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The role of non conventional oil in the attenuation of peak oil

Carlos de Castro[a*], Luis Javier Miguel[b], Margarita Mediavilla[b]
[a] Applied Physics. Campus Miguel Delibes. University of Valladolid. 47011 Valladolid, Spain
[b] Systems Engineering and Automatic Control. Paseo del Cauce s/n. University of Valladolid. 47011. Valladolid, Spain.
[*] Corresponding author: Tel/fax:34 983423545/34 983423358
E-mail: carcas@sid.eup.uva.es

Abstract
In this paper, the possible substitution of conventional with non conventional oil is studied using system dynamics models. The model proposed in this paper is based on geological, economic and technological aspects, and it fits approximately the behaviour observed by Hubbert. A first validation of the model has been made with the USA oil production data. These USA data show that there is a good coincidence between our model and the reality. This model has been expanded in order to include the substitution of the conventional oil with the non conventional one for the World. The results show that, even under optimistic scenarios, the attenuation of the peak oil decline through the non conventional oil requires very high investment profiles.

Keywords: non conventional oil, peak oil, system dynamics

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 the literature. A wide spectrum of research approaches show quite different predictions and results. A mainstream of studies are focused on the economic and technological aspects (EIA 2007, WETO 2003, IEA 2004a, IPCC 2001, IIASA 2004) and foresee scenarios without strong limitations (restrictions) of the fuel offer of a future rich in fuels. A second important group of research works put the emphasis on the geological data of oil discoveries and oil field behaviour, not paying so much attention to the economic aspects, foreseeing a future of scarcity (Campbell and Laherrère 1998, Hubbert 1956, Robelius 2007, ASPO 2008, Kooppelaar 2005, Skrebowski 2008, Aleklett 2008).

Research studies that take a look at the complete picture, paying attention both to the economic, geological and technological aspects are not frequent in the literature (Castro 2008, Bassi et al. 2007). System dynamics modelling have been proved to be a good methodology for such holistic approaches, since it enables the integration of different sources of knowledge and it allows including feedbacks between variables. Nevertheless, even in energy/economy/climate integrated models (MESSAGE model of IIASA –IIASA 2001-, MARKAL family models of IEA –IEA 2004b-, NEMS model proposed by EIA –EIA 2004-…) the feedback relationships between the energy and the economy variables are scarce. Consequently they do not capture medium and long-term trends dynamically (Bassi et al. 2007). A relevant exception of model where those feedbacks are fully explored, is World 3, the model of Limits to Growth (Meadows et al. 1972). After this first approach, few models have applied this general perspective and most of them have focused on specific problems (emission rights, energy taxes, etc. Nail 1992, Fiddaman 1997) or local players (Bassi et al. 2007, Sterman et al.1987, with very rich for USA Energy-Economy relationships but very poor for USA-World relationships, Tao and Li 2007, for China oil production) loosing the holistic approach and/or neglecting the mentioned feedback relationships.

On the other hand, the World contains large quantities of non conventional oil, which is assumed to compensate the decline of the conventional oil peak (Farrell and Brandt 2006, Brandt and Farrel 2007). Some detailed models show that, having passed the conventional oil peak, the non-conventional oils are unlikely to come on-stream fast enough to offset the conventional's decline (Soderbergh et al. 2005, Robelius 2007, Greene et al. 2006) The work presented in this paper is aimed at throwing some light on this question.

This work has used system dynamics mainly for two reasons. First, it allows different kinds of variables that have different knowledge sources, such as economic, geological and technological variables, to be managed and integrated. The second reason is the relevant phenomena of feedback for understanding the dynamic evolution and the relationships of the variables involved. The feedback relations are easily represented with system dynamic tools. The presented model tries to help us understand the dynamics of the main variables involved in the economy-energy system, and contributes to an analysis of possible scenarios in order to make the best decisions for our common future. This work is part of a wider work and is focused on the role of non-conventional oil to compensate the future decrease in conventional oil production.

The model presented in this paper covers aspects of the conventional oil peak, its relationship with the economy and the substitution of conventional oil with non conventional oil. Our model is based on a series of qualitative hypotheses that we describe as:

- Hypothesis "Hubbert": the discoveries of oil fields and the production of oil vary with the stocks of undiscovered resources and/or reserves. Therefore the less stock there is to be extracted (discovered), the more difficult it is to increase the annual extraction of this resource. It describes the idea established by K. Hubbert (Hubbert 1956, 1982) based on experimental extraction data from several oil fields and countries. But, rather than assume a bell (or Hubbert) curve or other assumptions over how it will be the best oil production fit (Deffeyes 2002, Hubbert 1982, Laherrère 2005), we use a theoretical approach based on Hubbert ideas.
- Technology hypothesis: the rate of innovation, or technological variation, must increase with time if exponential growth of the extraction of a non renewable resource is to be obtained. It describes the role of technological innovation in the extraction process. It is an optimistic hypothesis that states that technological innovation increases over time and is based on the ideas described, for example, in Ayres et al. 2005.
- Hypothesis "Hirsch": the sensitivity between the increase of oil consumption and the increase of GDP is approximately one. This hypothesis establishes the relationship between the oil demand and the GDP or the economy and is based on the conclusion of Hirsch (Hirsch 2008).

- Population hypothesis: World population is considered an exogenous variable, which will follow approximately the median global population projections of the United Nations (UN 2007). This hypothesis will be used to estimate the growth in World population. We do not consider 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 the UN estimates for the XXI century for granted.
- Hypothesis "Meadows": the available capital for technological advance depends on the GDP and if growth is stuck, it will tend to grow more slowly. It is based on the ideas of Meadows (Meadows et al. 1972, 1992). Technological innovation will reach a maximum rate over our initial year because the growth of GDP stagnate or because physical constraints. We do not always use this hypothesis.
- Non conventional oil hypothesis. The growth of non conventional fuels can be as desired and this growth does not feedback with GDP: the investments required to increase extraction do not decrease GDP. The introduction of the non conventional oil is optimistic. The Hubbert hypothesis that makes the extraction of oil more difficult when the stock of reserves decreases is not applicable to non conventional fuels.
- Simple model hypothesis. Other factors that could also influence the energy/economy relationship, such as Climate Change, political or armed conflicts, or regional disparities, will not be considered.

In section 2 we describe a model for oil extraction and consumption based on these hypotheses and tested and calibrated using the data of the USA oil discoveries and extraction (Laherrère 2005). Since the model fits USA historical data, we use the same model structure to understand the World data behaviour and forecast some near future scenarios. In section 3 we propose a similar model to investigate the role of non conventional oil and the possibilities for the substitution of conventional oil with non conventional oil in the World. Finally, the conclusions are given in section 4.

2. Model of oil production. The USA case.

The peak oil theory (Hubbert 1956, Campbell and Laherrère 1998) establishes that oil extraction over time follows a bell shape profile. This curve is based on the experience observed in most fields and on the geological fact that the lower the stock of oil remaining in the field, the most difficult is it to extract. But the extraction curves are conditioned by many different factors, not all of them geological, such as the investments, the technology and the demand. In fact, the simple geological fact that the extraction becomes more difficult the more oil is extracted, would not explain the initial growth of the bell shape curve.

In this section we describe a model that *explains* and imitates the curves observed by Hubbert. The model is not just a fit of real data into a more or less arbitrary mathematical function (such as Laherrère 2005, Campbell and Laherrère 1998, Hubbert 1982, Feng et al. 2008); it is aimed at describing the inner phenomena that cause the extraction profile to be as observed, in a similar but different way as in Bardi (2005) or in Mohr and Evans (2007); but without the limitations of an analytical theoretical model.

Our model is based on considering that the annual oil discoveries, production and demand tend to growth as a percentage of previous ones. This way we model the inertias involved in all those actions, and imitate, for example, the fact that investments done on the extraction depends on the previous benefits obtained from it. The geological constrains are modelled using what we call "effort factor". This "effort" makes it more difficult the extraction the lower the stock of oil. Technological improvement is also taken into account.

We will take basically our hypotheses "Hubbert" and "Technology" to construct the model, and compare the simulation results with the real production data from the USA (without Alaska), since these data are the best available of a well known oil extraction cycle. We will use the stocks and flows of Forrester diagrams to represent our model and simulate it using a POWERSIM simulation program.

In figure 1 we can see this first model. There is a stock of *non discovered resources* (the tonnes of oil on earth still undiscovered). An annual flux of discoveries (*annual discoveries*) withdraws oil from the stock of *non discovered resources* and leaves it in the stock of *reserves*. The stock of *reserves* decreases with the extraction at a rate called *annual production.* Notice that *discoveries variation* and *production variation* are the percentage growth or decrease of *annual discoveries* and *annual production.*

We model the hypothesis Hubbert by making the *production variation* and *discoveries variation* depend on a variable we call *production effort* and *discoveries effort*:

- 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 the effort factor

We also take into account technological innovation using the Technology hypothesis. It states that the rate of innovation, or technological variation, must increase with time if an exponential growth is maintained over time for a non renewable resource (Ayres et al. 2005).

- The variation of the production of a non renewable resource depends on technological innovation, defined as:

  technological innovation = b· t +c

  Where *b* and *c* are positive constants and *t* is time.

Notice that this is a very optimistic view of technological advance, since it increases constantly with time, instead of showing the saturation which is common in technological advance. The complete equations of the model can be seen in appendix 1.

The production variation will depend on a variable that we call *demand variation* that, so far, we consider as constant (will be treated in more detail in next models).

Time t starts in 1902, the initial year of the simulation, and the first technological advance starts the first production year, 1860, for discoveries, and 32 years later for production, since this is the temporal lag between the curves of discoveries and production. Since it is easier to adapt a model to data when there are two parameters instead of one, we restrict ourselves to an equal technological increase, *b (0.0004)*, for both discoveries and production (see also Appendix 1 for equations, fitting data and data sources).

We can see in figures 2 and 3 the results of the simulation of our model compared with the real data. Our system dynamics model, which only takes into account the physical restrictions for production, reserves and discoveries, describes the dynamics of oil discoveries and production with a very reasonable level of accuracy, therefore we will use it as the basis for our complete World oil model.

3. Model of non conventional[1] world oil production and demand

Let us now describe the global World oil model that includes most of the hypotheses described in section 1: the "Hubbert" hypothesis and the Technology hypothesis already used in our previous model, the "Hirsch" hypothesis, for the relationship between the oil consumption and the economy, the Population hypothesis for the calculation of the population, and the Non Conventional Oil hypothesis. The World model structure can be seen in figure 4.

For this World model we start our simulations in 1985, because the political crisis of the seventies had important effects on the World oil supply that were not caused for internal relationships between oil production, reserves and the economy, which are the variables we take into account in our models. Therefore we start the simulation in 1985 and consider that there are no restrictions to demand due to political reasons.

In 1985 the discoveries of oil had already started a decreasing profile; therefore we will simplify the model of figure 1 using a proportional dependence between *annual discoveries* and *non discovered resources*, which is enough to fit the exponential decrease observed since 1985.

"Hirsch" hypothesis. For the modelling of the "Hirsch" hypothesis we consider that oil availability influences the World economy, and therefore, GDP depends on the available oil. On the other hand, the increase of the GDP and population imply an increase in oil demand. We can see that in these relationships there is a very obvious closed loop: the variation of the GDP depends on the variation of oil production, which depends on the variation of the GDP. These kinds of feedback relationships can be seen in real life and in system dynamics examples very often, but they cannot be simulated and conceived without a delay in between. We choose a one year delay to make this relationship valid (the GDP behind the oil production).

[1] Defined as in WEC 2004.

This relationship between oil production and GDP variation is one of the key points of our model. It has been studied by several authors (Huang et al. 2007, Lee and Chang, 2007, Chiu et al. 2008, Cleveland et al. 1984, Ayres et al. 2005, Castro 2004, Ockwell 2008, Barret et al. 2008), Hirsch, for example, postulates that the variations in oil and GDP are related in such a way that (Hirsch 2008):

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

In our models we translate this into a more formal way by establishing:

- The GDP per capita variation depends on the oil production variation. The variation of oil production depends (if all else remains constant) on the variation of the GDP. Therefore:
  GDP per capita variation(%) ≈ oil production variation(%)
  oil demand variation(%) = population variaton(%) + 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 historical data show a higher correlation with the per capita GDP (PPP $), as can be seen in figure 5.

Non Conventional Oil hypothesis. The Non Conventional Oil hypothesis models the rhythm of substitution of conventional with non conventional oil. There are several sources of non conventional oil (tar sands, gas to liquids, extra heavy oil…), and the reserves are estimated to be large, the URR (Ultimate Resources Recovery) could be twice or more as large as those of conventional oil (WEC 2004). The amount of non conventional oil extracted right now could be only 1% of the amount of reserves. Although this seems to be good news, it is in fact one of the problems that makes it difficult for non conventional oil to substitute conventional oil. The annual production of non conventional oil today is very low; it does not even cover 5% of the global oil demand (EIA 2007).

The growth of non conventional oil in the past decades has been 4-5% annually, and most of this growth has been due to refinery gains (2/3). The most important part of this growth is based on the oil sands of Canada and the heavy oil of Venezuela. The shale oil, coal to liquids (CTL) and gas to liquids (GTL) have a small amount compared to the total.

There are several aspects of non conventional oils, though, that are not considered in our model:

- Non conventional oil has rates of energy return (EROEI, Cleveland et al. 1984) much lower than conventional oil. One barrel (approximately 7,5 barrels is a tonne of oil) of non conventional typically implies 0.3 barrel of other energy sources (such as natural gas) in order to be extracted and refined (Soderbergh et al. 2007). If we want to make a complete and realistic description of the whole problem we should take this fact into account, since it is one of the most important drawbacks of non conventional fuels, but it would imply modelling other types of energies, not only liquid fuels. In this model, which is restricted to oil, therefore, we ignore this fact, which makes our model very optimistic in this aspect. If the conclusions of our simulation are pessimistic even ignoring this fact, we might discard an optimistic result.

- The growth of non conventional oil requires huge capital investments in new infrastructure that could cause economic growth to slow down, which would be a description of what we call "Meadows" hypothesis. In our models, we do not take this hypothesis into account as we consider that the growth of the non conventional oil production can be achieved at the desired rate, despite the variations of the GDP and the amount of conventional oil or other energy sources available. Again, we are using an optimistic model.

- For the non conventional oil we do not apply the hypothesis "Hubbert". This means that the extraction flow of non conventional fuel is not limited by the amount of reserves, and non conventional oil can be extracted at the desired growth rate. This could be justified by the fact that the URR of non conventional fuels are estimated to be very large.

All of these assumptions mean that the Non Conventional Oil hypothesis may be considered quite an optimistic framework for any scenario: we simply assume a constant growth of non conventional oil production, to test the minimum value it should achieve in order to avoid economic trouble when the conventional fuel production declines. Therefore we make: *production variation NC* = constant in the model of figure 4.

4. Simulations and scenarios.

The model described in section 3 is to be tested in three different scenarios. First we shall see the '*only conventional oil scenario'*, where only conventional fuels subject to depletion under the "Hubbert" hypothesis are exploited. This model will be used to fit the parameters of the model based on historical data. Once the model is calibrated we introduce the non conventional oil in two different scenarios. The '*business as usual'* scenario will consider that the growth rate of non conventional fuels over the next decades is the same as now (*production variation NC* =0.045, 4.5% annual increase). The '*crash program'* scenario will search for the growth in the extraction needed in order to avoid economic recession. The parameters for this model can be seen in Appendix 1.

The simulation results of the ***only conventional oil scenario*** are shown in figures 6 and 7. It can be seen that the model matches the data until 2005, and shows a peak both in oil production and GDP around 2010, followed by a steep decline. If we add the Meadows hypothesis then the decline is steeper both for oil production and GDP (results not shown).

The ***business as usual*** scenario gives the results shown in figures 8 and 9. We can see that the peak of the GDP cannot be avoided with this growth rate of non conventional oil. The decline is a bit slower than in the *only conventional oil* scenario but the trend is the same.

The ***crash program*** scenario with an increase of non conventional oil of 10% annual gives the results shown in figures 10 and 11. In this scenario, the GDP does not peak, but it must undergo a long period of 20 years of stagnation. This is a pessimistic result, the 10% annual growth is a high growth for the non conventional oil production since it doubles today's growth and it cannot avoid an extremely long period of economic stagnation. Notice that the total production reaches very high values at the end of the simulation (by 2040), but this is not realistic, since the physical restrictions of the "Hubbert" hypothesis have not been applied to the non conventional oil, and this is acceptable for the first years of the simulation, when the extracted oil is low, but not latter.

If we add the Meadows hypothesis on business as usual scenario the decline is much more pronounced. For the crash program scenario the Meadows hypothesis means than it must be an increase of non conventional oil of 12% in order to avoid the oil and GDP decline (results not shown).

5. Discussion.

The dynamic models presented offer two interesting results. The model of the USA conventional oil extraction matches the real data with good accuracy and offers a model of oil extraction which explains the production curves. Very few attempts are being made to model on theoretical ideas without presuppose a curve (Bardi 2005, Mohr and Evans 2007), to our knowledge this is the first one based solely on logic and Hubbert geological ideas. On the other hand, the model of the non conventional oil offers long term predictions of the oil extraction and the economy. The results of this model (figures 10 and 11) show that, in order to avoid an economic recession, the growth of the non conventional oil must undergo a crash program of a sustained growth over 10% annually. Achieving this sustained growth is not an easy task, as it doubles the actual growth, and the increase of the production of non conventional oil requires important investments. The results become more pessimistic if we do not ignore several hypotheses that would make the substitution even more difficult, if not impossible (the "Meadows" hypothesis applied to conventional and non conventional oil and "Hubbert" hypotheses applied to non conventional oil, the shortage of other kinds of energy, the environmental constrains, the EROEI, etc.)
There are other more complex effects that our model could not take into account and may lead to more optimistic results, such as:

- the role of the remaining energies and the substitution of liquid fuels with other kinds of energy,
- the reaction of society and the economy to adapt rapidly to a scenario of oil shortage.

Whether or not such optimistic or negative hypotheses will have more weight on the end result would be an interesting extension of our model for future work.

6. Conclusions

This work has presented a model that studies the relationship between economic, geological and technological variables, in order to understand the global economy-energy system. The simplicity of the model was intentionally chosen to focus attention on the main variables and be able to explore the feedback relationships between them. The model is based on several, frequently accepted hypotheses; therefore, it gives qualitative clues of the system behaviour in the near future, under fulfilment of the hypothesis described. A first relevant result is the good fitness of our model to the well known Hubbert curve for peak oil. It has been shown, first for the USA case, and then for the World case. The second relevant result of our models is the forecast of the non-conventional oil ability to substitute conventional oil. The simulation results show that a strong requirement of non-conventional oil production is needed in order to maintain the economic growth of the World's economy.

References

Aleklett, K., 2008. Wellcome Adress. VII annual international ASPO conference. Oct 20-21 2008. Barcelona. Spain

ASPO 2008. ASPO newsletter nº 95. Nov. 2008. www.aspo-ireland.org

Ayres, R.U. et al. 2005. A theory of economic growth with material/energy resources and dematerialization: Interaction of three growth mechanisms. Ecological Economics 55 (2005) 96– 118

Bardi, U., 2005, The mineral economy: A model for the shape of oil production curves: Energy Policy, v. 33, no. 1, p. 53–61.

Barret, M. et al. 2008. How to support growth with less energy. Energy Policy, Volume 36, Issue 12, December 2008, p. 4592-4599

Bassi, A.M. et al. 2007. Informing the U.S. energy debate with T21. Millennium Institute.

Brandt, A.R., Farrell, A.E., 2007. Scraping the bottom of the barrel: greenhouse gas emission consequences of a transition to low-quality and synthetic petroleum resources. Climatic Change (2007) 84:241–263

Campbell, C.J., Laherrère, J.H., 1998: "The end of cheap oil". Scientific American. March 1998. 78-83

Castro C., 2004. "Ecología y Desarrollo Humano Sostenible". Universidad de Valladolid. Spain.

Castro C. et al. 2008. World energy-economy scenarios with system dynamics modelling. VII annual international ASPO conference. Oct 20-21 2008. Barcelona. Spain

Chiou-Wei, S.Z. et al. 2008. Economic growth and energy consumption revisited Evidence from linear and nonlinear.... Energy Economics (2008), doi:10.1016/j.eneco.2008.02.002

Cleveland, C.J. et al. 1984. Energy and the US economy: a biophysical perspective. Science 225. 4665. 890-897.

Deffeyes, K. S., 2002. World's oil production peak reckoned in near future: Oil Gas J., v. 100, no. 46, p. 46–48.

EIA 2004. Integrated Module of the National Energy Modeling System: Model Documentation 2004. US department of energy.

EIA 2007: "International Energy Outlook 2007". Energy Information Administration. US department of energy.

Farrell A.E., Brandt A.R., 2006. Risks of the oil transition. Environ. Res. Lett. 1 pp1-6 (2006)

Feng, L. et al. 2008. China's oil reserve forecast and analysis based on peak oil models. Energy Policy. Volume 36, Issue 11, November 2008, Pages 4149-4153

Fiddaman, T. S. 1997. Feedback Complexity in Integrated Climate-Economy Models, Doctoral Thesis, Massachusetts Institute of Technology, Cambridge

Greene, D.L. et al. 2006. Have we run out of oil yet? Oil peaking analysis from an optimist's perspective. Energy Policy 34 (2006) 515–531

Hirsch, R.L. 2008. Mitigation of maximum world oil production: Shortage scenarios. Energy Policy 36 (2008) 881–889

Huang, B.N. et al. 2007. Causal relationship between energy consumption and GDP growth revisited: A dynamic panel data approach. Ecological Economics (2007), doi:10.1016/j.ecolecon.2007.11.006

Hubbert, M.K. 1956. Nuclear energy and the fossil fuels. Drilling and Production Practice. American Petroleum Institute.

Hubbert, M.K., 1982. Techniques of prediction as applied to production of oil and gas. US Department of Commerce, NBS Special Publication 631, pp. 1–121.

IEA 2004a: "World Energy Outlook". International Energy Agency

IEA 2004b. Documentation for the Markal Family of Models, Energy Technology Systems Analysis Programme, International Energy Agency, 2004

IIASA 2001. User's Guide for MESSAGE III, WP-95-69, International Institute for Applied Systems Analysis. Austria, 2001

IIASA 2004: Schrattenholter L. et al. "Achieving a sustainable energy system". IIASA. Edward Eldar. UK.

IPCC 2001: "IPCC Special Report on Emissions Scenarios".

Kopelaar, R. 2005. World oil production and peaking outlook. Peak oil Netherlands Foundation.

Laherrère, J. 2005. Forecasting production from discovery. ASPO Lisbon May 19-20, 2005

Lee C., Chang C., 2007. Energy consumption and GDP revisited: A panel analysis of developed and developing countries. Energy Economics 29 (2007) 1206–1223.

Meadows, D.H. et al. 1992. Beyond the limits : global collapse or a sustainable future. Earthscan Publications.

Meadows, E.H et al.1972. The Limits to Growth. New York: Universe Books

Mohr, SH, Evans GM, 2008. Peak Oil: Testing Hubbert's Curve via Theoretical Modeling. Natural Resources Research. Vol 17, nº 1. pp 1-11.

Naill, R. F., 1992. System Dynamics Model for National Energy Policy Planning, System Dynamics Review 8(1).

Ockwell, D.G. 2008. Energy and economic growth: Grounding our understanding in physical reality. Energy Policy, Volume 36, Issue 12, December 2008, Pages 4600-4604

Robelius, F. 2007. Giant Oil Fields -The Highway to Oil. Giant Oil Fields and their Importance for Future Oil Production. Acta Universitatis Upsaliensis. Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology . Uppsala

Skrebowski, C. 2008. Entering the foothills of peak oil. VII annual international ASPO conference. Oct 20-21 2008. Barcelona. Spain

Soderbergh, B. et al. 2007. A crash programme scenario for the Canadian oil sands industry. Energy Policy 35 (2007) 1931–1947.

Sterman, J.D. et al. 1987. Modeling the estimations of petroleum resources in the United States. MIT. D-3887.

Tao, Z., Li, M., 2007. System dynamics model of Hubbert peak for Chinas's oil. Energy Policy 35 (2007) 2281–2286

UN 2007. World Population Prospects. The 2006 Revision. United Nations.

WEC 2004. Survey of energy resources. World Energy Council. Elsevier.

WETO 2003: "World Energy, Technololgy and Climate Policy Outlook 2030". Directorate-General for Research Energy. European Commission.

Appendix 1

Equations of the model of conventional oil for the USA case of figure 1:

- *cumulative_production =∫ annual_production dt (initial value =1)*
- *non_discovered_resouces =- ∫ annual_discoveries dt (initial value =191)*
- *reserves = ∫ (annual_discoveries-annual_production) dt*
- *annual_discoveries=Annual_discoveries_delayed*(1+discoveries_variation)*
- *annual_production = annual_production_delayed*(1+production_variation)*
- *annual_discoveries_delayed(t) = annual_discoveries(t-1)*
- *annual_production_delayed(t) =annual_production(t-1)*
- *discoveries_effort = annual_discoveries_delayed/non_discovered_resouces*
- *discoveries_variation=0.09effort_factor_2*discoveries_effort+0.0004*(technological_innovation_1-1860)*
- *production_effort = annual_production_delayed/reserves*
- *production_variation=demand_variation-effort_factor*(production_effort)+0.0004*(technological_innovation-1982)*
- *technological_innovation = t*
- *technological_innovation_1 = t*
- *demand_variation = 0.12*
- *effort_factor = 3*
- *effort_factor_2 = 3*

The parameters we use in the simulation of this model are those of the production of the USA without Alaska of crude oil (we take as 200 Gbarrel in accordance with Hubbert 1956, Laherrere 2005 and our own calculations based on discoveries and production Gaussian and Lorentzian fitting), while, at the start of the simulation, *reserves* and *cumulative production* are chosen from data of our initial year of simulations, and take the initial reserves in 1902, 8Gbarrel, and the non discovered resources for 1902, 191Gbarrel. The initially delayed annual discoveries are 0.69Gbarrel and delayed annual production 0.069Gbarrels (that fits the real production). The discoveries variation in 1902 was 0.082 according to the Gaussian fitting and the production variation was 0.095. Therefore, most of the parameters are obtained from the data or from the adjustment of the data to a Gaussian fitting. Only conventional fuel (crude oil) is considered and we start our simulations in 1902 with the beginning of the records of backdated discoveries in the USA. The adjusted parameters are b, the technological innovation factor and the effort factor, which we take to be identical for both the production and the discoveries. Taking several values (1, 3, 5, 3.5) the value that fits the real data best is 3.

Equations of the model of non conventional oil of figure 4:

- *cumulative_production = ∫ annual_production dt*
- *non_discovered_resources = ∫ anual_discoveries dt*
- *reserves = ∫ (annual_discoveries – annual_production) dt*

- *annual_production_delayed_TOTAL= annual_production_delayed+annual_production_delayed_NC*
- *annual_production_NC= annual_production_delayed_NC*(1+production_variation_NC)*
- *annual_production_TOTAL = annual_production+annual_production_NC*
- *demand_variation = GDP_percapita_variation+population_variation*
- *GDP_percapita_variation(t)=production_variation_TOTAL(t-1)*
- *population_variation = 0.01*1.1316*exp(-0.0218*t)*
- *production_effort = annual_production_delayed/reserves*
- *production_variation=demand_variation-effort_factor*(production_effort)+technological_innovation*
- *production_variation = 0.12 (the addition of 3*(annual production delayed/reserves) plus the value of growth in 1902 that was 0.095)*
- *production_variation_NC = constant (elected depending on scenarios)*
- *production_variation_TOTAL=LN(annual_production_TOTAL/annual_production_delayed_TOTAL)*
- *technological_innovation = 0.0012*(t+20)*
- *effort_factor = 3*
- *(technological innovation = MIN (0.012*(t+20), 0.0225). (Meadows hypothesis)*

The parameters for this model are chosen using a value of 2250Gbarrel for the URR[2] (URR= *non discovered resources + reserves+ cumulative production*), taking the initial values for the *reserves* in 1985 (1100 Gbarrel) and the initial *cumulative production* (625 Gbarrel). The proportional factor between *non discovered resources* and *annual discoveries* is set at 22/525, the *annual production delayed* initially is established by taking the real data, while the *effort factor* and the parameter of *technological change* are chosen as fitting parameters. We adjust the model to fit the historical data: oil production must adjust to the real production between 1985 and 2005, per capita GDP must also adapt to the real evolution between 1985 and 2005 and per capita oil production must be approximately constant between 1985 and 2005.

[2] Following Laherrere2005, Hubbert1956 and our own calculations based on a careful literature review

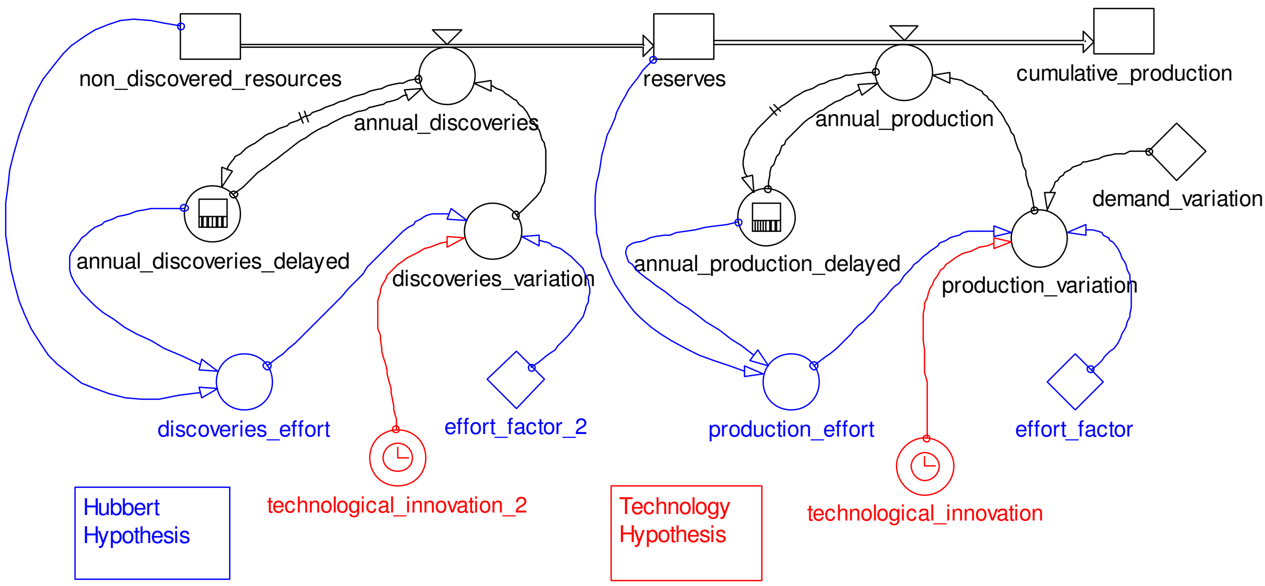

Figure 1: Model of oil production including Hubbert and Technology hypotheses. No economic feedback.

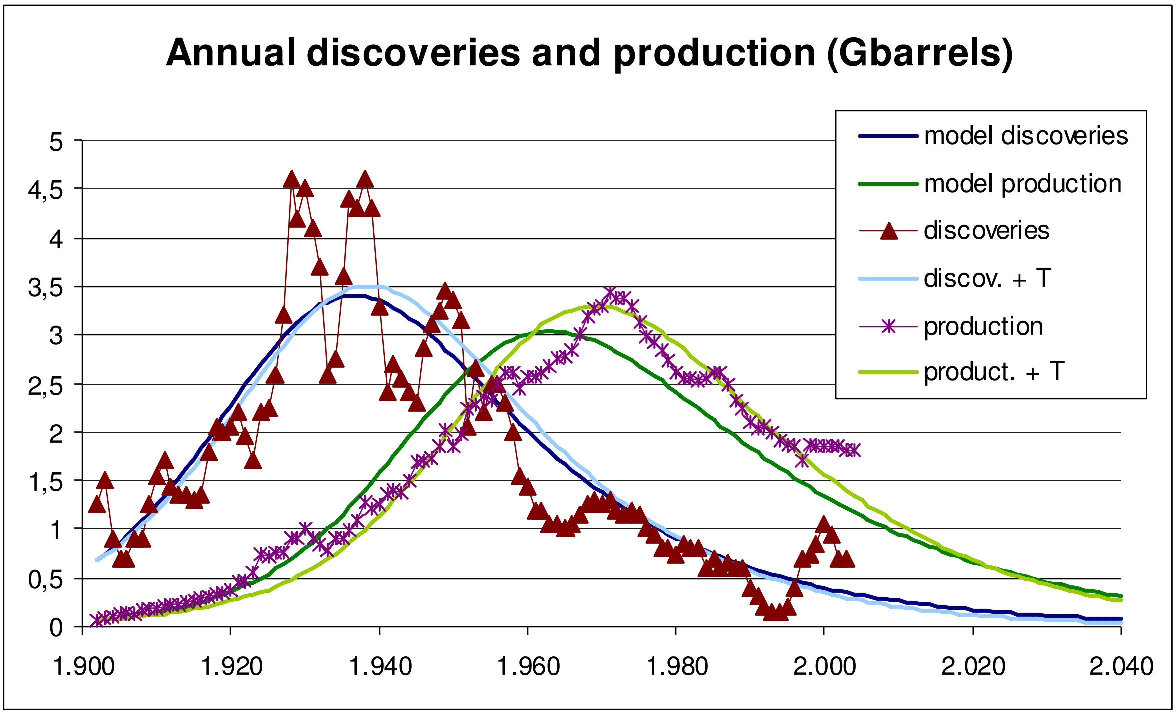

Figure 2: Results of the simulation of the model of figure 1 and comparison with real data (average of 5 years for discoveries). "T" is Tecnology

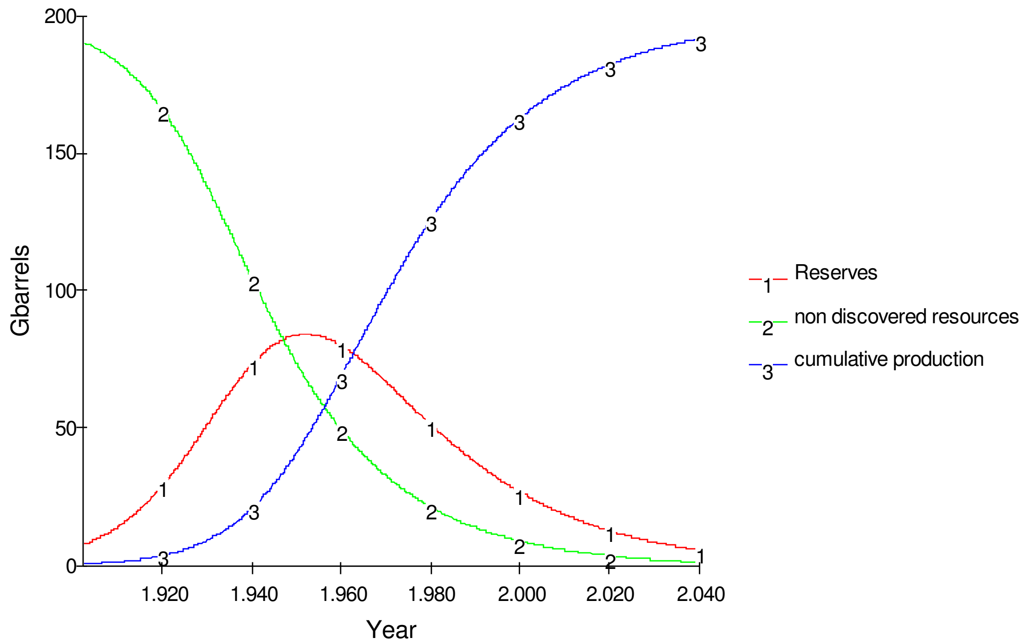

Figure 3: Results of the simulation of the model of figure 1.

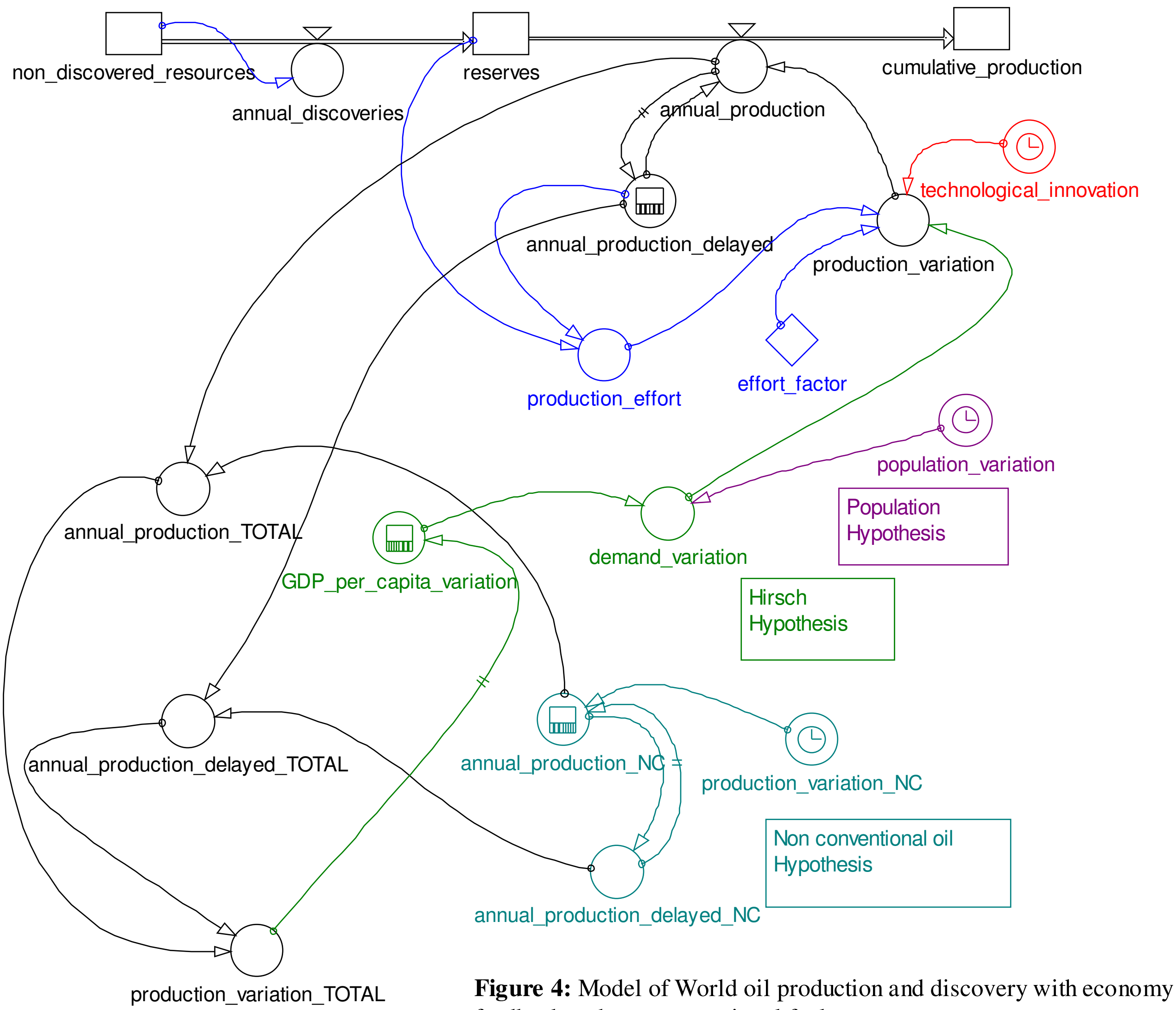

Figure 4: Model of World oil production and discovery with economy feedback and non conventional fuels.

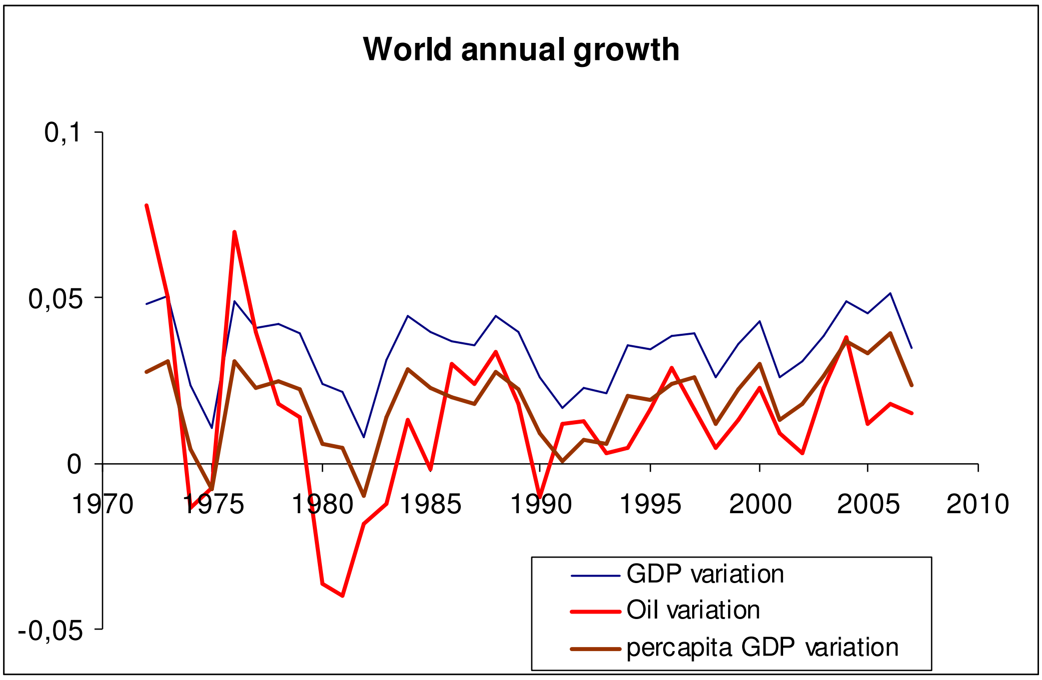

Figure 5: Percent variation of the GDP, per capita GDP and oil production variation.

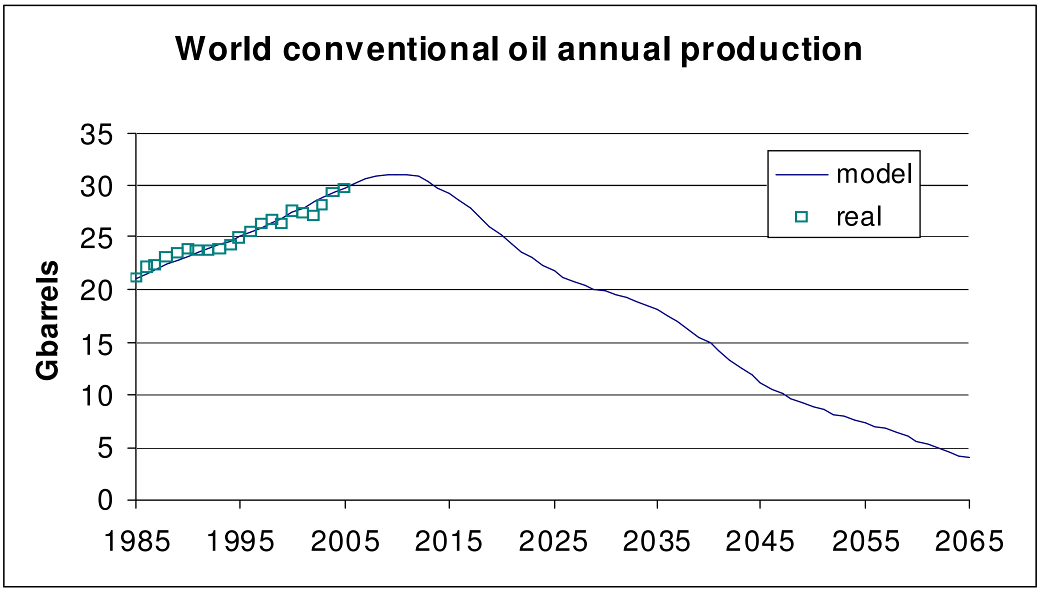

Figure 6: Results of the simulation of the model of figure 4, with the only conventional oil scenario.

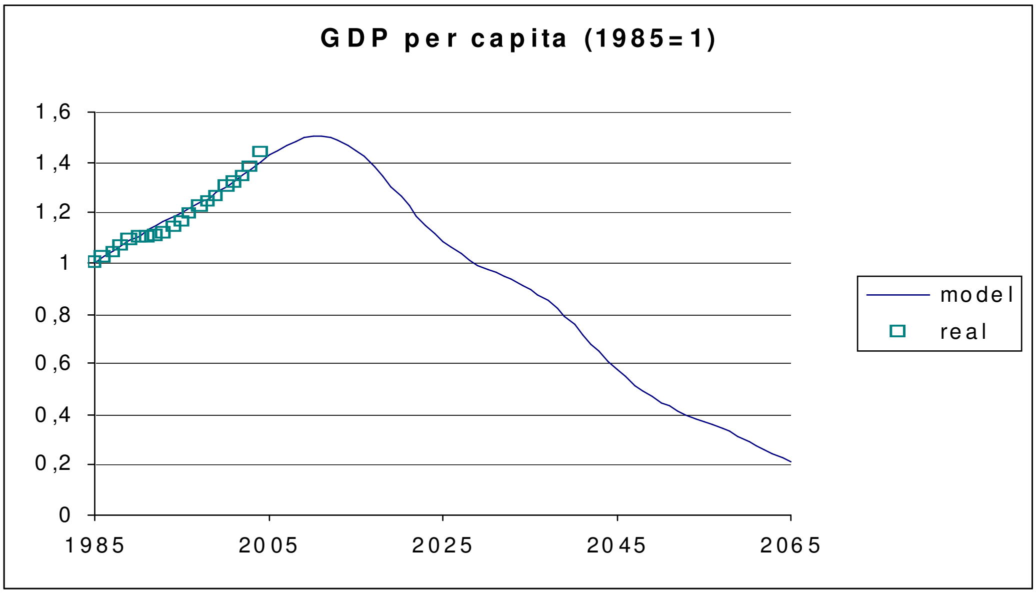

Figure 7: Results of the simulation of the model of figure 4, with the only conventional oil scenario.

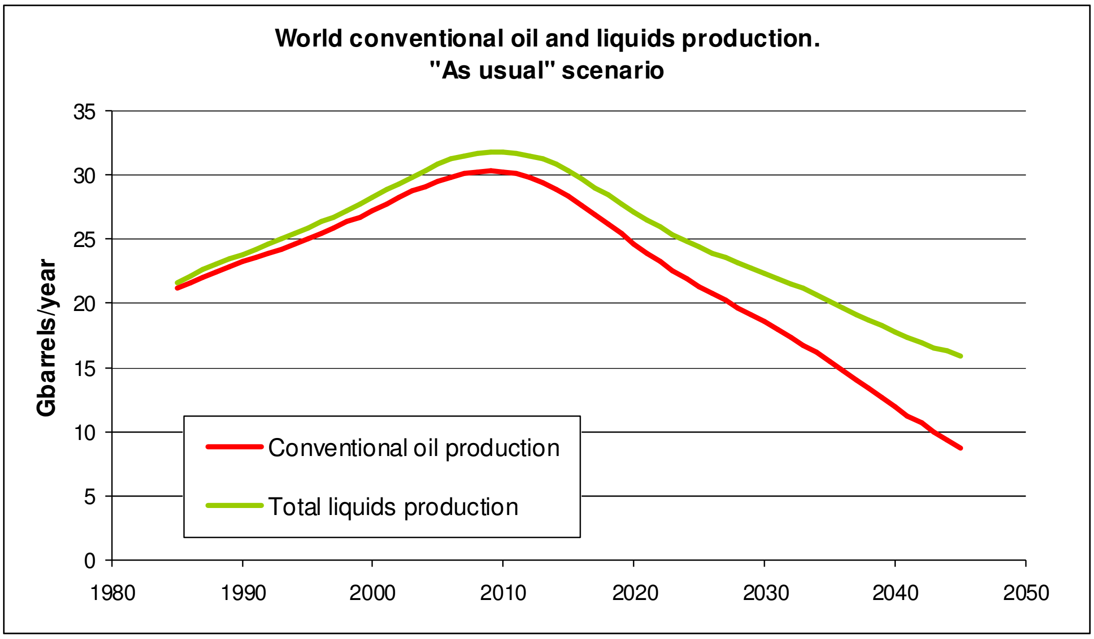

Figure 8: Results of the simulation of the model of figure 4, with business as usual scenario.

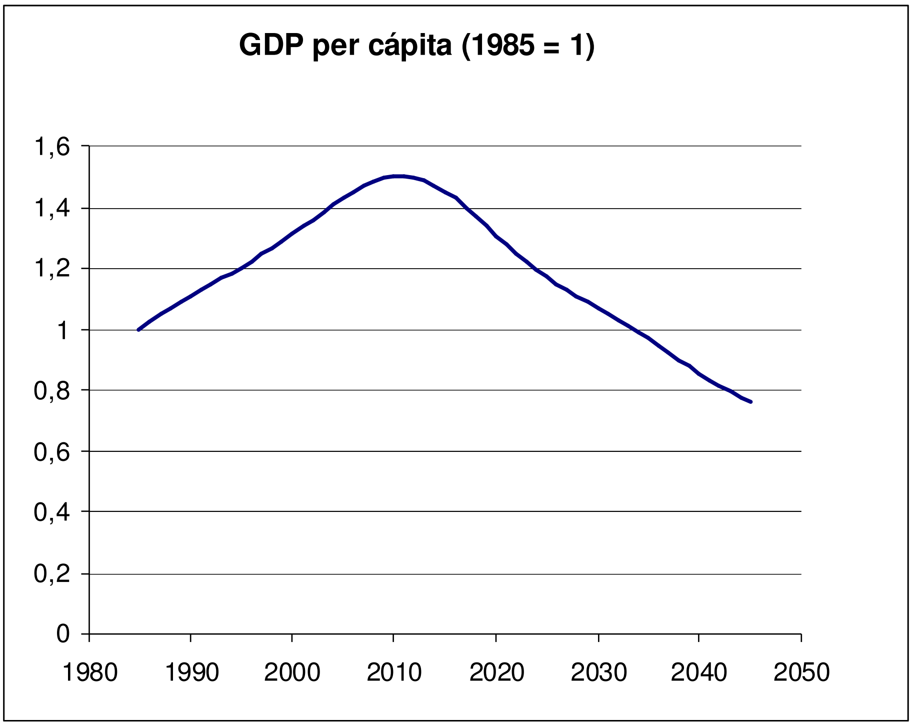

Figure 9: Results of the simulation of the model of figure 4, with business as usual scenario.

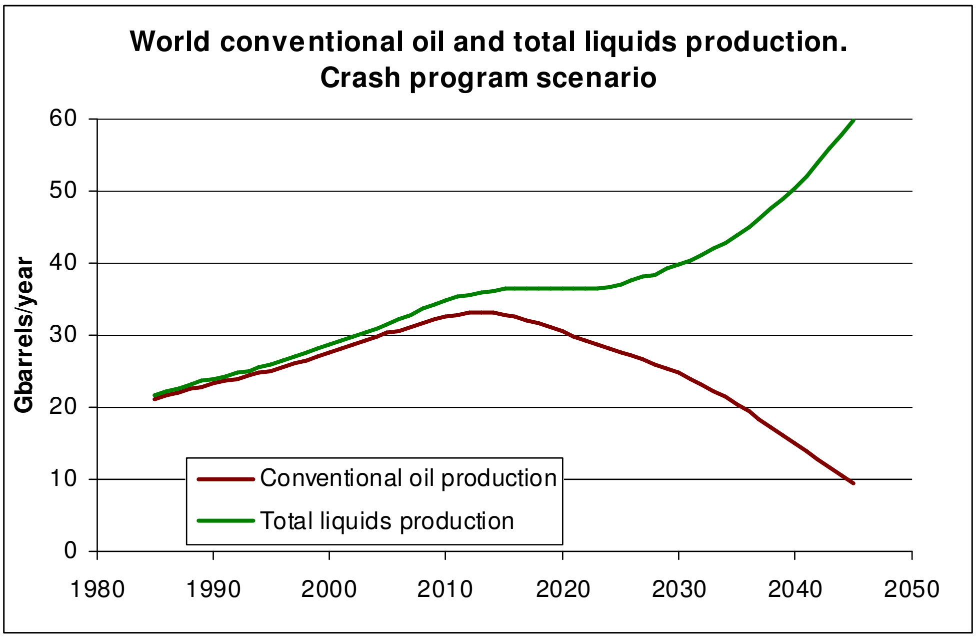

Figure 10: **R**esults of the simulation of the model of figure 4, with crash program scenario.

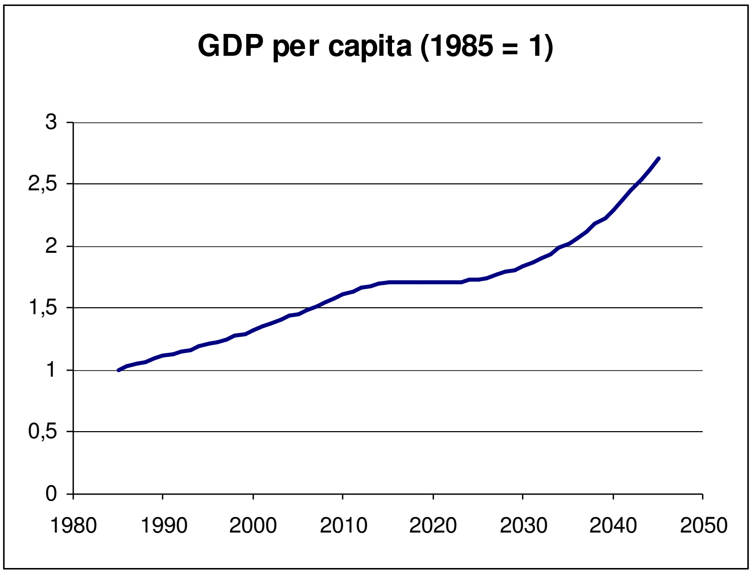

Figure 11: Results of the simulation of the model of figure 4, with crash program scenario.