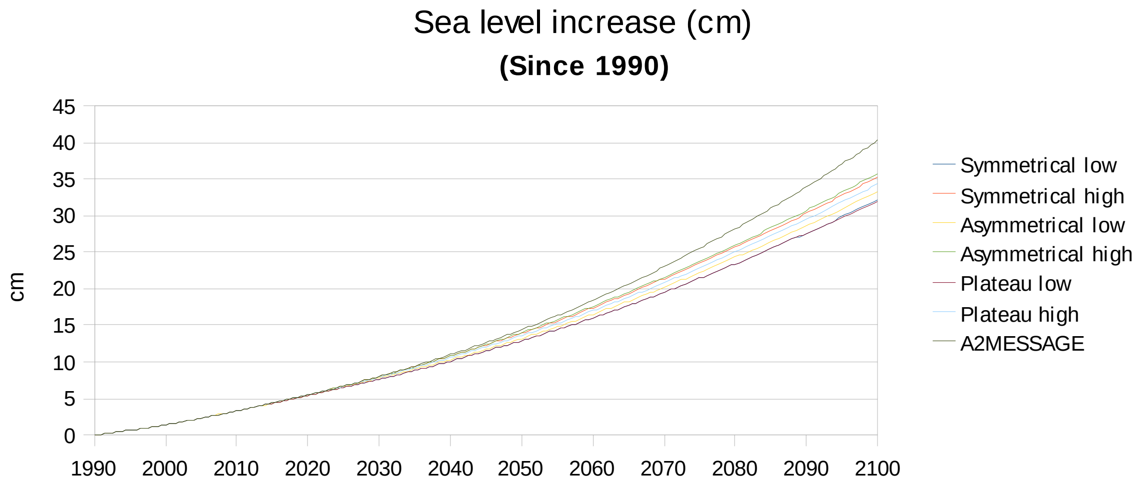
Although the higher emissions scenarios from IPCC could seem unrealistic, it does not mean at all than we should be unworried about climate change. The figures give some estimations of the possible effect of our scenarios in terms of GHG concentrations and its possible climate consequences. Calculations have been made by means of MAGICC, software developed by one the leading authors in IPCC simple climate modelling (Wigley, 2008).



CO_2 concentrations show similar patterns and in all six cases overcome the 450 ppm which is often considered the security level. Consistently with emissions paths, the Plateau curve presents the better performance although far from the quoted 450 ppm limit. Temperature increase in 2100 is in all cases above 2.5ºC and, in the worst case, above 3ºC. According to our model, sea level increase (Graph 10) will be slow in the first part of the XXIst century but will have already reached more than 30 cm at the end. A2 shows, as expected, a higher value.



Thus, the estimation of climate change effects of our scenarios are very dangerous. Besides, we should notice that there is a lot of uncertainty in the previsions on GHG concentration and, even more, in their effects. If adopt a precautionary principle approach this uncertainty is an additional reason to avoid emission paths as those found in this article.



6. Conclusions

Several publications (Kharecha & Hansen (2007); Brecha (2008); Nel & Cooper (2008)) relating peak fossil fuels extraction patterns with CO_2 emissions have put in doubt the reliability of, at least, some IPCC scenarios.

We agree with these authors that future emissions scenarios should take into account the availability of resources. So we have considered six different scenarios in order to connect climate change perspectives and fossil fuel depletion. The scenarios differ on the extraction function and the ultimate recoverable resource chosen for oil and gas. We have also supposed that more and more coal would be extracted to substitute the future oil and gas decline. Asymmetrical extraction patterns coupled with high oil and gas resources show the more adverse climate change consequences because of a higher fossil fuel levelling off, whereas symmetrical behaviours and low resources gives the less undesirable performance in relation with climate change prospect.

In spite of showing significantly fewer emissions than A2 IPCC scenario, concentration, sea level and temperature increases in our scenarios are worrying for two reasons: the estimated magnitude (temperatures above 1,5ºC respect 2000) and no sign of stabilization.

In consequence, we do not think the limited availability will be enough to avoid a dangerous emission path during this century. Even though emissions from oil and gas will likely decrease along next twenty or twenty five years, perhaps before, the emissions from coal –a more abundant resource- could more than compensate this reduction. So we coincide with Kharecha & Hansen (2007) when they say that the condition "to keep atmospheric CO_2 from exceeding about 450 ppm by 2100" imply "that emissions from coal, unconventional fossil fuels and land use are constrained" (p1). We also agree with the main conclusion of Brecha (2008): "The limited-fossil-fuel future (…) might be barely sufficient to limit CO_2 concentrations to the doubling preindustrial levels that optimists hope might limit temperature and sea-level rise within an acceptable range" (p3504). By contrast, we do not share at all Nel & Cooper (2008) conclusion "Our analysis proposes that the extent of Global warming may be acceptable and preferable when compared to the socio-economic consequences of not exploiting fossil fuels reserves to their full technical potential" (p15).

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Appendix

Parameters calibration

Coal extraction path before joint peak is defined by a logistic function with k = 3.13e-016. Oil and natural gas parameters can be looked up in Table 7.

	Low scenario					***High scenario***				
	Symmetrical	***Plateau***			***Asymmetrical***	***Symmetrical***	***Plateau***			***Asymmetrical***
Fossil fuel	***k***	***σ***	***Peak up***	***Peak down***	***σ_1***	***k***	***σ***	***Peak up***	***Peak down***	***σ_1***
Oil	2.6e-014	30.9	2004	2004	33.8	1.29e-014	36.9	2016	2036	43.5
Natural gas	2.8e-014	31.5	2017	2028	36.5	1.26e-014	41.1	2037	2057	47