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World Energy-economy scenarios with system dynamics modeling

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1 Introduction

Peak oil is becoming a major source of concern and forecast studies about oil consumption and production over the next decades are becoming frequent in literature. Predictions offer a wide spectrum of approaches and results. On one hand some focus on the economical and technological aspects (IIASA1998, WEO2007, EIA2007, IPCC2001, etc) and foresee scenarios of future rich in fuels. Other put the emphasis on the geological data of oil discoveries and oil field behaviour, not paying so much attention to the economical aspects, and foresees a future of scarcity (ASPO2008, Laherrere2005, Campbell1998, etc.).

Studies that take a look at the complete picture, paying attention both to the economical, the geological and the technological aspects are not frequent in the literature (Castro2007). System dynamics is a good methodology for such holistic approaches, since it enables the integration of several aspects and is designed to take into account all sorts of feedbacks among those aspects.

On the other hand, the World contains large quantities of non conventional oil, coal, natural gas, uranium and renewable resources which are assumed to compensate the decline of the conventional oil peak. We ask ourselves if the rest of energies are likely to come on-stream fast enough to offset conventional oil decline. And what would be the new scenarios of greenhouse gases if this would happen. The work presented in this paper is aimed at throwing some insight into those questions.

Scenarios hypothesis

In this paper the possible evolution of world energy production is studied using system dynamics models. The system dynamics scenarios presented in this work cover the aspects of the conventional oil peak, the relations with the economy, the implications on the rest of energies and the subsequent emissions of greenhouse gases. We are presenting two scenarios. The one we call “optimistic” scenario, and the one we call “pessimistic” scenario. Our models are based on a series of qualitative hypothesis that we describe as:

- Hubbert’s hypothesis[1]: describes the idea established by Hubbert (1956): the discoveries of oil fields and the production of oil (the same aply to the rest of non renewable resources like non conventional oil, coal, gas o uranium) vary with the stocks of undiscovered resources and/or reserves respectively. Therefore the less stock there is to be extracted (discovered) the more difficult it is to increase the annual extraction of this resource.
- Ayres hypothesis: Describes the role of technological innovation in the extractive process. It is an optimistic hypothesis that states that technological innovation

[1] See annex for details

increases at a constant rate. It is based on the ideas of Ayres (Ayres 2005) who states that, if an exponential growth of the extraction of a non renewable resource wants to be obtained, the innovation, or technological improvement, must increase constantly.

- Hirsch hypothesis: This hypothesis establishes the relationship between the oil demand and the GDP or the economy and we base it on the conclusion of Hirsch (2008) who states that world oil production growth and world GDP growth are strongly conected.
- UN population hypothesis: This hypothesis will be used to estimate the growth of the World population. We are not considering human population as an endogenous variable, since we do not make it depend on the energy or the GDP. Population is considered exogenous and we take as granted the UN estimations for the XXI century.
- Meadows hypothesis: This hypothesis, which we only use in the "pessimistic" scenarios, describes the relationship between GDP and the technological innovation and between GDP and renewables. It is based on the ideas of Meadows (1972, 2002) that established that the capital available for the technological advance depends on the GDP and if the growth is stuck it will tend to grow more slowly.
- Renewables hypothesis: The introduction of renewables and "future resources" (like fussion energy) is going to be very optimistic. We assume that the growth of renewables will be in such a way that will asymptotically approach technical potentials quickly, following Zerta2008. In the optimistic scenario this energy does not feedback with GDP and the investments required to increase production do not decrease GDP.
- EROEI hypothesis: We will loose energy for the production of energy (energy return on energy investment concept –Cleveland 1984, 1992, Hall2005). For each unit of non renewable energy we loose energy proportional to energy production modulated for an exponential over time. The less reserves the more energy we will need to extract it. This energy is lost for "real" economy, but it is not for emission scenarios.
- Emissions hypothesis: We will calculate from our models the CO_{2e} emissions (based on CO_{2e} per Jule from Farrel2007 calculations for non-conventional oil and IPCC1996 calculations for coal, natural gas and conventional oil).
- Other factors that could also influence the relations energy economy such as Climate Change, political or armed conflicts, or regional disparities will not be considered.

Scenarios

In figure 1 we can see a conceptual system dynamics model for our scenarios. *Reserves, non discovered resources* and *cumulative production* were chosen and corrected from Laherrere2005 Ultimate Resources Recovery for conventional oil, non conventional oil and natural gas, and from EGW2006, 2007, for coal and uranium.

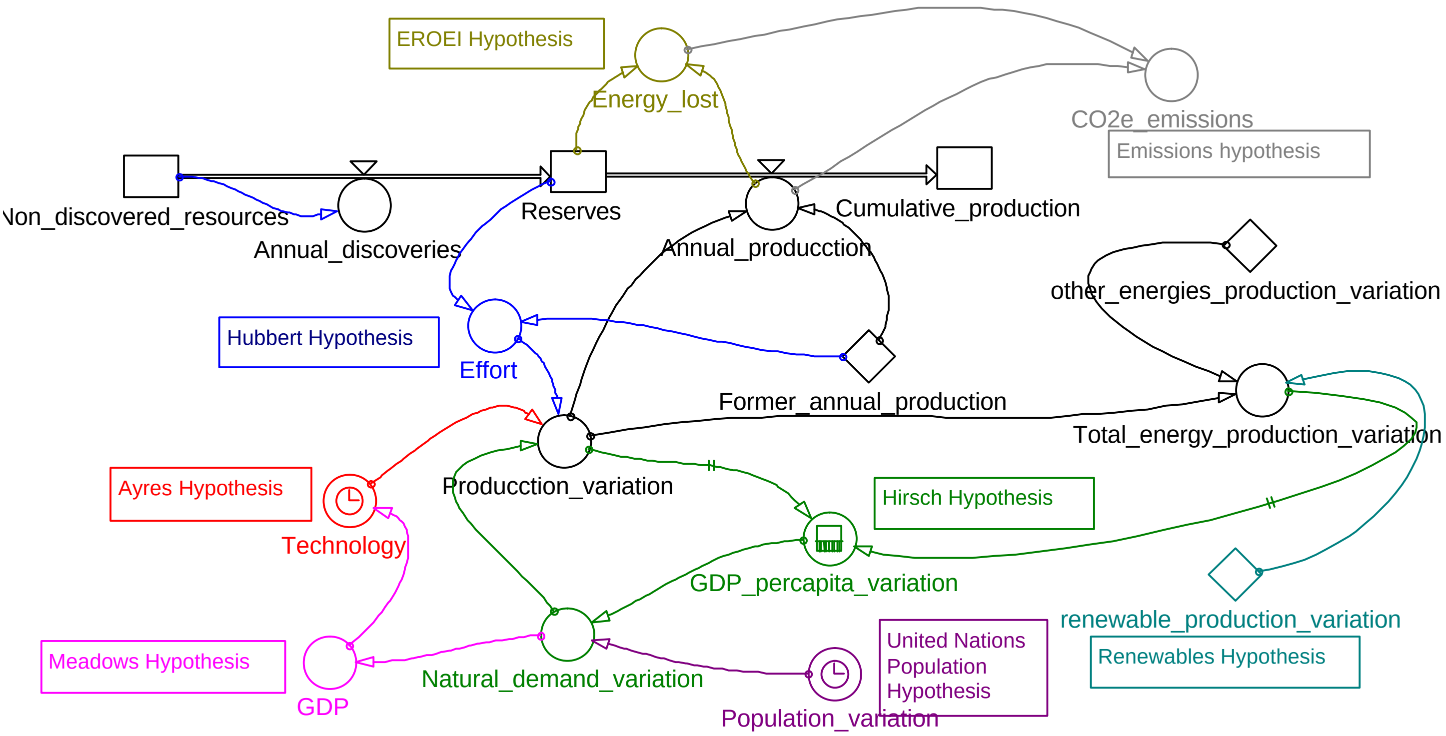

Figure 1. General model for the net conventional oil production with all the hypothesis. For the "optimistic model" Meadows hypothesis is not applied. For the "pessimistic model" the Renewables Hypothesis is not applied and Ayres Hypothesis is chosen a little bit less optimistic. This diagram is applied over each of *non renewable resources* and then we construct a total energy production variation and total CO2e emissions.

<u>Results of the simulations:</u>

Let us see some of the results of our model of energies. Two extreme scenarios could be designed, what we call "optimistic scenario" and "pessimistic scenario".

"Optimistic model":
In the "optimistic scenario" the Meadows hypothesis is not applied. This means that the capital available for technological advance does not depend on GDP, and therefore, when the GDP declines the technological advance is not affected. The renewable hypothesis, which is a very optimistic one, is applied in this model. The growth of renewable energies will approach technical potential quickly, and the investments required to increase production do not decrease GDP.

In figures 2, 3 and 4 the results of the simulation of this scenario are shown. In figure 2 we can see that the global energy production undergoes a 30 years plateau before continuing a steadily increasing growth. This is a very revealing result. Even using very optimistic hypothesis on the rhythm of substitution of energy and development of new sources, the decline of the global energy supply suffers a severe crisis when oil, gas and coal decline. In figure 4 we can see the estimated GDP, assuming that what we call "Hirsch hypothesis" remains constant, and, as could be expected, GDP suffers a long stagnation period too. On the other hand figure 5 shows the estimations of CO_2 emissions, which are among the most optimistic scenarios of the IPCC.

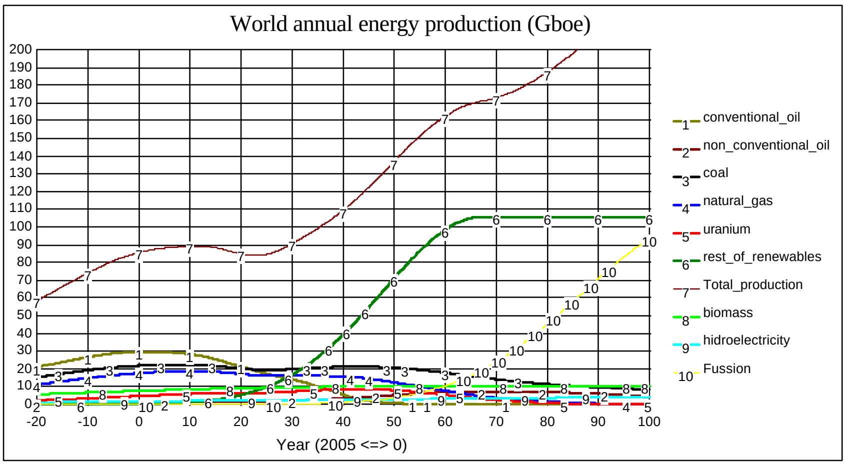

Figure 2: Optimistic scenario. Estimations of the World energy production. Despite the growth of the renewable energies and fusion production, a long period of energy stagnation cannot be avoided.

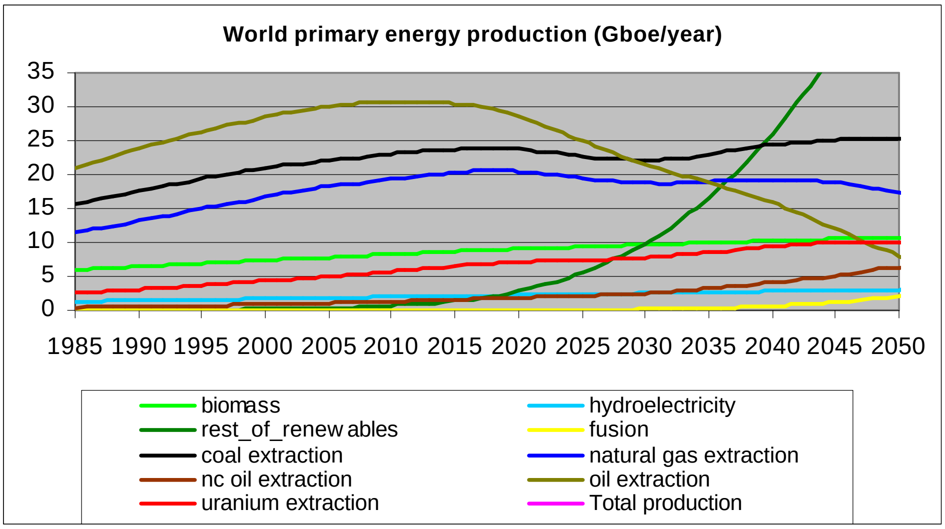

Figure 3: Optimistic scenario. Estimations of World energy production in more detail.

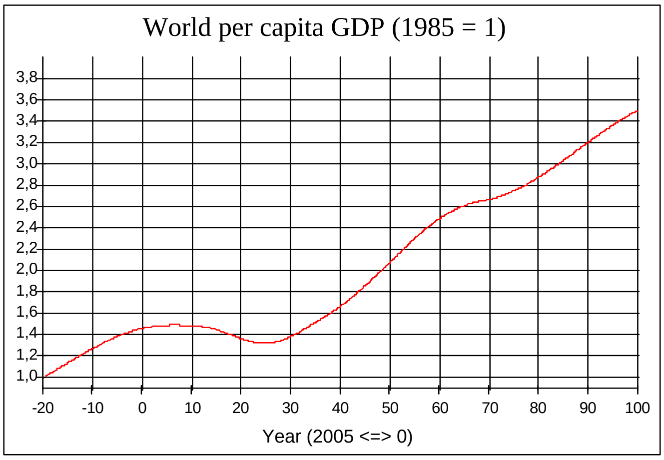

Figure 4: optimistic scenario. Estimations of World GDP.

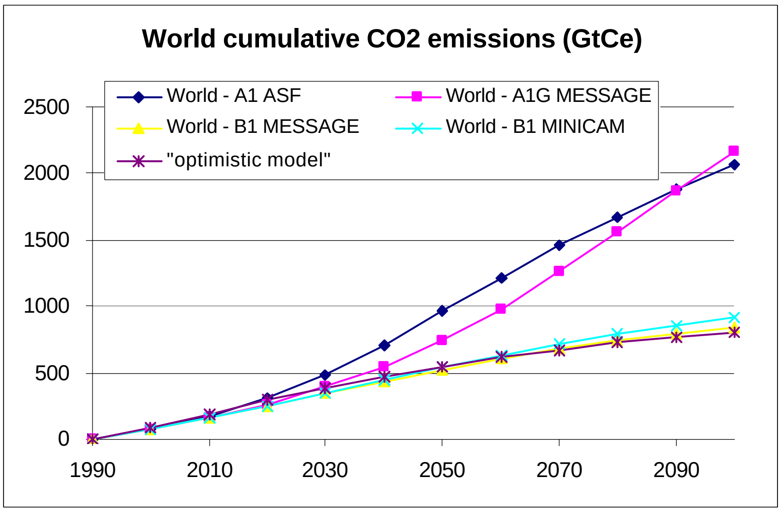

Figure 5: Optimistic scenario. Estimations of CO_{2e} emissions. The estimated emissions are similar to the more optimistic emission predictions of the IPCC. We represent 4 of the most representatives but extremes SERS scenarios (IPCC2001). IPCC is only CO_2 (not CO_{2e}) but include CO_2 from cement manufacture and other industrial process. Our CO_{2e} is more or less the same as IPCC CO_2 emissions from 1990 to 2005.

"Pessimistic model"

In our pessimistic scenario the Renewable hypothesis and the technology are modified. This means that the renewable energies are not developed quickly enough to prevent being directed by the economic crisis (like the rest of non renewable energies), then their contribution to total energetic mix will be marginal. The results of figure 6 show a peak in the global energy before 2015 and a catastrophic decline afterwards.

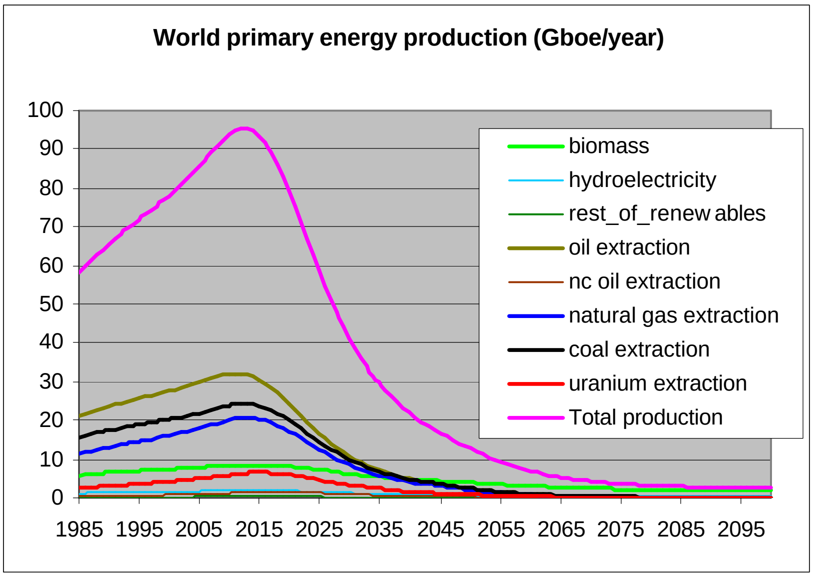

Figure 6: Pessimistic scenario. Estimations of World primary energy production.

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Conclusions

A system dynamics model of the global energy supply and demand has been developed. It combines the peak oil theories with some economic feedback. Our model includes the depletion dynamics of conventional and non conventional oil, coal, gas and nuclear energy. A strong rhythm of substitution of these energies by renewable and fusion energy is also modelled and simulated.
The model is a complex one with several aspects that might serve as forecast of different aspects, but a basic simulation of the substitution of fossil fuels has been shown in this resume. The results show that even strong and optimistic rhythms of substitution have a hard time to continue the growing demand of energy that characterises today's pattern. If the present relationship between energy and the economy is maintained these results lead to a long economic stagnation period in the most optimistic scenarios.

ANNEX:

Quantification of the hypothesis:

Hubbert hypothesis:
We model the Hubbert hypothesis by making the *production variation* and *discoveries variation* depend on a variable we call *production effort* and *discoveries effort* (see figure 1).
Let us establish what we call Hubbert's hypothesis in a more formal way:

- The variation of the production of a non renewable resource will depend (if all else remains constant) on the effort, which is defined as:
  effort = a · annual production/ reserves

Where *a* is a positive constant that we call effort factor. The effort factor is a parameter that adjust the real production over the 1985-2005 period.

Ayres hypothesis:

- The variation of the production of a non renewable resource depends on the technological innovation, defined as:
  technological innovation = Min (b· TIME, d)

Where *Min* is "the minimum of", *TIME* is the time[2], *b* is a positive constant, and *d* is chosen as 0.03 for the optimistic scenario. "b" is chosen for all the non renewables energies to adjust world GDP per capita and world energy primary production simultaneously.
Notice that this is a very optimistic view of technological advance for the optimistic scenario, since it increases constantly with time until reach a constant rate of 3%, these growths means that, if all else remains equal[3], the annual growth production of the resources will be at 3%.

The **UN population hypothesis** is established taking the World population dependent on time and matching the UN median estimations

For the modelling of the **Hirsch hypothesis** we will consider that the oil and the total primary energy availability influences the World economy, and therefore, the gross domestic product depends on the available energy (*GDP per capita variation* depends on

[2] The variable TIME in 1985 is chosed in our models as -20.
[3] Population, GDP per capita, reserves, effort…

production variation of oil and on *total energy production variation* in a mixed way). In 2005 we suppose that the GDP per capita variation depends fifty-fifty on oil and the total energy, 30 years later, we suppose that the GDP per capita is directly disconnected of oil and only depends of total energy production variation, between 2005 and 2035 oil will be linearly losing this dependency). On the other hand, the increase of the gross domestic product and the increase of population imply an increase on oil demand (*production variation* depends on *GDP per capita variation* and *population variation*).

The relationship between oil production and GDP variation is one of the key aspects of our model. This relationship has been studied by several authors (ChienChang2007, Ayres2005, Castro2004, Castro2007, see “Energy Economics” journal). Hirsch2008, for example, postulates that the variation of oil and the variation of GDP are related in such a way that:

$$\frac{\%\ change\ of\ GDP}{\%\ change\ in\ oil\ offer} \approx 1$$

In our models we will translate this into a more formal way establishing the Hirsch hypothesis as:

- The GDP per capita variation depends on the oil production variation and the energy production variation. The variation of oil production (or of other non renewable resource) depends (if all else remains constant) on the variation of the GDP. Therefore:

  GDP per capita variation =
  MAX(0,0.8(1-0.02*(TIME+20)))*oil production variation*
  + MIN(1,(0.2+0.016(TIME+20)))*total energy production variation*

  demand variation = population variation + GDP per capita variation

The establishment of this relationship between oil production and per capita GDP seems less intuitive than the original relationship of Hirsch, between oil production and GDP, but the data show a better correlation with the per capita GDP, as can be seen in figure 8.

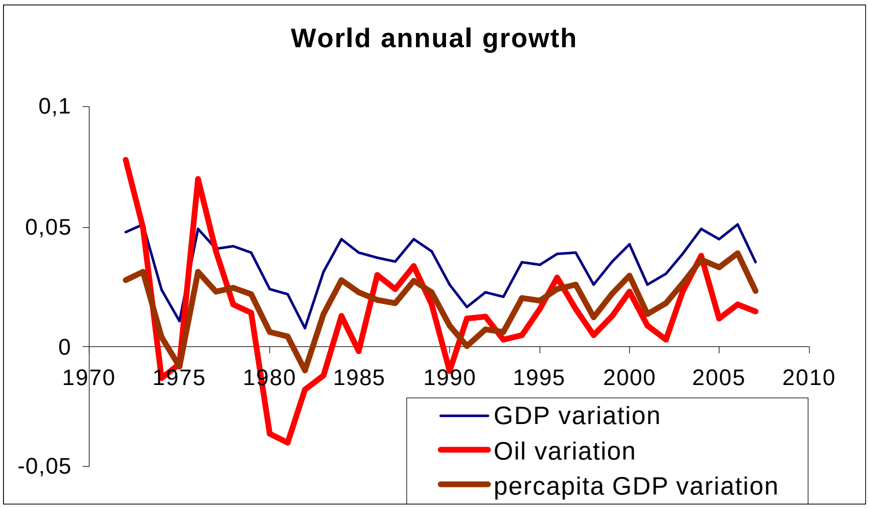

Figure 8: percentual variation of the GDP, per capita GDP and oil production.
Sources: elaborated from BP2007, United Nations, wikipedia and WEO2004

Meadows Hypothesis: We do the technological innovation depend of the World GDP per capita (only for pessimistic scenario):

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Tecnology = MIN(b*(TIME+20),0.02)*(a+LN(GDP per capita))

If economy is growing the technology will growth, but if the economy is decreasing then technology will growth less and less until, when per capita GDP will be less than 0,5 times the 1985 GDP, technology will decrease.

Also, we do the renewables growth linear dependent of GDP per capital growth:

Renewables growth = a + b·GDP per capita growth,

being “a” and “b” positive constants.

Renewable hypothesis:

For this hypothesis, we model in four separated resources: biomass, hidroelectricity, rest of renewable energies (solar, wind, etc.) and future new resources (“fusion” energy or others). For biomass we assume that the future growth will follow the human population growth according with UN hypothesis. For hidroelectricity we assume a linear growth extrapolating recent past growth (from 1975 to 2005).

For the rest of renewable energies the annual growth is:

If(TIME<2005, 0.075, Max(0.18-0.00263*TIME)

This means that for the recent past we mimic the real growth (7,5%) but from 2005 in advance the growth is at the beginning a much more impressive (18% in 2006) although descending linearly to a cero growth rate at 2070 year. With that function we obtain by the year 2070 the estimates of the Zerta2008 renewables technical potential of ˜ 100Gboe/year in 2070.

For the new resources, that we call “fusion energy” we represents the entrance of new resources of energy (it will be nuclear fusion, ocean thermal or whatever we could or not imagine). We chose a growth from 2025, which leads to a production of 90Gboe/year in 2100. With this hypothesis we will have an ever increasing total energy production from 2035 to 2100.

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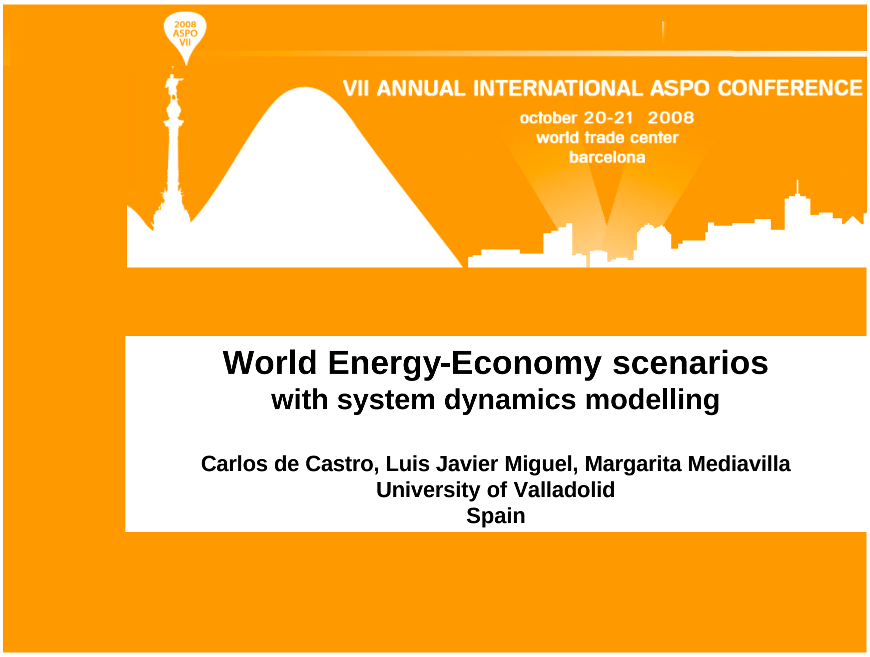
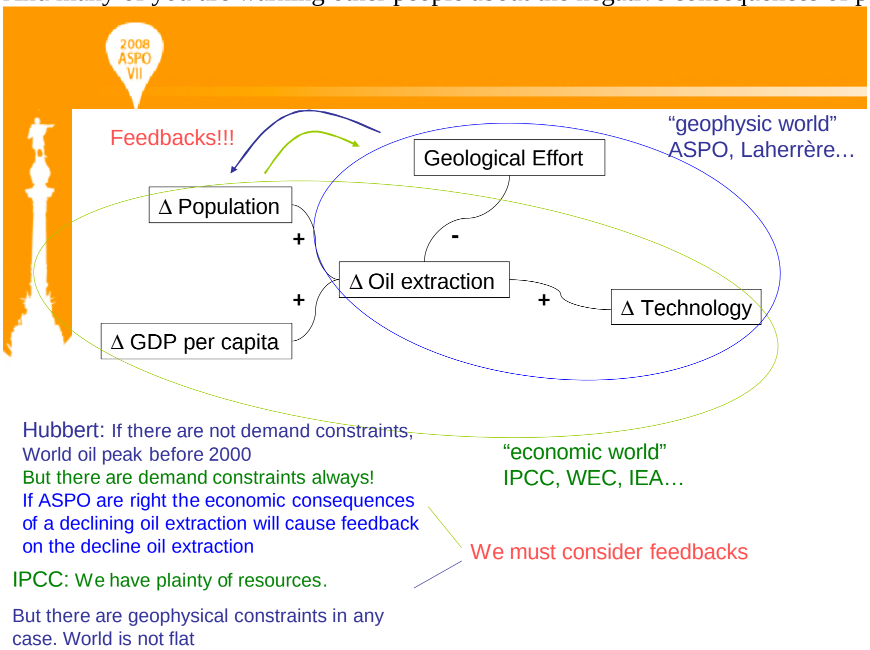
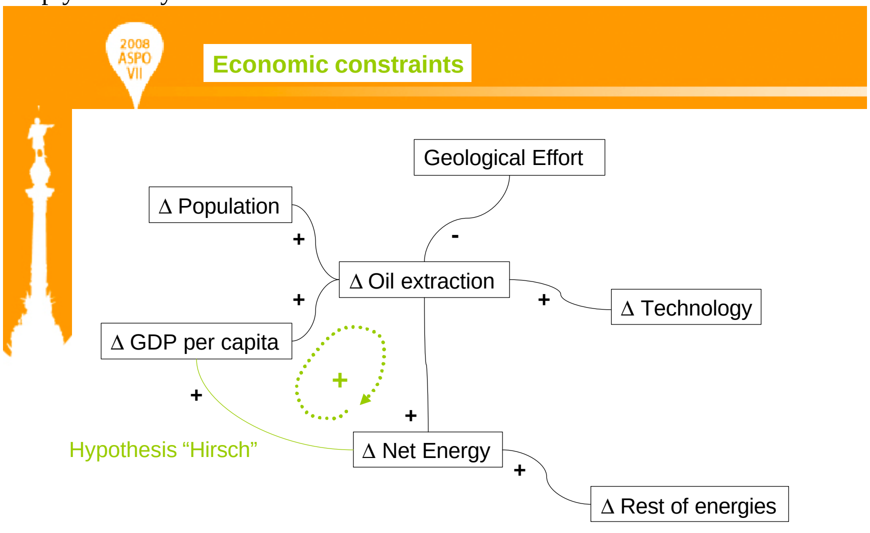


The work I am showing here: "World Energy-Economic scenarios with System dynamics modelling" is part of my phD thesis that I hope to defend next year in my University.
So, this dissertation and this ASPO-Conference will probably have positive feedback on my phD work.
Well…, System dynamics modelling is a good tool for both modelling and understanding the many factors involved in world energy production.
All of us work with "mental models" to try to understand reality.
Many of us, as "peakoilers", have a mental model of the future of oil and natural gas.
And many of you are warning other people about the negative consequences of peak oil.

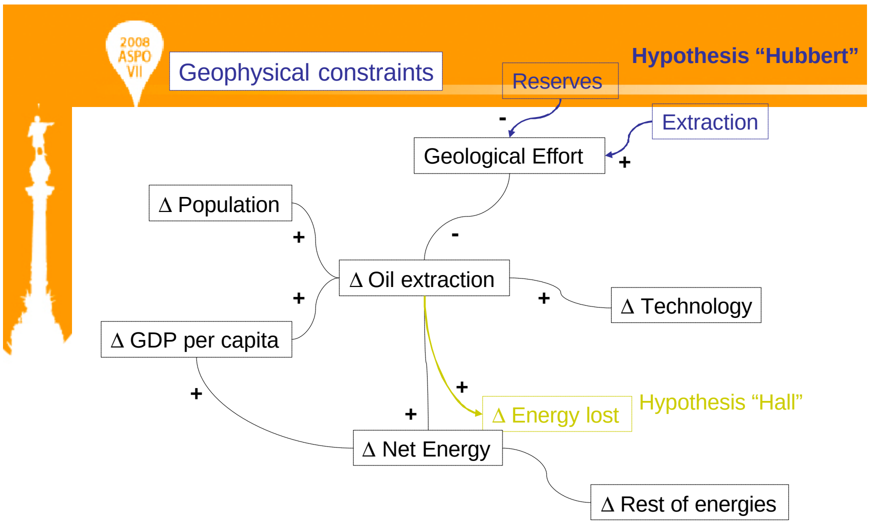


Peak oil is about the oil extraction variation now and in the very near future.
Good mental models need to show what the main factors are that cause such variation.
Some of these factors are population variation, Gross Domestic Production (or GDP) variation and technology.
All of them have a probably positive causal relationship between them and the effective oil extraction capacity.
For instance, the higher the population, the greater the extraction will be if all else remains equal.
But for many of us, and following the insights of King Hubbert, we believe there is another very important factor: we could call it "the Geological Effort". And over time, it is obviously negatively related to the oil extraction capacity.
There are two mental models, or rather views or ways of thinking in this case. One followed by those people who view things through an economy modulated lens. These people, within international agencies (such as the

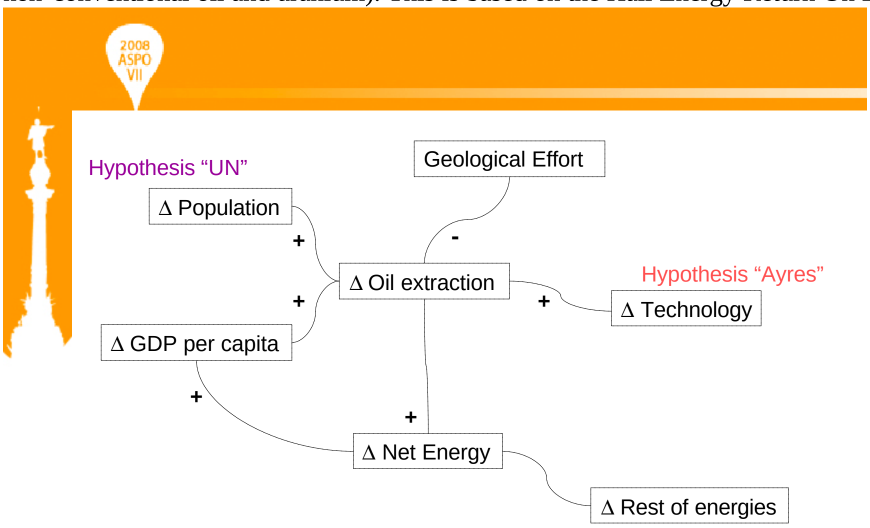
IEA), or governments, or even IPCC scientists, can see the variables and factors here, in the green oval, very well.
Peakoilers, however, think that Geological Effort will be the main factor driving oil extraction variation in the near future.
So, we have two opposed mental models under discussion. More or less, an economic versus a geophysical one.
System dynamics could easily join both ways of thinking (at least theoretically) and naturally take into account the feedbacks between economic and geophysical variables.
For IPCC energy scenarios and many others with economic lenses, there are plenty of fossil resources, but for peakoilers there are, in any case, geophysical constraints; for us, the world is not flat. There are limits to growth and we are sure of them, at least for non fossil fuels.
Frequently, however, many of us with the geophysical lenses do not sufficiently appreciate the economic constraints, as is the case of Hubbert who writes that “if there were no demand constraints, world oil would have peaked before 2000”. The problem is that there are and there ALWAYS will be economic constraints. And most importantly, if peakoilers are right, without a doubt, the economic consequences of a declining oil extraction will be important and will cause feedback on the declining oil extraction, making nonsense of our graphs concerning the decline in oil production, or at least making them obsolete, as they are based solely on bottom-up analysis of oil fields, to say nothing of our curve fitting approaches over past discoveries and extraction, etc.
In conclusion, we think it is very important to consider the feedbacks, because without feedbacks our mental models will not be complete enough and then, our mathematical models, depletion graphs and so on will simply be badly done.



Well, I shall now describe our mental models in greater detail.
Oil extraction variation adds to the net energy variation delivered to society. However, although it is probably the most important one, it is only one of several energy resources.
For us, we add economic constraints or feedbacks following a hypothesis that we shall call “Hirsch” because it is inspired by the work of Dr. Hirsch (who all of you know).
Our hypothesis Hirsch is a positive feedback between the net energy variation and the GDP per capita variation. This connection involves a circular positive loop between “economy” and “energy”. This positive loop implies an exponential growth in both economy and energy production.



We also add Geophysical constraints, which we shall call the hypothesis “Hubbert” (being inspired by the work of King Hubbert), and which establishes a relationship between reserves, annual extraction, discoveries, etc. and which we shall call Geological Effort.
We also add another geophysical restriction that we shall call the hypothesis Hall, which aims to calculate the energy loss involved in the extraction and processing of all non-renewable resources (oil, coal, natural gas, non-conventional oil and uranium). This is based on the Hall Energy Return On Energy Investment concept.



There are other hypotheses, such as the hypothesis we call “United Nations” or the hypothesis we call “Ayres”, which aim to integrate, respectively, the effects of population and technology into the models.

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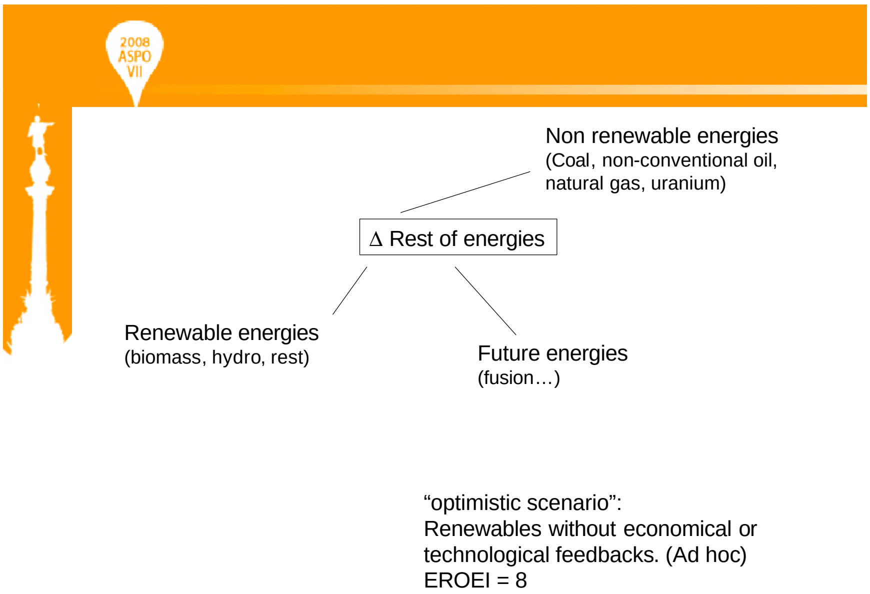
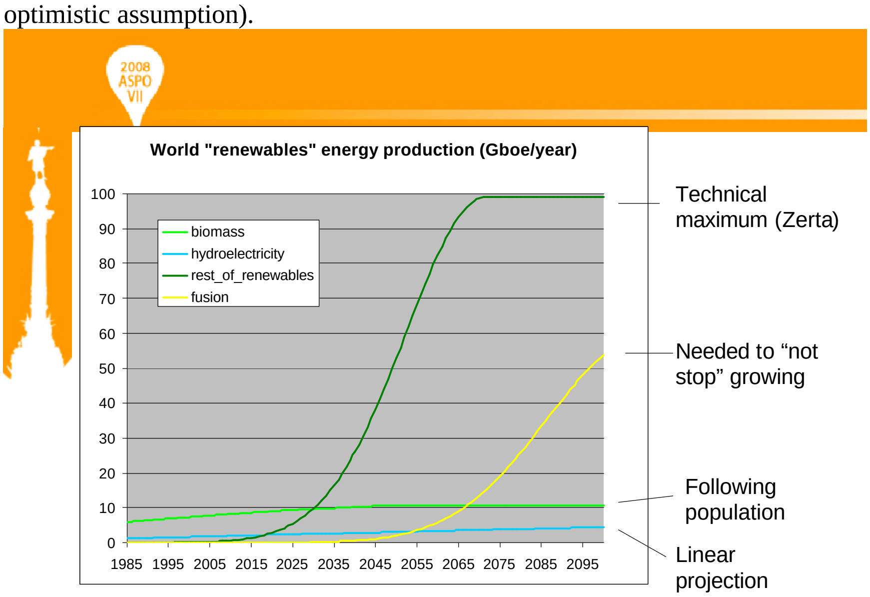


Our models not only take into account oil extraction but all other energies including renewables and even future energies such as fusion or whatever.
Well, we have elaborated two main scenarios for this dissertation: one we call “optimistic” and another which we call “pessimistic”.
In the optimistic scenario, we take a very optimistic evolution of renewables and future energies without economic or technological feedbacks.
We also consider that the growth of these energies has a very high Energy Return On Energy Investment, which means that we consider no energy to be lost in producing this class of energies (which is a very optimistic assumption).



So, in our optimistic scenario, we project the growth of these energies “ad hoc”, exogenously to our models.
For new renewables (such as wind and solar power), we assume a growth that very quickly approaches the theoretical technical maximum given in the work of Zerta (published this year).
We choose a population related growth for biomass, while for hydroelectricity, a linear projection following the same rate as in the last three decades is chosen.
For such “future” energies as fusion, we choose a growth rate that is simply what will be needed to “not stop” the growth in the demand of World energy during the twenty first century.

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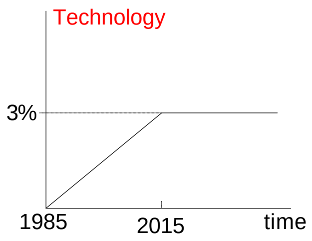
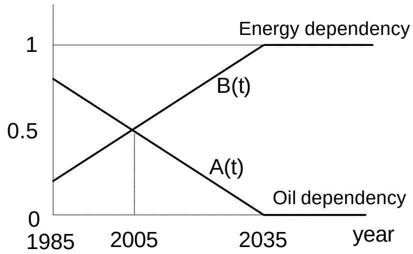
Model Hypothesis

- Hypothesis UN: World population following UN median estimations.
- Hypothesis Ayres: technological innovation (Technology).
  Technology = Min (b· TIME, 0.03)
- Hypothesis Hubbert: Geological effort.
  Effort = C · Annual extraction/Reserves
- Hypothesis Hirsch: GDP-Energy relationship
  ΔGDP per cápita = A(t)· Δ oil extraction + B(t)· Δ energy production

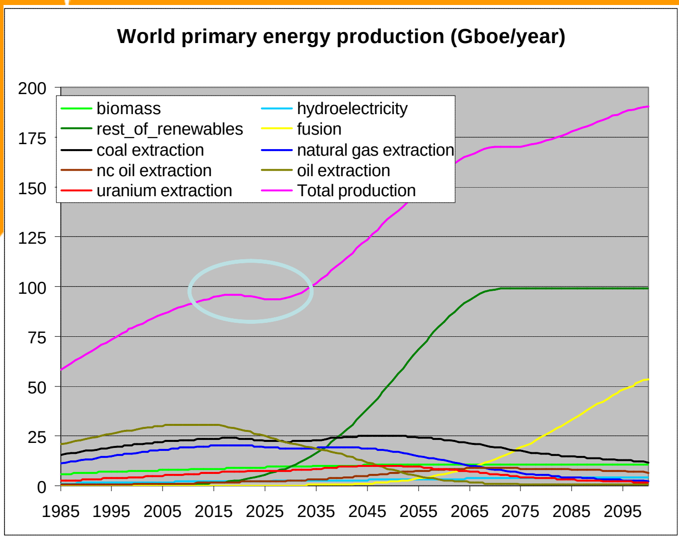
D **Oil extraction = Dpopulation + DGDP percapita + Technology - Effort**





For the rest of the hypotheses, we follow the simplest relationships we think could connect the variables.
The hypothesis "United Nations" establishes that population will follow average UN estimates.
The hypothesis Ayres is about technological innovation and we define "Technology" as a continuous improvement in the capacity of oil extraction variation until it reaches a growth rate of 3% annually from 2015 onwards.
We consider this hypothesis to be an optimistic one because, if all else remains equal, the extraction of oil will grow by 3% annually due only to technological innovation.
The hypothesis we call Hubbert (remember the Geological Effort) establishes that the variable Effort is directly related to annual extraction and inversely related to the Reserves.
Finally, the hypothesis Hirsch establishes the GDP-Energy relationship: GDP per capita variation will be proportional to the oil extraction variation and also to the net energy production variation. The constants of proportionality A and B actually vary with time following a decreasing dependency on oil that we choose to be 50% from 2005 until it disappears in 2035 and an increasing dependency on the energy mix delivered to world society.
So, oil extraction variation is simply the sum of the population, the GDP per capita variation and the Technology, minus the Effort.

"optimistic" scenario



One result of the world primary energy production for this optimistic scenario is shown here…
We can see the impressive growth we choose for the renewables, also the peak oil, and very importantly, the world energy production stagnation over more or less 20 years in a world of increasing population.

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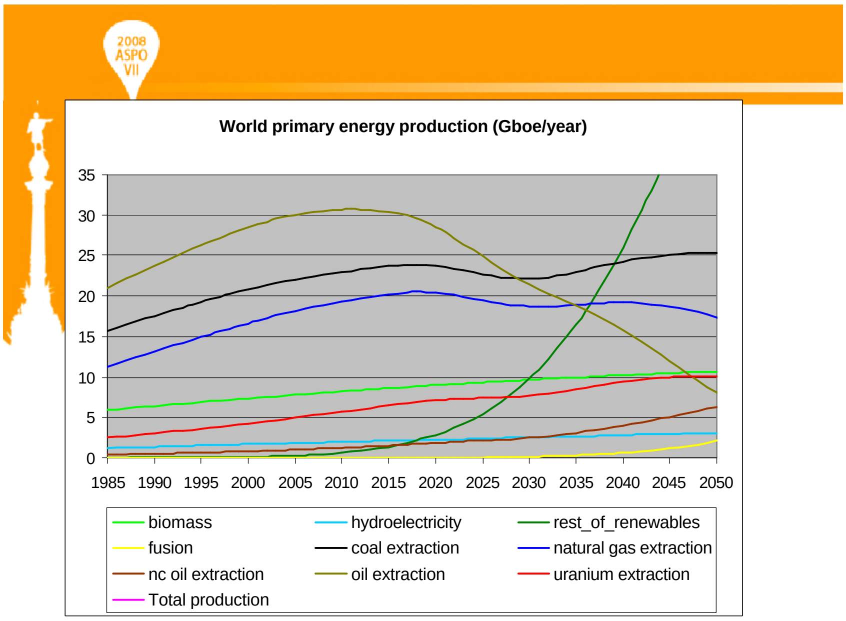
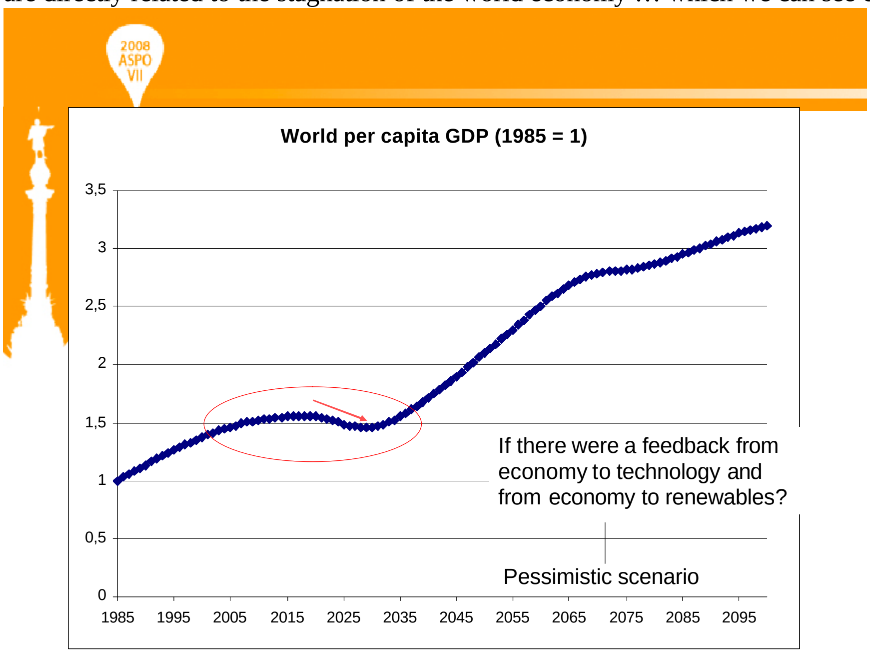


If we take a look in more detail at each energy graph for the next 50 years, we can see the peak (or maybe plateau) of conventional oil, and surprisingly, two peaks for natural gas and coal extraction. Both these peaks are directly related to the stagnation of the world economy … which we can see explicitly in the next slide...



The consequences of this stagnation will be entirely new from the point of view of the history of the last century. A lack of growth in the economy has never before been experienced over such a long period of time. For classical economists, this is probably impossible and would bring about a new socioeconomic order, one that breaks the energy-economy relationship (our Hypothesis Hirsch), or worse, results in unrest, wars, famines etc.

But this is the good news, because I must remind you that this is our optimistic scenario…

What would happen, for instance, if there were feedbacks from the economy to technology and renewables?

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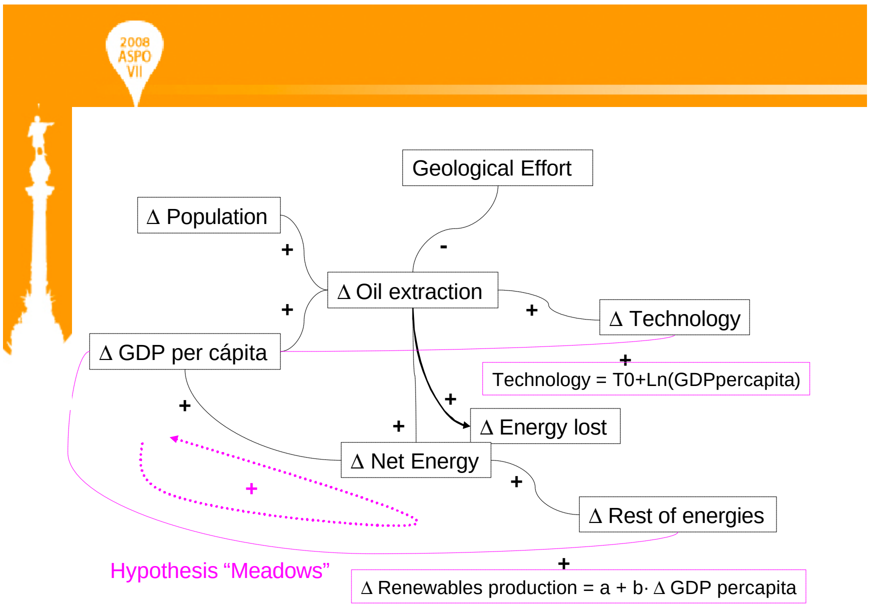
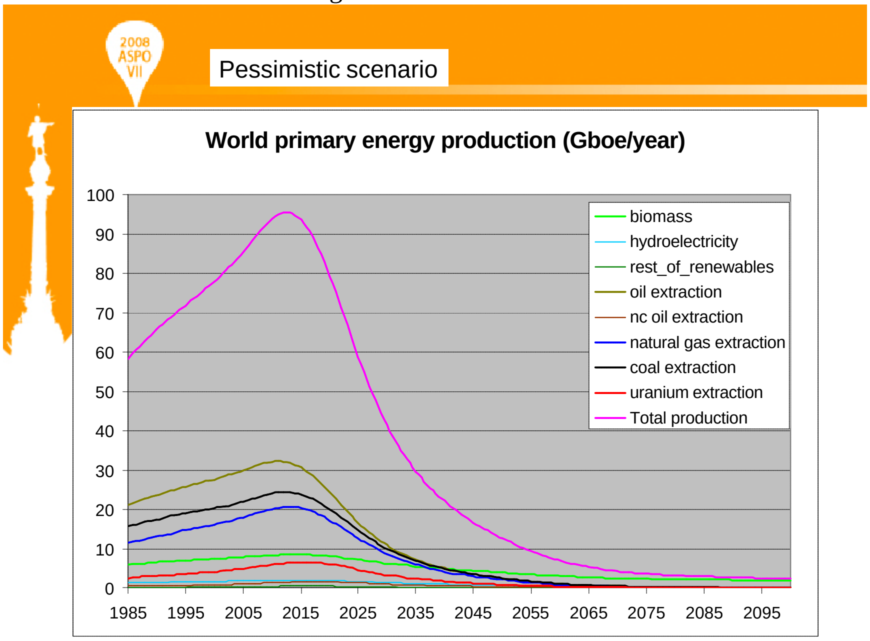


If we take this into consideration in our models, we get our pessimistic scenario. This scenario adds the hypothesis we call Meadows, following Forrester and the famous Meadows "limits to growth" way of thinking. We transfer Meadows' ideas by making the production of renewables linearly dependent on the growth of the GDP and modifying the Ayres technology hypothesis (here T0) by adding a dependency on the GDP per capita.

When we add this Hypothesis, we have once more a positive loop between economy and renewables similar to what we had for the other energies.



But the models then collapse. The pessimistic scenario has a catastrophic decline for all energy production and peak oil drags the rest of the peaks after it in only a very few years.

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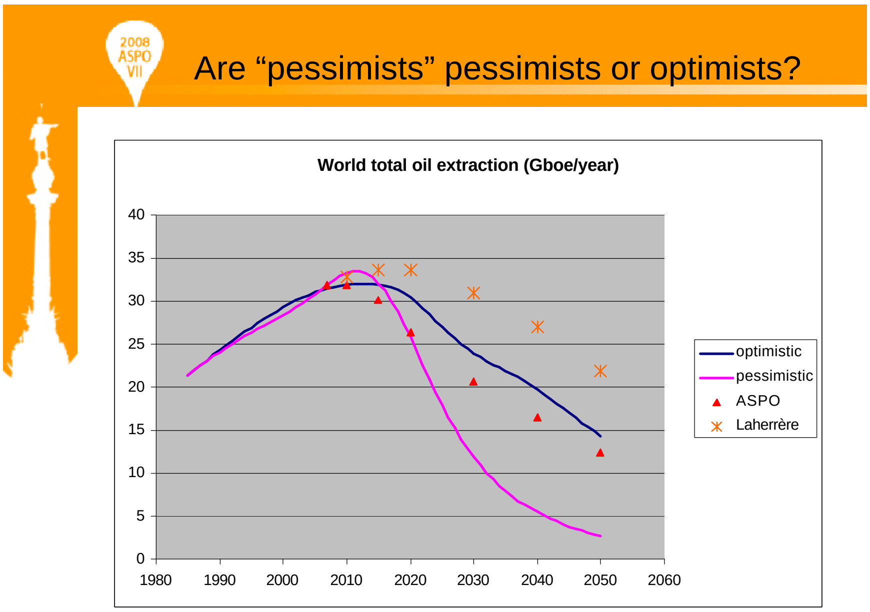
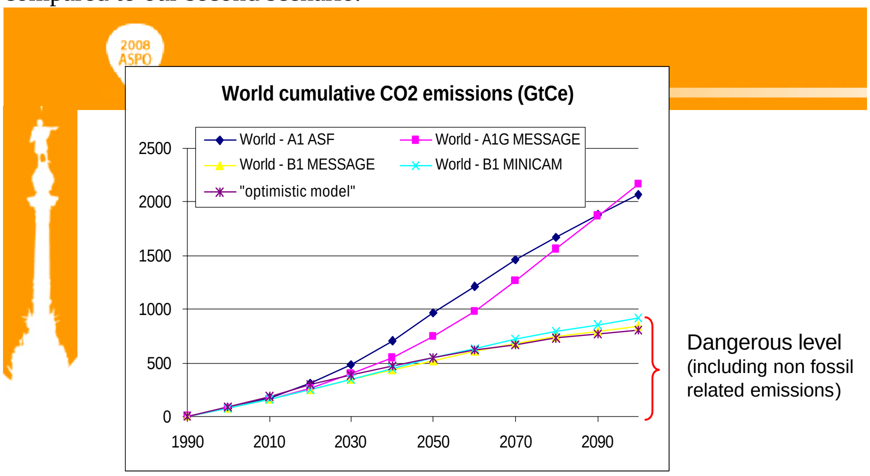


Conclusions:
We must ask ourselves whether peakoilers, frequently classed as pessimists, are really pessimists, or are they perhaps optimists.
Our optimistic model lies between the ASPO and Laherrère models, but all of them are very optimistic when compared to our second scenario.



Optimistic scenario. Estimations of CO_{2e} emissions. The estimated emissions are similar to the more optimistic emission predictions of the IPCC. We represent 4 of the most representatives but extremes SERS scenarios (IPCC2001). IPCC is only CO_2 (not CO_{2e}) but include CO_2 from cement manufacture and other industrial process. Our CO_{2e} is more or less the same as IPCC CO_2 emissions from 1990 to 2005.

And, what about CO2 emissions, for instance? Our models could also estimate the cumulative CO2 emissions because we have calculated the future extraction of all fossil fuels.
Our optimistic scenario is very similar to the bottom of IPCC scenarios. As you can see here.
But this is not a good new because even those emissions are at the top of the considered “dangerous level” for Humanity. So, our optimistic scenario probably must incorporate a new feedback between Climate Change effects and the world economy.

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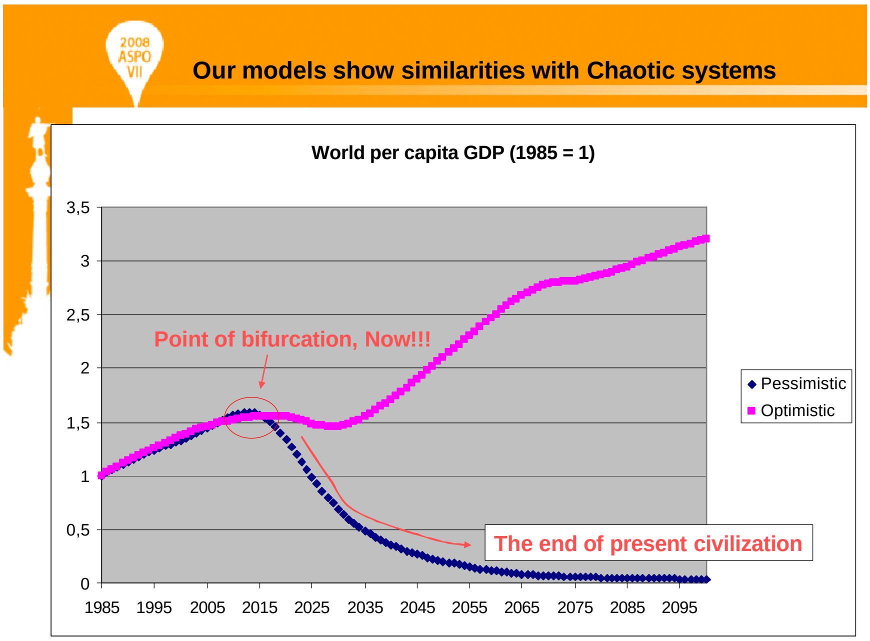


Finally, our models show similarities with chaotic systems that frequently exhibit what physicists call bifurcation points, points at which the system can follow extreme behaviours which are very difficult, if not impossible, to predict.

The problem we have, the problem the World has, is that, if our suppositions are correct, if peakoilers are right, we are at present right in the middle of this bifurcation point, with no time to react.

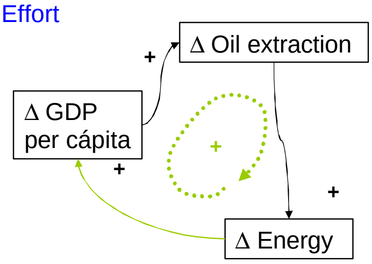
So, peakoilers must be wrong, if not…

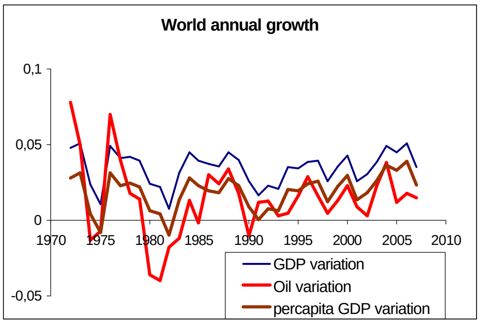
- **hypothesis Hirsch**: This hypothesis establishes the relationship between the energy production and the GDP and we base it on the conclusion of Hirsch (2008) who states that world oil production growth and world GDP growth are strongly connected.

$$\frac{\%\ change\ of\ GDP}{\%\ change\ in\ oil\ offer} \approx 1$$

ΔGDP per cápita = A(t)· Δ oil extraction + B(t)· Δ energy production

Δ Oil extraction = Δpopulation + ΔGDP percápita + Technology - Effort





Percentual variation of the GDP, per capita GDP and oil production. Sources: elaborated from BP2007, United Nations, wikipedia and WEO2004

Testing Hubbert (+ Ayres)

USA (-Alaska) oil discoveries and production.