*Article*

# Energy and Mineral Peaks, and a Future Steady State Economy

Antonio García-Olivares, Joaquim Ballabrera-Poy

**Technological Forecasting and Social Change, 2014**

**DOI: 10.1016/j.techfore.2014.02.013**

Institut de Ciències del Mar, CSIC
Passeig Maritim de la Barceloneta, 37-49. Barcelona, 08003, Spain.

E-Mail: agolivares@icm.csic.es (Antonio García-Olivares); joaquim@icm.csic.es (Joaquim Ballabrera-Poy)

---

**Abstract:** The coming fossil fuel peak may cause shortages in energy supplies and major disturbances in the global economy. The forecasts for the future of our way of life are very divergent depending on the prediction used for future human access to energy, and they range between collapse and indefinite growth. The LINEX production function, which depends on energy input, was modified, calibrated and used to model the gross domestic product (GDP) of the US economy under several different energy scenarios after the fossil fuel peak. The effects of information and communication technologies and technological innovation after energetic crises have been also modelled. A future renewable mix of global scale will require the use of a major fraction of the reserves of several important minerals. In this context, a future steady-state economy appears to be the best plausible scenario. Some of the implications and challenges derived from this steady-state economy are discussed.

**Keywords:** Energy security; Sustainable future; Steady-state economy; US GDP; Limits to growth.

---

## 1. Introduction

In terms of exergy (i.e. the amount of net energy available for use), Leslie White's Law of cultural evolution [1] states that, all other variables being equal, the degree of cultural development varies in correlation with the amount of technically available exergy. Since our origin as a species, increases in the amount of exergy have always led to improvements in the overall quality of life of societies, because they usually translate into increases in food harvests, individual possessions, educational standards and personal mobility. The power provided by the main prime movers has risen by approximately 15 million in the last 10,000 years, from the 100 W of human labor to the 1.5 GW of steam turbines. More than 99% of such increase has taken place during the 20$^{th}$ century [2]. In the last 50 years, we have consumed 80% of the total oil consumed by the humanity ever (see Fig. 2 below). Consequently, it can be said that we belong to the most fortunate generation that has ever existed, with access to cheap and abundant energy, prosperity and relative peace.

As stated by Earl Cook, "*the success of an industrial society, the growth of its economy, the quality of life of its people and its impact on other societies and on the total environment are determined in large part by the quantities and the kinds of energy resources it exploits and by the efficiency of its systems converting potential energy into work and heat*" [3]. In 2008, the global energy demand was mainly satisfied by oil (33.2%), coal (27.0%), gas (21.1%), biomass and waste (10.0%), nuclear (5.8%), and hydro (2.2%). On the other hand, the sum of geothermal, solar, and wind provided 0.7% of the global energy demand [4].

However, in their 2010 report, the International Energy Agency [5] did announce that crude production was at a plateau since 2006 and that it will not be easily increased. Heat energy production from coal is expected to peak before 2070 [6], while new forecasts suggest that coal reserves will run out faster than many believe [7]. The global peak in conventional gas may occur in the third decade of the 21st century [8] and the peak of all fossil fuels power is expected around 2028, with a standard deviation of 8.5 yr [9]. Nuclear energy prospects are dim after the Fukushima disaster and the subsequent announcement by Germany and Japan of their planned denuclearization, but also because uranium is a finite mineral whose production is expected to peak between 2015 and 2035 at the current rate of usage [10][11].

In the context of the current dependency of modern industrial societies on high energy consumption rates [12], the thesis of Japanese economist Osamu Shimomura (1911-1989) stating that societies must not seek economic growth when the conditions for growth are not in place, should be considered again (Shimomura originally referred to the 1973 energy crisis in Japan).

Contemporary technological systems are highly energy-dependent. In order to ensure their survival, present-day institutions (in a broad sense) need a network of materials, energy and information exchange [13]. All that we take for granted in modern societies relay on the persistence of such network. On the other hand, human ecology and ecologic economy have shown that, inside this network, energy exchange generates constraints on social practices and living standards [14][15]. Most current technological systems rely on the use of abundant and cheap oil, and many of these social constraints cannot be fulfilled without energetic resources. Thus, in the context of depletion of fossil fuels, one of the question that society must confront is if there is any primary energy mix that could serve as an alternative to fossil fuels.

In a recent article, we have shown that a solution, based on a global renewable mix and employing relatively abundant materials, exists [16]. However, it was shown that the renewable generation mix scaled to respond to global energy demand would use 330-384 Mt of copper (49-56% of current reserves). Moreover, platinum, lithium, nickel and (in a minor proportion) zinc for transportation would also represent a substantial part of the required reserves. Although reserves tend to increase along time responding to new demand and rising price, the increase cannot be expected to be limitless [17]. If the current estimation of Reserve Base ($10^9$ t) is assumed to be the future reserve by the end of this century, still 33-38% of copper reserves would have to be kept for the "technosphere" of the new electric economy. Consequently, continuation of the energy exponential growth would be soon impeded by the limitation of copper and other minerals.

Since there are no plausible alternative primary energy sources available in the short and medium term (other than the currently known renewable), waiting until the decline of fossil fuel production could be the most disruptive event ever for contemporary economies, as we discuss below. Therefore, in line with the point of view already stated by Boulding [18], a steady-state economy would be the best feasible scenario after the implementation of an alternative energy solution to fossil fuels in the second half of this century.

This manuscript focuses on the evolution of GDP according to an energy-dependent Production Function constrained by a peak in the production of fossil fuels. The impact of different scenarios for the development of a renewable energy mix is investigated using this model.

The structure of the manuscript is the following. In Section 2 we quantitatively explore some important feedbacks between energy and economic variables by means of a simple model of future global GDP. Next, we discuss some models to estimate future evolution of capital, labor, and exergy input into the US economy. In section 3 we apply this model to three scenarios of energy supply evolution over the secular scale: (i) non-substitution of the primary energy based on fossil fuels and renewable generation at the same level as today, (ii) deployment of new renewable sources with the same growth slope as over the past ten years, (iii) a ten-year increase in the slope of the deployment of renewables to achieve the slope necessary to generate 11.5 TW after a further 50 years. In the final section we discuss the results obtained, some of the implications that these scenarios could have on the economy and the society of the future, and we introduce a fourth scenario to discuss the possibility that fusion energy and new materials may provide a persistent exponential growth in exergy production.

## 2. A model for GDP growth as a function of net energy

Production Functions (PFs) are intended to capture the relationship between output (at the level of a firm, industry, or an entire economy) and various inputs. For years, the only production factors considered were Capital and Labor. The formulation of PFs assumes that engineering and managerial problems of technical efficiency have been already solved. Thus, PFs contain the relationship between the maximal technically feasible output and the inputs needed to produce that output.

Since the energy crisis in the early 1970s, economists do formulate energy (exergy) - dependent PFs [19][20]. In these models, capital ($k$) and labor ($l$) make energy available but, in turn, they are "nourished" by it. Kümmel [21][22][23] introduced the linear exponential (LINEX) PF:

$y = u\ exp\ \{\ a\ [2 - (l+u)\ /k] + a\ b\ (l-u)\ /u\ \}$ (1)

which was used by Warr and Ayres [24] to simulate the economic growth of the US during the 20th century and to predict its evolution to the early 21st one. In equation (1), *y* is the simulated GDP, and *u* is the useful energy (or "exergetic services") used by the economy. In contrast to the Cobb-Douglas production function, there is a limited substitutability of capital for labor and energy implicitly included in equation (1). This is plausible if capital and energy are to a great degree complementary, as suggested by [25]. By using this PF, Warr and Ayres [24][26] showed that use of useful exergy (useful work) as an additional production factor makes it possible to explain most of the Solow residual.

The simplest version of equation (1) uses "*a*" and "*b*" as constants being adjusted with historical data of GNP, capital stocks, labor and energy consumption. Capital invested in information technology has been introduced in two LINEX-derived PFs [27][28] to explain the rising effect of information technologies on economic efficiency after the 1970's. A problem with these two new production functions is that their labor (and in the second case, also capital) productivities do not satisfy the asymptotic conditions imposed by Kümmel [21][22]. This makes the long-term evolution of factor productivities (FPs) to lack of interpretation. A way to avoid that is to introduce the ratio, *i*, between information capital stock and the total capital stock, in the following way:

$$y = q u^{\varepsilon} \exp\left\{\left[2a - a\left(\frac{l+u}{k(1-i)}\right) + ab\left(\frac{l}{u} - 1\right) + ci\right]\varepsilon\right\}$$

and its linearized form:

$$y = q u^{\varepsilon}\left(1 + c\varepsilon i\right) \exp\left\{\left[2a - a\left(\frac{l+u}{k(1-i)}\right) + ab\left(\frac{l}{u} - 1\right)\right]\varepsilon\right\} \qquad (2)$$

With factor productivities (FP) or elasticities given by:

$$\alpha = \frac{k}{y}\frac{\partial y}{\partial k} = \varepsilon \frac{a(l+u)}{k(1-i)} \qquad (3)$$

$$\beta = \frac{l}{y}\frac{\partial y}{\partial l} = \varepsilon\left[\frac{b}{u} - \frac{1}{k(1-i)}\right] \qquad (4)$$

$$\gamma = \varepsilon - \alpha - \beta\ = \varepsilon[1 - a(u^2 + blk(1-i))\ /\ (uk(1-i))\ ] \qquad (5)$$

Where *i* is the fraction of capital stock fixed in information and communications technologies (ICT), *c* is a new adjustable constant and ε is the relative decrease of the FPs due to erosion of natural capital. Scenarios with ε≤1 would allow the study of the possibility of decreasing returns to scale after some future date. According to these elasticity equations, *a* is the efficiency by which labor and energy make work the capital stock and *b* is the maximum rate of use of useful energy per unit of physical capital, which could take place eventually in a situation of complete automatization.

In this work, the Production Function given by equation (2) will be used to explore the consequences of different energy scenarios on the future GDP of a developed country such as the US. With this purpose, the useful exergy *u* is calculated as the product between the Raw Primary Energy, *E*, and a conversion efficiency $f_c$ which is a function of the technological efficiency of a given economy:

$$u(t) = f_c(t)\, E(t) \qquad (6)$$

The first step in this work has been to fit the Production Function (2) to the available data for the US [28]. Kümmel et al. [29] used time-dependent parameters *a*(t) and *b*(t) that were changed after energetic crises following either Heaviside or logistic functions. This modification lead to improvement of the realism of the reconstructed evolution of economic sectors of the US, Germany and Japan after the energetic crises of the seventies. Consequently, we have fitted the US GDP from 1900 to 2000 allowing parameters *a* and *b* to change after 1977 following a Heaviside step function. The fit to data increases from $R^2$ = 0.9980 to 0.9986 and reproduces better the high frequency oscillations of the time series. A logistic increase and decrease of variables *a* and *b* respectively should be expected after future energetic crises, and we have included this plausible change in the current version of our model. In particular, major energetic crises should be expected after 2038, with the peak of fossil-fuels and oil, and (in our "optimistic renewable" O scenario) after 2094 with the whole deployment of the 11.5 TW renewable power, but rising copper scarcity. Another parameter allowed to change logistically will be the technological efficiency of conversion of raw exergy into useful work for the fossil-fuel based and the electricity-based sectors of the economy ($f_f$ and $f_e$ respectively).

The future evolution of the US economy is simulated here using the calibrated parameters q=1.36, a=0.29, b=2.46 and c=2.66, and the 1900-2000 historical data of *l, k, u* (compiled by [30]), and *i* (according to the EU-KLEMS database, http://www.euklems.net/). After 1977, *a* is allowed to increase 19% and *b* to decrease 22%, to simulate technological improvements that enhanced capital efficiency and reduced energy demand in response to energy crises. Variables *k, l, u* and *y* are normalized by respect their 1900 value. Table 1 explains the different variables and parameters used in this work as well as the equation where they are used.

| | | | |
|---|---|---|---|
| y | 1,2,3,4 | variable | Gross Domestic Product (GDP) |
| u | 1,2,3,4,5,6 | variable | Exergetic services (useful energy, useful work) |
| l | 1,2,3,4,5 | variable | Labor force |
| k | 1,2,3,4,5 | variable | Capital stock |
| a | 1,2,3,5 | parameter (*) | Labor and exergy ability to get capital efficiency |
| b | 1,2,4,5 | parameter (*) | Maximum rate of energy use per capital stock |
| q | 2 | parameter (*) | GDP integration constant |
| c | 2 | parameter (*) | ICT efficiency to amplify output |
| i | 2,3,4,5 | variable | Ratio of ICT capital stock to total capital stock |
| ε | 2,3,4,5 | parameter | Decrease factor of the factor productivities. Set to 1 |
| α | 3 | variable | Output elasticity (productivity) of capital |
| β | 4 | variable | Output elasticity (productivity) of labor |

| | | | |
|---|---|---|---|
| $\gamma$ | 5 | variable | Output elasticity (productivity) of energy |
| E | 6 | variable | Raw primary "energy" (Raw primary exergy) |
| $f_c$ | 6,10 | variable | Effective conversion efficiency |
| $f_f$ | 10 | variable | Conversion efficiency from fossil fuels |
| $f_e$ | 10 | variable | Conversion efficiency from electricity |
| P | 7 | variable | Fuel annual production |
| $u_r$ | 7 | parameter (*) | Fuel ultimately recoverable resources |
| g | 7 | parameter (*) | Fuel production growth rate |
| $t_p$ | 7 | parameter (*) | Fuel production peak year |
| $c_e$ | 8 | parameter (*) | EROEI scaling factor |
| $f_r$ | 8 | variable | Fraction of remaining fuel |
| $\eta$ | 8 | parameter | EROEI power law exponent |
| $m_i$ | 9 | variable | Fraction of the i-th fuel in energy generation mix |
| d | 11 | parameter | Capital depreciation rate |
| r | 11 | variable | Capital gross investment rate |

Table 1. Parameters and variables used in the model. Second column corresponds to the equation number where the item is used. Asterisks in column 3 indicate parameters that have been obtained by fitting with historical data.

### 2.1 Future labor intensity and useful energy

After year 2000, the US labor force is assumed to be proportional to the curve of the world population evolution, as predicted by the United Nations under its "medium" scenario [31]. Fig. 1 shows the resulting curve.


**Fig 1. Labor intensity used in our simulations. The time series is based on the US statistics (1900-1998) and on the "medium" scenario of the UN world population projections (1999-2200).**

The amount of exergetic services consumed by the US economy comes from [30]. The amount of energy consumed in the world is derived from the historical datasets of fossil fuel consumption collected from the Shift Project data portal (http://www.tsp-data-portal.org). For future world consumption, every fossil fuel dataset has been adjusted to one (three in the case of oil) Hubbert function [32] of the form:

$$P = u_r\, g\, \frac{e^{-g(t-t_p)}}{\left[1+e^{-g(t-t_p)}\right]^2} \qquad (7)$$

In equation (7), $P$ is the annual production of each given fuel, $u_r$ is its ultimately recoverable resource (URR), $g$ is the growth rate parameter and $t_p$ the year of peak production. It must be noticed that Hubbert functions have two limitations: (i) they assume that the URR is fixed along time although there is evidence that it may increase along time and that it is a function of investments made in its exploration; (ii) they also assume that production is the result of a single exploitation cycle that depends only on the URR, but not on the time-changing economic efforts made to extract the resource.

The first limitation is partially accounted for by way in which the variable URR is normally estimated. Reserves tend to increase with time, especially when the rate of new discoveries is higher than the rate of consumption. As the rate of new discoveries dwindles, ulterior increases in the estimate of the URR will slow because it has to extrapolate the trend of discoveries while trying to include the development of the new extractive technologies that can be envisaged from the present. However, new energetic technologies need many decades to become economically viable. On the other hand, exploration investments do reduce as the cost of extraction increases (the latest two IEA reports denounced the insufficient investment in exploration and new extraction technologies as the reason of the present plateau in oil production since 2006). In that vein, Murray and King (2012) have noticed that oil production has become inelastic after 2005. That is, despite swings in oil prices, little variation has been observed in oil production. Based on their results, Murray and King identified an apparent production cap of about 75 million barrels per day of crude oil. Such inelasticity and the apparent cap do not support the idea of the existence of a proportional relation between price rise (and subsequent investment) and additional production (and new reserves). For these reasons, the assumption of a constant URR value could be considered robust in the scale of many decades even in the case of occurrence of future technological revolutions.

The second limitation can be partially addressed by fitting the historical data of production data as the superposition of separate Hubbert functions representing different cycles of extractive effort or new resources. In this work, the fitting of the oil production uses three Hubbert functions characterized by the following parameters: $URR_1$= 169 Gb, $URR_2$=1856 Gb, $URR_3$= 975 Gb and $t_{p1}$= 1975, $t_{p2}$=2007 and $t_{p3}$=2047. The resulting fit has a coefficient of determination of $R^2 = 0.999$. The URR for liquids, gas and coal have been reported by [33] and [6] in a detailed study. The reported values are 400 Gtoe (16748 EJ) for liquids; 300 Gtoe (12561 EJ) for gas; and 750 Gtoe for coal. To be conservative, in this work it is assumed that 400 Gtoe is the URR of oil, condensate and natural gas liquids (hereafter “oil”) and not all liquids.

Fig. 2 shows the historical data and the corresponding fitted models for each fuel type. The curve of total fossil fuel consumption and the integrated curve of all the separate fits are also displayed. As can be observed, the predicted peak of oil may persist until 2040. Peaks of gas and coal take place in 2029 and 2065 respectively. The aggregated power produced by all the fossil fuels is expected to peak in 2038. Our estimation, is slightly above the upper part of the Leggett and Ball [9] range.

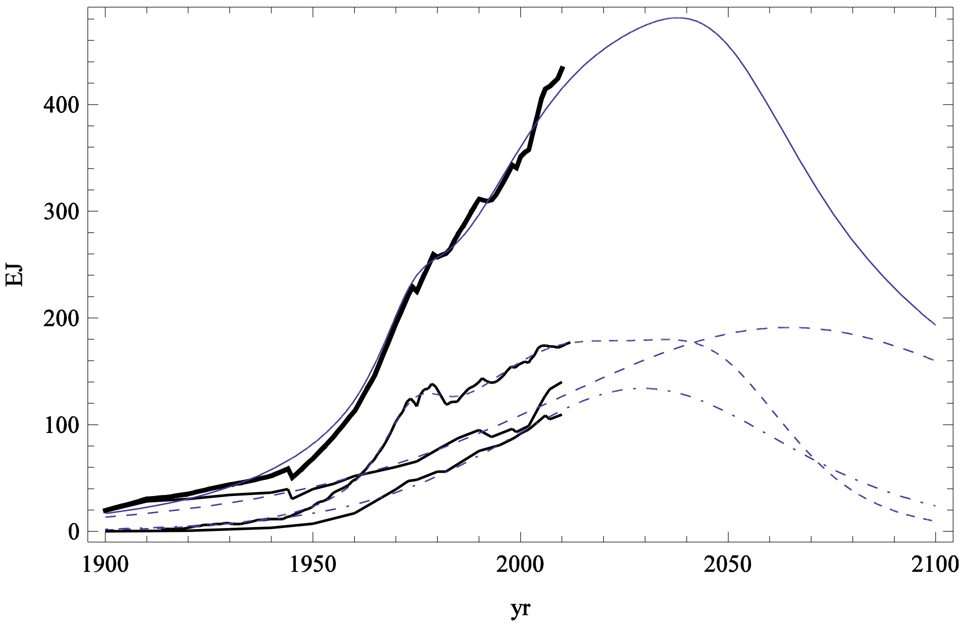


**Fig. 2. Historical data of fossil fuel production and corresponding fitted models for each fuel: oil (dotted line), coal (dashed line) and gas (dot-dashed line). The curve of total fossil fuel consumption (upper thick line) and the integrated curve of all the separate fits (thin continuous line) are also displayed.**

Finally, to obtain the total global energy consumption, the contributions of hydroelectric, nuclear and renewable energy are added to the previous mix. The historical production from these three sources from 1900 to 2010 has been compiled by the Shift Project Data portal on energy and climate data (http://www.tsp-data-portal.org/). We have assumed that the consumption of hydroelectric and nuclear will remain stable after 2010.

Calculation of the remaining fraction of each non-renewable fuel can now be calculated from the area of the Hubbert curve already used in relation to the total area (equal to $u_r$). It is assumed that the energy returned over energy invested (EROEI) of a given fuel decreases according to the following expression, which is a generalization of that taken from [34]:

$$EROEI(t) = c_e 100\ f_r(t)^{\eta} \qquad (8)$$

where $f_r(t)$ is the fraction of remaining fuel and $c_e$ is a constant to be adjusted to reproduce the reported value of the EROEI in the year 2000. We have taken the values of 20, 20, and 53 for the EROEI of oil, gas and coal in 2000, respectively (see [35]). García [34] uses η=2 in her model, but here the η value for oil is taken as 3.5 to approximately match the two values reported by [35] in their Fig. 5.5 (95±10 and 20±10 for 1930 and 2000, respectively). The EROEI of the whole society at year $t$ can be estimated by:

$$EROEI_s(t) = \sum_i m_i(t)\, EROEI_i(t) \qquad (9)$$

In equation (9), $m_i(t)$ is the fraction of the i-th fuel in the energy production mix at year $t$, and can be calculated from $m_i(t) = P_i(t) / P_t(t)$, where $P_i$ (t) is the production of fuel-i and $P_t(t)$ is the total power production at time t.

The ratio between the US primary production of useful energy ("primary exergetic services" under the Ayres denomination) and the global production of energy can now be obtained. The result shows that, while such a ratio has a tendency to decrease between 1980 and 2000, it has remained approximately constant and equal to 0.30. As a first approach, it is assumed that this value will continue to decrease in the next two decades to a value of 0.29 due to the growing consumption of emergent economies. In each of the following scenarios we will assume that the demand of useful energy in the US will be proportional (through this ratio) to the growth of the global energy demand and to its present weight in the global demand.

Future values of the technological efficiency of fossil fuel conversion, $f_f$, will be extrapolated from the fit of a logistic function (see Annex A. equation A.1) to the historical data for the US obtained by Warr et al. [30] (supplementary material).

According to [24] and [36], the value of $f_f$ has increased from 1900, but has slowed down its growth since 1970, following the shape of a logistic curve as the ones described in Annex A. Our fit of these data to the logistic curve (A.1) provides the values of $r = 0.029$ and $f_\infty = 0.1395$ ($R^2 = 0.99$). We have extended this curve by the means of another logistic function starting at year 2036, and characterized by $f_o = f_f(2036)$ and $f_\infty = 0.20$. It represents the expected increase in efficiency after the energetic crisis produced by the fossil fuels peak (see lower gray curve of Fig. 3).

To account for the expected increase in the energy to useful work conversion efficiency associated with the transition to a fully electric exergy system, we will now estimate what the conversion efficiency of the current US economy would be if the primary energy source were electricity alone. To this end, we have used 5 target economic sectors and assumed that their respective weight in the future economy would be equal to the current ones. The set of weights and current efficiencies of these 5 targets have been calculated by [37] (Supplementary material) and are provided in Table 2. We assume five final destinations for energy use: low temperature heating of residential and industrial spaces, high temperature industrial heating (> 600 ºC), motion production (transport and industrial engines), use of animal work, and chemical transformations. Energy losses associated with using primary energy to produce electricity (currently 83% in the US) would not occur in an economy based on renewables since the primary energy would come from source in electric form.

Electricity does not represent a considerable advantage for high temperature heating, since a heat pump has almost the same efficiency as a resistor to produce high temperature heat. The efficiency of 0.31, reported by [37] for high-temperature heating, is used here. Heat pumps are more efficient than fossil fuels in producing low-temperature heating and cooling. However, the rate of installation of new heat pumps is slow and, to be conservative, we assume that low-temperature heating would have the same efficiency as that observed in the present economy. The efficiency of chemical transformation with electricity is assumed to be similar to the one using oil in the present economy (i.e., 0.5). However, mechanical drive production in industry is very variable and depends on the use of motion. Pumping uses, which share 25% of industrial electric motion, have efficiencies comprised between 0.31 and 0.72 [38], while traction with electric engines has efficiencies of 0.80-0.87 [39]. We have assumed an average efficiency of 0.60 for all the industrial uses of motion.

| Target Economic Sector | Weight | Conversion Efficiency |
|---|---|---|
| High Temperature | 0.07 | 0.31 |
| Low Temperature | 0.27 | 0.03 |
| Mechanical drive work | 0.38 | 0.60 |
| Chemical Transformations | 0.07 | 0.50 |
| Animal Work Uses | 0.21 | 0.04 |
| Total | 1.00 | 0.30 |

**TABLE 2**. Technical efficiency of five economic sectors in the US if the primary energy source were electricity alone. Future weight of each sector is assumed to be equal to the current one.

The difference with the current efficiencies (based on fossil fuels) is assumed to reside in the mechanical drive work (calculated to be 0.12) as well as in the existence of a conversion from fossil fuels to electricity, with an efficiency of 0.17 [37]. Thus, according to these assumptions, current average efficiency of the economic system is about 0.12. However, the current average efficiency of an electrified society would be 0.3 (Table 2). We further assume that this efficiency will increase to 0.4 over the next two centuries, taking into account a plausible augment of electrical technology efficiency. Thus, $f_e$ is assumed to behave as a single logistic curve starting at the value 0.3 and saturating at 0.4 (upper curve in Fig. 3). The evolution of this curve from 2000 to 2050 is close to a forecast of Warr and Ayres [24] (see "high" efficiency scenario in their Fig. 14) and our $f_f$ curve is close to their "low" efficiency scenario.

Finally, the effective efficiency $f_c$ used in equation (6) is calculated from

$$f_c(t) = \frac{P_f(t)}{P_f(t)+P_e(t)}\, f_f(t) \;+\; \frac{P_e(t)}{P_f(t)+P_e(t)}\, f_e(t) \qquad (10)$$

That is, the effective energy conversion efficiency is the weighted average of the $f_f$ and $f_e$, with weights given by the evolving relative contribution of fossil fuels and renewable sources to the mix. The value of the useful work, *u,* used in (2) is the minimum of (6) and *bk(1-i),* to be consistent with the definition of *b*.

### 2.2 Estimation of future capital stock

Warr et al. [30] provide historical timeseries of capital *k* and GDP *y* in the US from 1900 to 2000. In our simulations, the capital previous to year 2000 will come from the empirical data of US capital stocks. Future values of the capital will be modeled as a fraction, *r*(*t*), of the GDP of the previous year together with a depreciation rate *d*:

$$k(t) \;=\; \left[1-d\right] k(t-1) \;+\; r(t-1)\, y(t-1) \qquad (11)$$

The value of *d* is estimated to be equal to the average depreciation documented for the US between 1999 and 2011 (according to the US Bureau of Economic Analysis: www.bea.gov), which is $d = 0.044$. On the other hand, previous to 1999, the gross investment rate *r*, is given by its historical values. After 1999, the gross investment rate is assumed to depend on the capital available after discounting the capital invested in energy:

$$r(t) = r_o \left[1 - \frac{1}{EROEI_s(t)}\right]\left[1 - \frac{1}{EROEI_{so}}\right]^{-1} \tag{12}$$

The value $r_o$ is estimated as the averaged gross investment rate during the period 1999-2011 (0.19) normalized by respect its 1900 value. Thus, $r_o = 0.034$. Equation (11) assumes that the fraction of capital invested in the energy sector with respect to GDP is the same fraction as the energy invested in energy production with respect to the total energy consumed, i.e. *1/EROEI*. With these parameterization, $r$ diminishes with the $EROEI_s$.

Finally, the fraction $i$ of information technologies capital to total capital is derived for the US from data in the EU-KLEMS database (http://www.euklems.net/) for 1970 to 2007. After 2007, it is modelled with the help of the logistic function (A.1) with $\tau = 2007$, $\kappa = 0.1$ when $f_o$ is taken equal to the observed rate at 2007 (0.14) and saturation value, $f_\infty$, is assumed to be 0.33. A value of $f_\infty = 0.25$ is also used to explore the model sensitivity to the asymptotic value of this parameter. Although the future evolution of information technologies is uncertain, it seems plausible that about 1/4 to 1/3 of the capital stock may revert into information technologies because most of the social necessities are based on tangible goods and will continue to be so in the near future. The restriction could be removed if the future economy would produce and demand most of its goods and services as information. So far, such a scenario is difficult to conceive.

With these parameterizations and by fitting the model to the US data for the period 1900-1999, the resulting model is able to correctly simulate the observed GDP of the US between 2000 and 2007 (validation data). After the validation period, the slow down between 2008 and 2012 in the US GDP is reproduced if it is assumed that $r$(t) decreases by 15% relative to pre-crisis value.

## 3. Three scenarios of future economic development

Three evolution scenarios are explored here. In the first scenario, the energy mix is composed of fossil fuels and a constant production of hydroelectricity, nuclear and renewables at the same level as in 2010 (scenario P or "Pessimistic"). The other two scenarios assume a different growth for the relative weight of renewable sources. Namely, the second scenario (hereinafter called M, or "Medium") assumes that the useful energy in the US economy will be that derived from the expected evolution of fossil fuels production (according to the Hubbert models obtained above and to the fraction of the global energy that plausibly will be consumed by the US) and from a future renewable installation with the same growth slope as over the past 10 years (about 0.48 EJ/yr globally). The third scenario (hereinafter O, for "Optimistic") assumes that, after the peak of fossil fuels (2038), renewable sources worldwide will increase their growth slope in ten years to achieve the slope necessary to generate 11.5 TW in 50 years. This figure was considered sufficient to supply the global demand of energy in 2030 [40]. Further increase of the renewable installation is considered unlikely due to scarcity of copper and other minerals.

Combining the input of fossil fuel exergy obtained (Fig. 2), the hypotheses made on the future deployment of renewable energy production, and the conversion efficiencies of Table 2, we obtain different time evolution of the efficiency of technology conversion to do useful work (Fig. 3). Curves for the evolution of aggregated fossil-fuel conversion efficiency (bottom continuous line) and aggregated conversion efficiency in a completely electrical economy (upper continuous line) are also included.

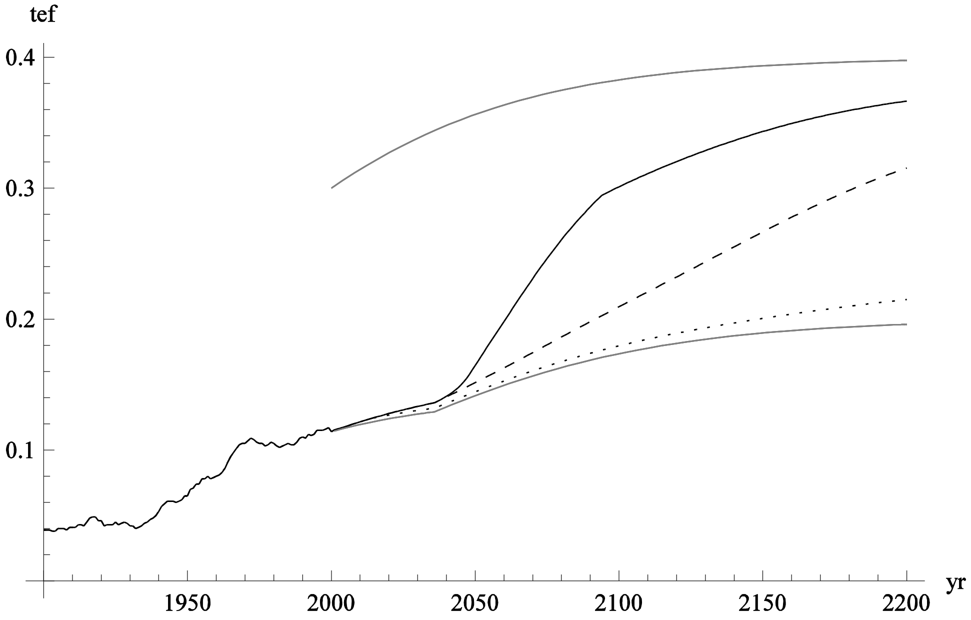


**Fig. 3. Evolution of the effective efficiency of conversion to useful work (fc in eq. 7) obtained by the model for Scenarios P (dotted line), M (dashed line) and O (black continuous line). Time evolution of aggregated fossil-fuel efficiency conversion ff (bottom gray continuous line) and aggregated efficiency in a completely electrical economy fe (upper gray continuous line) are also included.**

The resulting useful energy production for scenarios P, M and O is shown in Fig. 4.

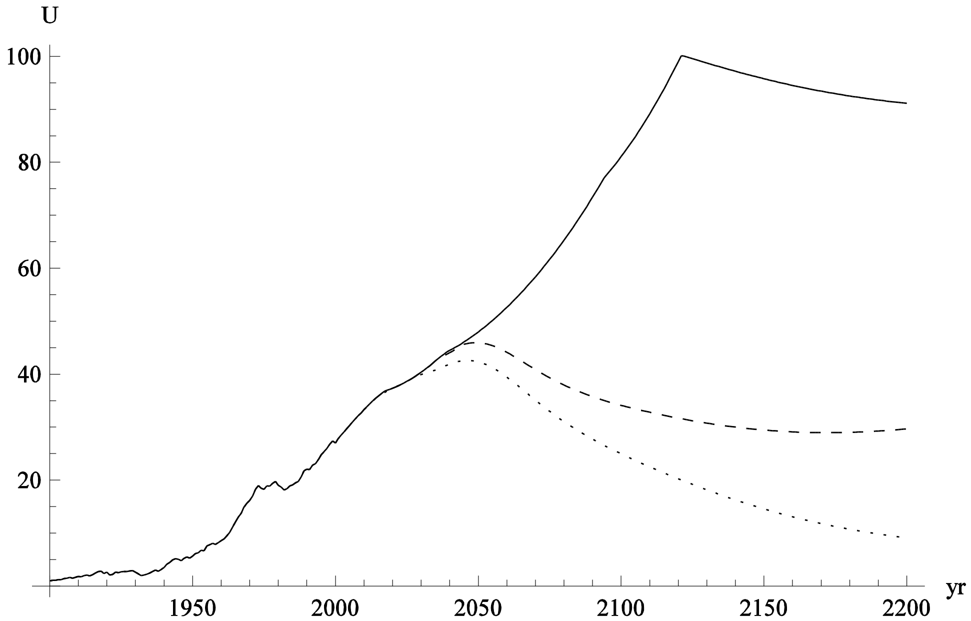


**Fig. 4. Evolution of the useful energy under Scenario P (dotted line), M (dashed line) and O (continuous line).**

Fig. 5 shows the evolution of the EROEI of the different fossil fuels and the social EROEI as a function of time in scenario M. As can be observed, the effective social EROEI falls from about 45 in 2000 to a minimum value of 12 by 2120 and then it rises to a steady value of 20 in the long term, due to the dominance of renewable sources in the mix. In our model, this change has a limited effect on $r(t)$, which suffers a decrease of 9% between 2000 and 2090 (13% and 6% for models P and O, respectively). If no renewable mix were used to substitute fossil fuels, the effect on $r(t)$ would be much more important. Fig. 6 shows the capital stock evolution for the three scenarios P, M and O.

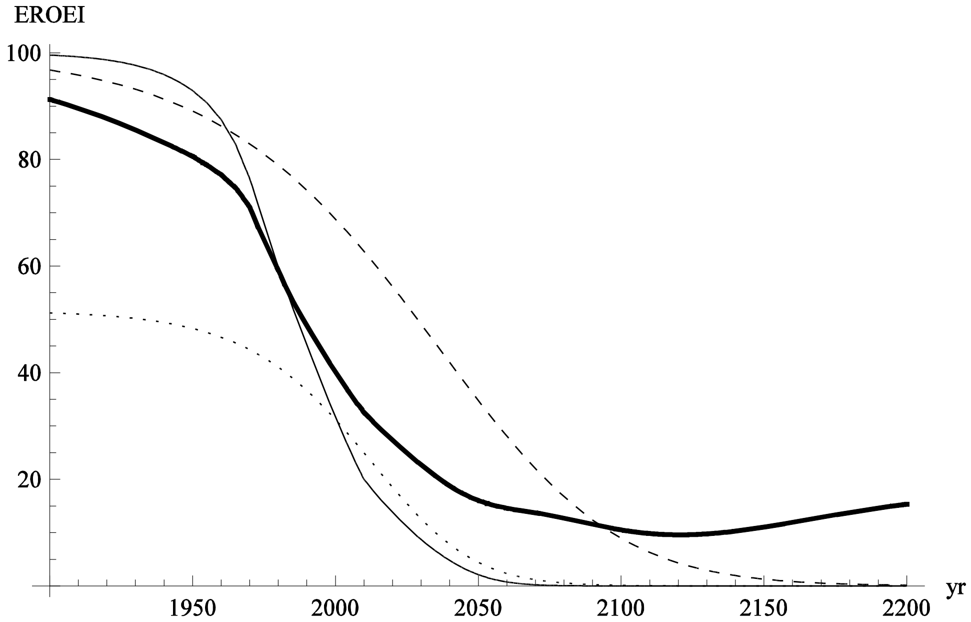


**Fig. 5. Evolution of the EROEI as modeled for Scenario M for: liquids (thin continuous line), gas (dotted), coal (dashed) and effective social EROEI (thick continuous line).**

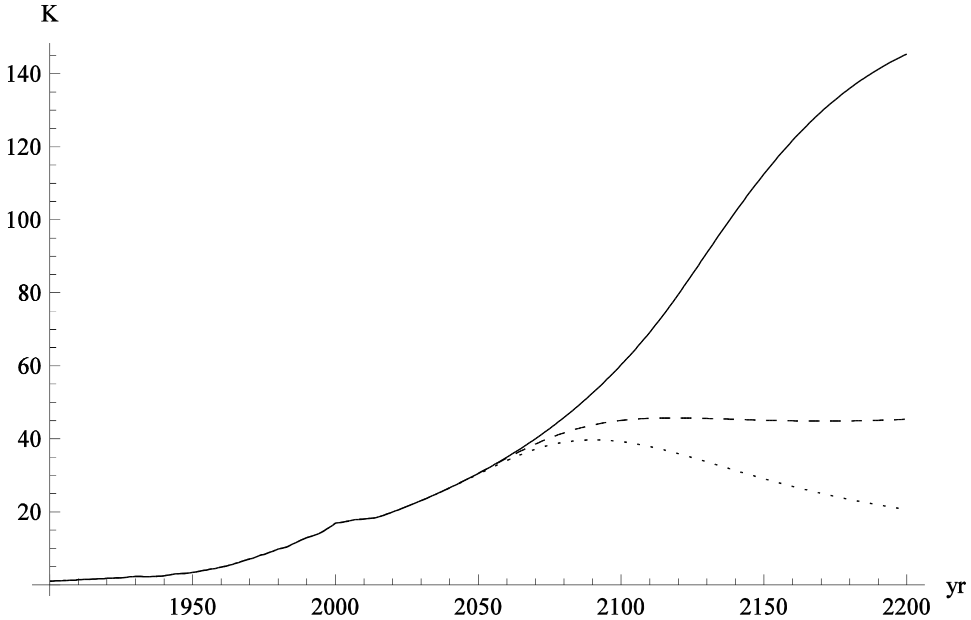


**Fig. 6. Evolution of capital stock as simulated for Scenarios P (dotted), M (dashed) and O (continuous line).**

In the next set of simulations, the parameters *a* and *b* of the Production Function (eq. 2) are allowed to change after the major energetic crises in the same proportion than we obtained for the seventies in our best fit. Thus, in scenario P and M, *a* changes following the logistic function eq. (A.1) with the following parameters: $f_o$=0.29, $f_\infty$=1.19 $f_0$, $\kappa$=0.02, $\tau$=2038, while b changes according to $f_o$= 2.46, $f_\infty$=0.78 $f_0$, $\kappa$=0.02, and $\tau$=2038. In scenarios O and I, the parameters *a, b* evolve in this same way, with the difference that a second transition is allowed at time τ=2094, following the same logistic function described above with the exception of $f_o$, which is taken as *a*(2094) and *b*(2094) respectively. In a similar way, Kümmel [29] modeled the innovation diffusion after major energetic crises. Parameter κ (corresponding to a characteristic saturation time of 35 yr in our case) has only a smooth influence on the results.

Fig. 7 shows the GDP evolution predicted for the P, M and O scenarios when ICT capital is assumed to tend asymptotically to 33% of total capital, and the O scenario with ICT tending to 25% of k (dotdashed line). It forecasts a production peak by 2070 followed by a decline to levels below the current ones (scenario M), an asymptotic steady state after 2080 (scenario M) and a persistent growth until 2150 followed by a slowing down towards a steady state after 2200 in scenario O. This curve is highly correlated to the evolution of *u* (Fig. 4). In the three cases there is a delay between the maximum (or steady state) of *u* and the maximum (or steady state) of the GDP. The cause is the permanent improvement of the conversion efficiency to useful work, the increased contribution of ICT capital in the production and the improvement of capital efficiency (increase of *a*) and capital dematerialization (decrease of *b*) assumed after the energetic crises.

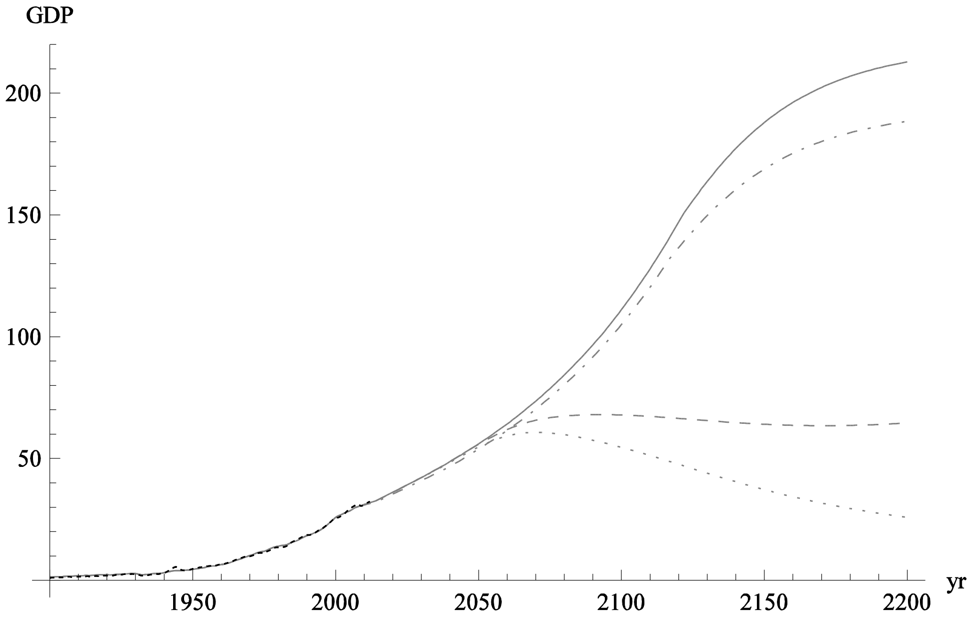


**Fig. 7. GDP evolution of the US economy (relative to 1900) predicted for the scenarios P (dotted line), M (dashed line), O when the capital fixed in information and communication technologies is assumed to tend to 25% (33%) of total capital stock (dot-dashed and continuous line, respectively). The historical GDP until year 2012 is also displayed as a black dotted line.**

Regarding scenario O, with an electrified economy and a fossil fuel economy working together, it could be more appropriate to use a PF such as (2) for the former and another PF with the same form and different set of parameters *a,b,c* for the latter. However, the lack of historical experience on an electrified economy makes difficult to estimate its appropriate parameter values. In this scenario, by the end of the massive installation of all types of renewables, the economy would interrupt its exponential growth and would start a slow growth, controlled by the rising conversion efficiency, to a steady state, which cannot be altered except by new improvements in conversion efficiency. The final production level is approximately seven times that of the present one. The ultimate cause of this high steady state is due, as in the previous scenarios, to the high conversion efficiency to useful work that can be obtained, plausibly, in an electrified economy, in cooperation with a massive use of information technologies (up to 1/3 of the total fixed capital) and technological improvements that enhance capital efficiency (through increasing *a*) and reduce energy demand (through decrease of *b*).

The growth of GDP from 2000 to 2012, taken from www.indexmundi.com, has been added to the dataset used by [30] and the resulting curve is included in Fig. 7. As can be observed, the GDP evolution between 2000 and 2007 is adequately predicted by all the models, even though the PF was calibrated with data from 1900 to 2000. To simulate the evolution during the present economic crisis, between 2007 and 2012, the capital formation to GDP rate (ρ) was assumed to decrease 15%, compared to its value at 2006, during the whole period. No specific effort has been made to fit this very special period since our goal was to project the long-term GDP evolution, but the projection agrees well with the observed GDP when this simple approach is used.

The use of the PL scenario for population does not change the qualitative behaviour of these curves, suggesting that labor has a smaller influence than exergy and capital in the GDP evolution of contemporary economies.This is confirmed by the FPs obtained by the model and displayed in Fig. 8 for scenario O.

As can be observed, the PF (2) does not allow for a growth in the GDP if the exergy is stationary. Ayres [38] comes to a similar conclusion by using PF (1), since in three of his simulations a decline of the US GDP is predicted between 2009 and 2038.

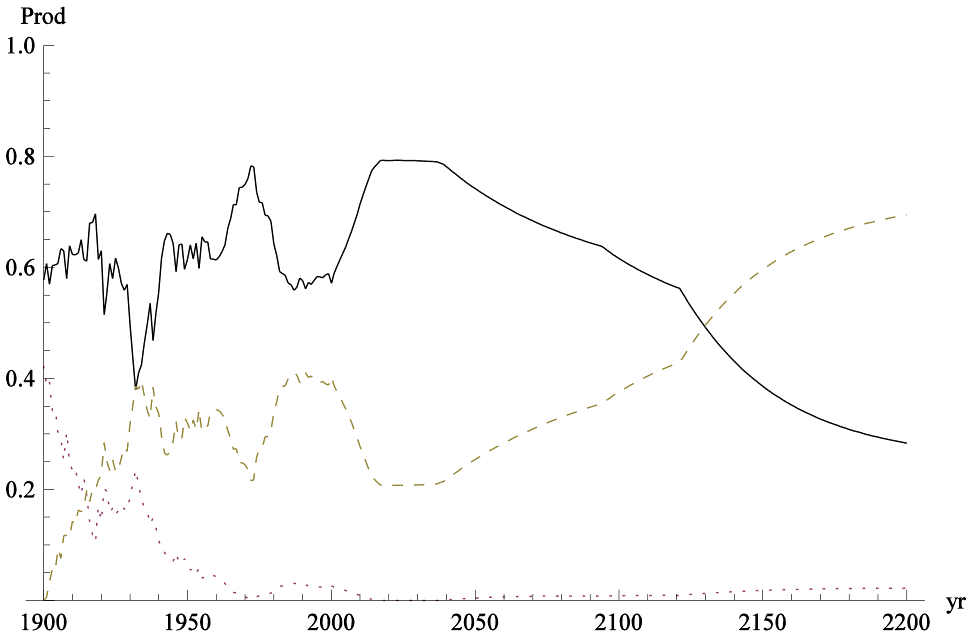

**Fig. 8. Factors productivities for capital (continuous line), useful energy (dashed line) and labor (dotted line) in Scenario O.**

## 4. Discussion

As discussed by [41], there are good reasons to think that peak oil is close. The recently observed inelasticity of oil production to price [42] supports this opinion. Other authors believe that peak oil will only take place on a very late date or never. However, these latter opinions have been accused to be either biased by commercial interests, unsubstantiated belief in market and technical solutions, or narrow paradigmatic focus, which makes them to use unreliable reserve data and unrealistic assumptions about utilization of unconventional sources [41].

For instance, some technological optimists such as Rogner [43], and Adelman and Lynch [44], neglected the evidences of the imminence of peak oil with the argument that reserves will further increase driven by growing knowledge. These expectations have been criticized by authors such as Hook et al. [45], Campbell [46], Laherrère [47], and Ivanhoe and Leckie [48], who consider creditable only the extraction technologies that may be envisaged from the present.

Regarding unconventional oil and gas, another technological optimist [49] believes that new discoveries and new extraction methods, of conventional and unconventional oils will generate new production capacity, and that it will be able to add more than 4.1 Gb/d each year until 2030. However, as emphasizes Euan Mearns [50] the development of new wells of unconventional oil in Canada and US has been exponential since 2003 but, despite the immense scale of investment required in these new fields, global oil production remains glued to its 82 Mbpd plateau since 2005, proving that the growth of unconventional oil supply is not compensating the decline rate of the conventional fields. It has been so in spite of the large increase in the oil price during these years, which increased from about 30 $2010 per barrel in 2001 to 80 $2010 per barrel at 2010 and 87$ at 2013. This rise of price has stimulated large deployment of new extraction technologies also in conventional reservoirs that were un-commercial one decade ago, such as the giant Claire Field off the west coast of Scotland, and the Haradh segment of S Ghawar and the Khurais field, both in Saudi Arabia. The conclusion of Mearns is that without this steady stream of new developments, the oil industry will fail to maintain production at current levels and production will enter the decline phase.

Recently, a lot of expectative has been put in new sources of non-conventional oil. However, attenuation of the peak oil decline does require more than 10% of sustained growth of nonconventional oil production over at least the next two decades [51] and such sustained growth rates have not been seen for any of the global energy systems in history, and is not expected by either of the dominating forecasting agencies, as IEA, EIA or the BGR Institute [45].

In our opinion, although the arguments of the early peak advocates are convincing, the main goal of this paper is to assess what should be the response of the present developed economies (represented by the US economy) if they were to be subjected to the pressure of a prochain energy shortage, rather than trying solve the discussion about the occurrence and timing of peak oil.

The numerical simulations reported here illustrate the strong dependence that growth has on useful work. Apparently, the only way to grant an indefinite growth is to grant an indefinite growth of exergy production. The question is thus, is there any limit to the amount of exergy production? A plausible limit could be the peak of fossil fuel if no policy is taken to stimulate the in-time deployment of alternative sources. Scenarios P and M illustrate this possible situation.

There are a few renewable energy technologies that have been already proven, that do not rely on scarce materials, and that have a good social perception such as wind, hydroelectricity and thermo-solar stations. These technologies are the best positioned to be developed after the peak of fossil fuels. Photo-voltaic distributed domestic generation will probably accompany the deployment of these stations, even though its global deployment will be possible only if they rely on common materials such as Pyrite, amorphous silicon without the use of silver, and zinc phosphide ($Zn_3P_2$) [16,52].

Substitution of renewable power for the declining fossil fuels and the subsequent electrification of the economy could be socially acceptable and economically viable. The current *Desertec* project [53] could be the seed of it. However, the growth of renewable power cannot be expected to be indefinite because it is limited by the availability of some minerals, especially copper [16]. Scenario O illustrates this possible situation.

The incorporation of the fusion energy to the electric grid is expected in some date close to the end of this century [54,55], however a fusion-based energetic system has the same dependence than renewables have on copper-based devices (for instance, electric generators as well as electric engines need 1 ton of copper per megawatt transformed [16]), and thus the electrified economy that it makes possible is as copper-consuming as the one based on renewables.

Thus, in the case of an energy production mix based on renewables and fusion, the only way to grant the further continuation of the customary GDP exponential growth, would be to try a major substitution of copper by aluminum (which is abundant), graphene, and high temperature superconductors (HTS) in electric generators, engines and wires. Methane hydrates layers are thin and disperse, which makes most of the resource not exploitable. Boswell [56] estimates the resource potentially exploitable to be about 100 Tcfg (trillion cubic feet of gas), or $2.8 \times 10^{12}$ $m^3$, i.e. about 1% of the present gas URR, despite the fact that the total resources are orders of magnitude higher. However, it cannot be rejected the possibility of some environmentally safe extraction of methane hydrates in the future. These possibilities are represented by a fourth scenario (I, for “Ideal”). In this I scenario, installation of new power is assumed to be indefinite at the same rate than at the end of scenario O (363 EJ/yr of additional global power every 50 years).

Such an ideal scenario would generate a persistent exponential growth if constant returns to scale are assumed to hold indefinitely (upper curve of Fig. 9). However, in order to indefinitely sustain GDP growth requires avoiding, in some way, the pollution and wastes produced, since they could lead to decreasing returns to scale in the economic output [23].

This is quite a challenge, since the peak of fossil fuels will probably start a new era of expensive fossil fuels, increase the use of the more polluting unconventional fuels, increase the pressure on freshwater, reduce the net energy produced by fuels, and lead to an increase of externalities [57]. Given the strong dependence that the present economic system has on oil, Heinberg [58] believes that these externalities, with a lower capital investment, could trigger the end of growth. Even more, Barnosky *et al*. [59] alert that 43% of the global ecosystems are now seriously perturbed due to increasing GDP and population. They estimate that a perturbation larger than 50% will probably be a tipping point for a critical shift in the biosphere, with biological ‘surprises’ at global and local scales. On the other hand, the pressure of a rising population will add economic and social threats to the decades following 2030, due to critical loss of arable land, high costs of fertilizer and agricultural fuel, and degradation of freshwater [60]. Finally, the peak of phosphorus production, that has been estimated to occur at 2040 [61] or 2040-2050 [62] will also put additional pressure on crop productivity and farm outputs. All together make plausible that the period between 2025 and 2050 might be considered the start of a "period of consequences" with regard to the natural capital degradation and its effects.

To account for these environmental and resource constraints, Kümmel ([23]; [29]) proposed to introduce a dependency of ε in the elasticity equations (Eqs. 3 to 5) on entropy production and critical recycling frequencies. Here, we take a simple approach based on the findings of Bradshaw et al. [63] who concluded that national income per person was the most important correlate of environmental impact and that population size accounted for the remaining variation in absolute environmental impact. Given that a (Kaya-type) expression for environmental impact is:

$$I = p\left[\frac{y}{p}\right]\left[\frac{I}{y}\right]$$

where *I* is impact and *p* is population, andgiven that the ratio impact by GDP, *I/y*, does not seem to decrease with GDP, contrarily to the Kuznet theory [64], it seems more accurate to suppose that *I* is proportional to *GDP*. In consequence, we explore the possible consequences of a future decreasing return to scale by assuming that ε=1 in equations (2) until 2045, and that after that date:

$$\varepsilon(t) = \left[\frac{y(2045)}{y(t-1)}\right]^{\delta},$$

Where y(t) is the GDP predicted by eq. (2) at year t, y(2045) is the GDP predicted for 2045 and $\delta \leq 1$. The cases $\delta$=1, 1/2, 1/4, 1/8, 1/16, 1/32 and 0 (i.e. $\varepsilon$=1) have been used to study a faster or slower decrease of the factor productivities, associated with increases of the GDP (Fig. 9). Barnosky et al. [59] considers 2045 as a probable date for their projected environmental tipping point. When the exponent δ is low ($0 < \delta < 1/32$), the effect of y(t) on ε(t) is small (ε decreases 2% or less for a doubling of the GDP relative to 2045) and the GDP may continue its exponential growth. If the influence of y(t) on ε(t) is stronger than this, the result is a long term steady state of the GDP.

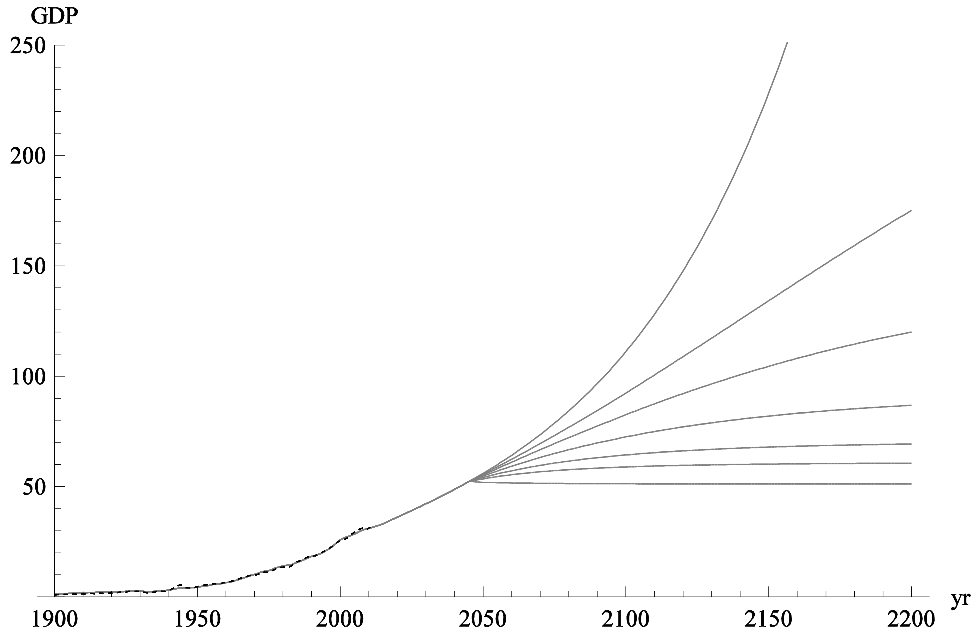


**Fig. 9. GDP evolution simulated for Scenario I (continuous lines) with several models of decresing returns to scale (see text). Bottom to top continuous lines correspond to δ=1, ½, ¼, 1/8, 1/16, 1/32 and 0 (ε=1) cases. Historical GDP in the US economy (dotted line) is also included.**

Thus, if degradation of natural capital cannot be significantly limited, then a steady state economy would be the only long-term sustainable scenario even in scenarios with energy abundance.

From the discussion above, policymakers should be advised that it should be expected that growth will come to an end in the next 100 years due to the combination of: (i) peak oil and the difficulty of substituting an oil-based industry and transport; (ii) peak of fossil fuels and difficulty of a large-scale electrification of the economy; (iii) difficulty of a marketable and environmentally safe exploitation of methane hydrates; (iv) uncertain possibility to replace copper in a future electrified economy by aluminum, grapheme and HTS; (v) probable decreasing returns to scale between 2025 and 2050 due to erosive effects of GDP and population growth on natural capital.

These external factors will happen together with a set of internal factors exposed by [36] and [28] and that, they alone, may produce the end of growth [36]. According to these authors, although specialization of labor was a very important driver of growth, it probably peaked during the climax of Taylorism; Benefits of scale from international trade have also peaked; monetization of services made by women and farmers is now largely complete in the urbanized countries; borrowing from the future to increase consumption in the present cannot feed a lasting and sustainable growth; finally, technological efficiency to convert raw materials and fuels into useful work increased enormously in the first part of the 20th century, but the rate of increase of this conversion efficiency has slowed down significantly since 1970 and is constrained in the long term by thermodynamic limits.

Thus, given the difficulty to conceive the idea of an indefinite exponential growth with no environmental impact and starting from our present economy and technology, the steady-state economy is a sound concept that should be planned from the present in order to avoid unmanageable ecological and economic surprises. As noted by [65], most classic economists agreed upon the possible existence of a steady-state economy, and some of them regarded it to be desirable. The first to mention it was Adam Smith in 1776 [66], but as a state equivalent to social poverty. For Malthus [67] it was the inability of the human society to attain a stationary state that condemned it to misery. John Stuart Mill [68] had a very optimistic vision of the stationary state and he was convinced that humans would be content with being stationary long before necessity compelled them to it. However, the enormous technological innovation of the industrial revolution, fuelled by coal and oil, changed economists' visions of the stationary state, because growth started to appear to be unlimited [65]. Only a few economists with a wider perspective were exceptions to this tendency during the 20th Century: Keynes [69], Schumpeter [70], Georgescu-Roegen [71], Boulding [18], Meadows and Meadows [72] and, more recently, Daly [73], Martinez-Alier [74], Ayres [36] and many new economists related to the Ecological Economics School. This school and related research programs today contribute important new concepts that may possibly be the base of a future economic paradigm.

## Annex A. Logistic function

Logistic functions are a family of functions used to describe certain kinds of growth. These functions have an initial phase of exponential increase, followed by a phase at which the growth becomes slower, until a moment at which the variable levels off, reaching a definite asymptotic value.

The simplest form of logistic functions is

$$f(t) = \frac{1}{1-e^{-t}},$$

which is solution of the following differential equation

$$\frac{df}{dt} = f(1-f),$$

subject to the initial condition $f(0) = 1/2$. A more general form of the logistic function is obtained from the solution of the following differential equation:

$$\frac{df}{dt} = \kappa\, f\left(1-\frac{f}{f_\infty}\right), \quad f(0) = f_o$$

whose solution is:

$$f(t) = \frac{f_o\, f_\infty\, e^{\kappa t}}{f_\infty + f_o\left(e^{\kappa t}-1\right)}.$$

The parameter $\kappa$ determines the rate of growth and $f_\infty$ corresponds to the asymptotic saturation value. The logistic functions being used in this work also include a third parameter, $\tau$, that serves to translate the logistic function along the abscissa axis:

$$f(t) = \frac{f_o\, f_\infty\, e^{\kappa(t-\tau)}}{f_\infty + f_o\left(e^{\kappa(t-\tau)}-1\right)}. \quad \text{(A.1)}$$

So, now $f(\tau) = f_o$.

## Conflict of Interest

The authors declare no conflict of interest.


## Acknowledgments

We sincerely thank our colleagues for many useful comments, particularly Antonio Turiel, Jordi Solé and Emili García Ladona and the two reviewers whose comments greatly contributed to the improvement of the final manuscript. This work has been partially supported through the project TIC-MOC (CTM2011-28867) of the R+D Spanish research program.


## References


1. L.A. White, Energy and the evolution of culture. American Anthropologist 45 (1943) 335 356.

2. V. Smil, World history and energy, in: Encyclopedia of Energy, Vol. 6, Amsterdam, Elsevier, 2004, p. 549-561.

3. E. Cook, The flow of energy in industrial society, Scientific American, **224**(3) (1971) 134 148.

4. IEA 2010a, Key World Energy Statistics 2010. International Energy Agency ed., France.

5. IEA, 2010b: World Energy Outlook 2010. International Energy Agency ed., France.

6. J. Laherrère, Update on Coal. The Oil Drum. http://www.theoildrum.com/node/9583

7. R. Heinberg, D. Fridley, The end of cheap coal. Nature 468 (2010) 367 369.

8. R.W. Bentley, Global oil and gas depletion: an overview. Energy Policy 30 (2002) 189 205.

9. L.M. Leggett, D.A. Ball, The implication for climate change and peak fossil fuel of the continuation of the current trend in wind and solar energy production. Energy Policy (2012). Doi:10.1016/j.enpol.2011.11.022

10. D. Fleming, The Lean Guide to Nuclear Energy: A Life-Cycle in Trouble. The Lean Economy Connection Publications, London, 2007.

11. Energy Watch Group, Uranium Resources and Nuclear Energy. EWG-Series No 1/2006, 2006.

12. R. Heinberg, The Party's Over: Oil, War, and the Fate of Industrial Society, 2005, New Society Publishers, Gabriola Island, Canada.

13. W. E. Bijker, T. P. Hughes and T. Pinch (eds.), The Social Construction of Technological Systems, The MIT Press, Cambridge, MA, 1989. See specially the contributions of Callon, Law and Hughes .

14. H. Odum, H. Environment, Power and Society, New York, Wiley-Interscience, 1971.

15. N. Adams, Energía y Estructura, Fondo de Cultura Económica, Mexico, 1983.

16. A. García-Olivares, J. Ballabrera, E. García-Ladona, A. Turiel, 2012, A global renewable mix with proven technologies and common materials, Energy Policy 41 (2012) 561 574.

17. R. U. Ayres, L. W. Ayres and I. Rade (2002), The Life Cycle of Copper, its Co-Products and By-Products, International Institute for Environment and Development (IIED). http://pubs.iied.org/pdfs/G00740.pdf

18. K.E. Boulding, The Economics of the Coming Spaceship Earth, in H. Jarret et al, eds., Environmental quality in a growing economy, John Hopkins Press, Baltimore, 1966.

19. G. Tintner, E. Deutsch, R. Rieder, A Production Function for Austria Emphasizing Energy, in: F.L. Altman, O. Kyn, H.J. Wagener (Eds.), On the Measurement of Factor Productivities, Vandenhoek & Ruprecht, Göttingen, 1974.

20. E.A. Hudson D.W. Jorgenson, US energy policy and economic growth, 1975-2000. Bell J. Econ. Manage. Sci. 5 (1974) 461 514.

21. R. Kümmel, 1982. The impact of energy on industrial growth. Energy 7 (2), 189 203.

22. R. Kümmel, Strassl, W., Gossner, A., & Eichhorn, W. Technical progress and energy dependent production functions. Journal of Economics, 1985, 45(3), 285 311

23. R. Kümmel, Energy as a factor of production and entropy as a pollution indicator in macroeconomic modelling, Ecological Economics 1 (1989) 161 180.

24. B. Warr, R. Ayres, REXS: A forecasting model for assessing the impact of natural resource consumption and technological change on economic growth, Structural Change and Economic Dynamics 17 (2006) 329 378.

25. A. Atkeson, P. Kehoe, Models of Energy Use: Putty-Putty versus Putty-Clay, American Economic Review 89 (4) (1999).

26. R. U. Ayres, B. Warr, 2009. *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*, Cheltenham, UK & Northampton, Massachusetts: Edward Elgar Publishing, ISBN 978-1-84844-182-8,

27. R.U. Ayres, L.W. Ayres, B. Warr, Useful work and Information as Drivers of Growth. INSEAD Working Papers (2002) 2002/121/EPS/CMER. www.insead.edu/facultyresearch/research/doc.cfm?did=1211

28. B. Warr, R. Ayres, Useful work and information as drivers of economic growth. Ecological Economics 73 (2012) 93 102.

29. R. Kümmel, J. Henn and D. Lindenberger (2002) Capital, labor, energy and creativity: modeling innovation diffusion. Structural Change and Economic Dynamics 13, 415 433

30. Warr, B., Ayres, R., Eisenmenger, N., Krausmann, F. and Schandl, H., Energy use and economic development: A comparative analysis of useful work supply in Austria, Japan, the United Kingdom and the US during 100 years of economic growth, Ecological Economics 69 (2010) 1904 1917.

31. UN Depatment of Social Affairs, World Population to 2300, ST/ESA/SER.A/236, United Nations, New York, 2004.

32. M. King Hubbert, Nuclear Energy and the Fossil Fuels. Drilling and Production Practice, *American Petroleum Institute & Shell Development Co. Publication No. 95, 1956, See pp 9-11, 21-22*.

33. Laherrère, Fossil fuels: what future?, Workshop “Global Dialogue on Energy Security”, The Dialogue International Policy Institute, China Institute of International Studies, 2007. http://hubbertpeak.com/laherrere/Beijing20061009.pdf .

34. D. García, A new World Model Including Energy and Climate Change Data, First International Workshop "Mission Earth-Modeling and Simulation for a Sustainable Future", AGSME, Zurich, Switzerland, January 2009. http://europe.theoildrum.com/node/5145

35. Ch. Hall, R. Powers, W. Schoenberg, Peak Oil, EROEI, Investments and the Economy in an Uncertain Future, in: D. Pimentel (Ed.), Biofuels, Solar and Wind as Renewable Energy Systems, Springer, Berlin, 2008, p. 109-132.

36. R. U. Ayres, Turning Point: The end of exponential growth? Technol. Forecast. Soc. Change 73 (2006) 1188 1203.

37. R.U. Ayres, L.W. Ayres, B. Warr, Exergy, power and work in the US economy, 1900-1998. Energy 28 (2003) 219 273.

38. T. Fleiter, W. Eichhammer, J. Schleich, Energy efficiency in electric motor systems: Technical potentials and policy approaches for developing countries, United Nations Industrial Development Organization, Vienna, 2011.

39. M.A. Rosen, C.A. Bulucea, Using Exergy to Understand and Improve the Efficiency of Electrical Power Technologies. Entropy 11 (2009) 820 835. Doi: 10.3390/e11040820.

40. M.Z. Jacobson, M.A. Delucchi, Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials, *Energy Policy* 39(3) (2011) 1154 1169.

41. I. Chapman, The end of Peak Oil? Why this topic is still relevant despite recent denials. Energy Policy (2013). DOI: 10.1016/j.enpol.2013.05.010

42. J. Murray, D. King, Oil's tipping point has passed, Nature 481 (2012) 433 435.

43. H.H. Rogner. An assessment of world hydrocarbon resources, Annual Review of Energy and the Environment, 22 (1997) 217 262

44. M.A. Adelman , M.C. Lynch, Fixed view of resource limits creates undue pessimism, Oil and Gas Journal, 95(14) (1997) 56 60.

45. M. Höök, A. Sivertsson, K. Aleklett Validity of the fossil fuel production outlooks in the IPCC Emission Scenarios. Natural Resources Research 19(2) (2010) 63 81. doi:10.1007/s11053-010-9113-1

46. C.J. Campbell, Oil Crisis. Multi-science Publishing Co, Brentwood, 2005.

47. J. Laherrère, 1994. Published figures and political reserves, World Oil, January 1994, p. 33.

48. L.F. Ivanhoe, G.G. Leckie, Global oil, gas fields, sizes tallied, analyzed, Oil and Gas Journal, 91(7) (1993) 87 91

49. D. Yergin, There Will Be Oil, The Wall Street Journal, Europe Edition, Saturday, September 17 (2011) http://online.wsj.com/article/SB10001424053111904060604576572552998674340.html

50. E. Mearns, Peak Oil- Now or Later? A Response to Daniel Yergin, The Oil Drum, 2011. http://www.theoildrum.com/node/8391

51. C. De Castro, L.J. Miguel, M. Mediavilla, The role of non conventional oil in the attenuation of peak oil, Energy Policy, 37(5) (2009) 1825 1833

52. C. Wadia, A.P. Alivisatos, D.M. Kammen, Materials availability expands the opportunity for large-scale photovoltaics deployment. Environmental Science and Technology 43 (2009) 2072 2077

53. G. Knies, Global energy and climate security through solar power from deserts, Trans-Mediterranean Renewable Energy Cooperation (TREC) in co-operation with The Club of Rome, 2006.

54. K. Tokimatsu, J. Fujino, S. Konishi, Y. Ogawa, K. Yamaji, Role of Nuclear Fusion in Future Energy Systems and the Environment under Future Uncertainties, Energy Policy 31 (2003) 775 797.

55. C. Llewellyn, D. Ward, Fusion. Energy Policy, 36 (2008) 4331 4334.

56. R. Boswell, Is gas hydrate energy within reach? Science 325 (2009) 957 958.

57. A. García-Olivares, A. Turiel, The Second Half of the Fossil Fuel Age: Environmental Externalities, Net Energy and Energy Security Concerns , In Kumar (Ed.): Fossil Fuels: Sources, Environmental Concerns and Waste Management Practices, Nova Publishing, NY, USA, 2013.

58. R. Heinberg, The End of Growth. New Society Publishers. Vancouver, 2011.

59. A.D. Barnosky, E.A. Hadly, J. Bascompte, E.L. Berlow, J.H. Brown, M. Fortelius, W.M. Getz, J. Harte, A. Hastings, P.A. Marquet, N.D. Martinez, A. Mooers, P. Roopnarine, G. Vermeij, J.W. Williams, R. Gillespie, J. Kitzes, C. Marshall, N. Matzke1, D.P. Mindell, E. Revilla, A.B. Smith, Approaching a state shift in Earth's Biosphere. Nature 485 (2012) 52 58. doi:10.1038/nature11018.

60. J. Grantham, Welcome to Dystopia! Entering a long-term and politically dangerous food crisis. GMO Quarterly Letter, July 2012. http://www.commodityintelligence.com/images/2012/aug/8th/J-grantham-letter.pdf

61. I. Steen, Phosphorus availability in the 21st Century: Management of a non-renewable resource. Phosphorus and Potassium 217 (1998) 25 31.

62. D. Cordell, J.-O. Drangert, J.-O., T.S.S. Neset, The story of phosphorus: global food security and food for thought, Global Environmental Change 19 (2) (2009) 292 305.

63. C.J.A. Bradshaw, X. Giam, N.S. Sodhi, Evaluating the Relative Environmental Impact of Countries. PLoS ONE 5(5) (2010) e10440. doi:10.1371/journal.pone.0010440. www.plosone.org

64. D.P. Knight, Economic growth, Population growth, and Climate Change, Winchester Action on Climate Change and Foundation for the economics of Sustainability and Feasta, 2013. http://www.feasta.org/2013/08/26/economic-growth-population-growth-and-climate-change/

65. C. Kerschner, Economic De-growth vs. The Steady State Economy: complements or contradiction. Proceedings of the First International Conference on Economic De-growth for Ecological Sustainability and Social Equity (2008) 125 130. Paris, April 18-19 2008.

66. A. Smith, An Inquiry into the Nature and Causes of the Wealth of Nations, Oxford Clerendon Press, 1776.

67. T.R. Malthus, An Essay on the Principle of Population, Oxford/New York, Oxford University Press, 1993 [1798].

68. J.S. Mill, Principle of Political Economy with some of their applications to Social Philosophy, London, Longsmans, green & Co, 1888.

69. J.M. Keynes, The General Theory of Employment, Interest and Money, Cambridge MS, Macmillan Cambridge University Press, for Royal Economic Society, 1936.

70. J.A. Schumpeter, Capitalism, Socialism and Democracy, Taylor and Francis, 2003 [1942].

71. N. Georgescu-Roegen, The Economics of Production, The American Economic Review, Papers and Proceedings of the Eight-second Annual Meeting of the American Economic Association 60 (2) (1970) 1 9.

72. D.H. Meadows, J. Randers, D.L. Meadows, W.W. Behrens, The limits to growth: a report for the Club of Rome's project on the predicament of mankind, New York, Universe Books, 1972.

73. H.E. Daly, Steady-State Economics: Concepts, Questions, Policies, Ecological economics, GAIA I (6) (1992) 333 338.

74. J. Martinez-Alier, Socially sustainable economic degrowth, Development and Change 40 (6) (2009) 1099 1119.

**Antonio García-Olivares** has a Ph.D. in Physics and finished Bachelor in Politics and Sociology. He is a staff scientist of the Spanish Council of Scientific Research (CSIC), in the Institute of Marine Sciences, Barcelona. He has worked as researcher in the Energy, Technology and Environment Research Center in Madrid, in the Combustion Technologies Research Center (Zaragoza), and in the Marine Sciences Institute. Main specialization in mathematical simulation, which he has applied in areas as: plasma physics, fusion reactors, radio-ecology, contaminant dispersion, climate change, physical oceanography, energy security, complex systems and social change dynamics.

**Joaquim Ballabrera Poy** is Ph.D. in Physics and Staff Scientist of the Spanish Council for Scientific Research, Institute of Marine Sciences, at Barcelona, Spain.
Research lines: data assimilation (Kalman Filter, adjoint variational and nudging), numerical simulation of the ocean general circulation, oceanography from space, coupled models, statistical models, data analysis and energy security.