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The Peak of Energy and Minerals and the Economic Future

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Abstract: The coming peak of fossil fuels may cause shortages in the energy supply and major disturbances on the global economy. The forecasts for the future of our way of life are very divergent depending on the prediction used for the future human access to energy. Steady-state or collapse seems to be the two plausible scenarios for society after the fossil fuel peak and exhaustion of mineral resources that the new energetic mix will require. The LINEX production function, which is dependent on energy input is used to model the gross domestic product (GDP) of a western economy in several different energetic scenarios after the fossil fuel peak. A future steady-state economy with zero population growth appears as the best possible 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 energy the energy available to be used), Leslie White's Law of cultural evolution (White, 1943) states that, other things 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 has always led to improvements in the overall quality of life of societies, because it usually translates to increases in food harvests, individual possessions, educational standards, and personal mobility. The power provided by the main energy resources has rose approximately 15 million times in the last 10,000 years, with more than 99% of the rise taking place in the 20th century (Smil, 2004). In the last 50 years we have consumed 80% of the total oil ever consumed by humanity (see Fig. 5 below), so it can be said that we belong to the most fortunate generation that have 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*" (Cook, 1971). 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%). Combined, geothermal, solar, and wind provided 0.7% of the global energy demand (IEA 2010a).

However, in his 2010 report, the International Energy Agency (IEA, 2010b) did announce that crude production was in a plateau since 2006, and that it will hardly increase much more. The heat energy production from coal is expected to peak before 2030 (Mohr and Evans, 2010), while new forecasts suggest that coal reserves will run out faster than many believe (Heinberg and Fridley, 2010). The global peak in conventional gas may happen in the third decade of the 21st century (Bentley, 2002), and the peak of all the fossil fuels power is expected around 2028, with a standard deviation of 8.5 yr (Leggett and Ball, 2012). Nuclear energy prospects are dim after the Fukushima disaster and the announcement by Germany and Japan of their denuclearization and because uranium is a finite mineral, whose production is expected to peak between 2015 and 2035 at the current rate of usage (Fleming, 2007; Energy Watch Group 2006).

Due to the dependency of modern industrial societies on high energy consumption rates (Cook, 1971), the thesis of Japanese economist Osamu Shimomura (1911-1989) that societies must not seek economic growth when the conditions for growth are not in place, should be reconsidered again (Shimomura originally referred to the 1973 energy crisis in Japan). However, the range of mid and long term economic growth is divergent, depending on the expectation of the future access to energy. In such a context, the two extremes are: (i) resources will always be adequate (Grossling, 1970), and (ii) the resource-depletion is unavoidable (Wright, 1971) and it will lead the industrial society to its end (Duncan 1989).

Technological systems are very energy-dependent. However, the Actor-Network theory (Latour 2005; Law and Hassard 1999), a framework highlighting the relationships between technological advances and the surrounding infrastructure (material and conceptual), has shown that, on the contrary that masses, institutions have no inertia. Thus, in order to maintain themselves along time, institutions (in the broad sense) need a network of material, energy and information exchanges (Callon 1989; Law 1989; Latour 2005). All what is given for granted in societies sustain upon that network. On the other hand, human ecology and ecologic economy have shown that, inside that network, the energy exchanges generate constraints on social practices and life standards (Odum, 1971; Adams, 1983). Most of the current technologic systems are very dependent on the use of abundant and cheap oil, and many of these constraints cannot be overcome by using non energetic resources.

Is there any primary energy mix available that could be an alternative to the decline of the fossil fuels after 2030? In a recent article, we showed that this solution exists in principle (García-Olivares et al. 2012), based on a global renewable mix that would employ materials relatively abundant.

However, when focusing on the current material production rates, it has been shown that a renewable generation mix, scaled to respond to the global energy demand, would use 60-69% of the current copper reserves. Moreover, the use of platinum, lithium, nickel and (in a minor proportion) zinc for transportation would be also a substantial part of the reserves. Consequently, continuation of energetic exponential growth would be impeded by the exhaustion of these limiting minerals. Therefore, in line with the point of view already stated by Boulding (1966), a steady-state economy would be the best feasible scenario after the implementation of an energetic solution alternative to the fossil fuels.

However, there are no plausible alternative primary energy sources available in the short and medium term other than the currently proven renewable ones. And waiting until the decline of the fossil fuel production (about 2028) could be the most disruptive event for the capitalist dynamics, as it will be discussed below. Therefore, only a steady state economy based on renewable sources remains as the best predictable alternative for the decades between 2030 to the end of the century.

This manuscript focuses on the evolution of the GDP according to an energy-dependent production functions 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.

In Section 2 we explore quantitatively some important feedbacks between energetic and economic variables by means of a simple model for the future global GDP and apply this model to three scenarios of energy supply evolution in the secular scale: (i) no-substitution of the primary energy based in fossil fuels and renewable generation at the same level than today, (ii) deploy of new renewable sources at the same growth slope than in the last ten years, (iii) ten-years increase in the slope of deployment of renewables to get the slope necessary to generate in another 40 years 11.5 TW. In the final section we discuss the results obtained and some of the implications that these scenarios could have on the future economy and society.

2. A model for the DGP growth as a function of net energy

Production Functions (PFs) are intended to capture the relationship between the output (at a level of a firm, industry, or an entire economy) and the various inputs. During years, the only primary production factors were Capital and Labor. The formulation of the 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 70s, economists do formulate energy (exergy) -dependent PFs (Tintner et al., 1974; Hudson and Jorgenson, 1974). In these models, Capital (*K*) and Labor (*L*) make Energy (*E*) available but, in turn, are “nourished” by it. Kümmel (1982) introduced the linear exponential (LINEX) PF:

$$Y = U\, exp\, \{ \; a \, [2 - (L+U) /K] + a\, b\, (L - U) /U \; \} \qquad (1)$$

where *Y* is the simulated GDP, U is useful energy (or “exergetic services”) used by the economy, *L* is labour force and *K* is capital. There is a limited replaceability of capital for labour and energy implicitly included in this expression.

In its simplest version, “*a*” and “*b*” in (1) are constants that can be adjusted from historical data of GNP, capital stocks, labour and energy consumption. This PF has been used to fit the evolution of the US economy since 1900 with good accuracy (Warr and Ayres 2006).

It is possible to use this PF to explore the consequences of different energetic scenarios on the future GDP of a developed country. With this purpose, the primary exergy *U* is calculated as the product of the Raw Primary Energy *E* and the conversion efficiency *f*, which is dependent on the technological efficiency of the given economy: $U = f\,E$. Warr and Ayres (2006) have studied the historical evolution of these variables in the US economy, which are shown in Fig. 1 (raw energy) and Fig. 2 (conversion efficiency).

Figure 1. 20th Century raw primary energy used by the US economy, normalized to the 1900 value

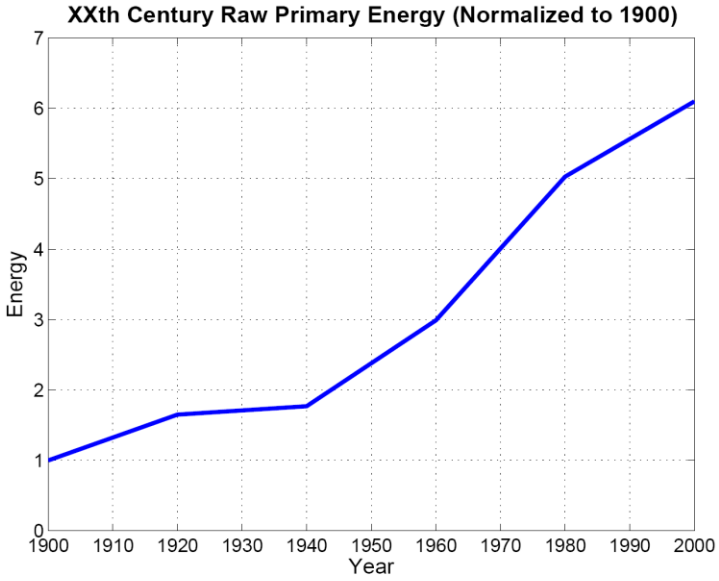
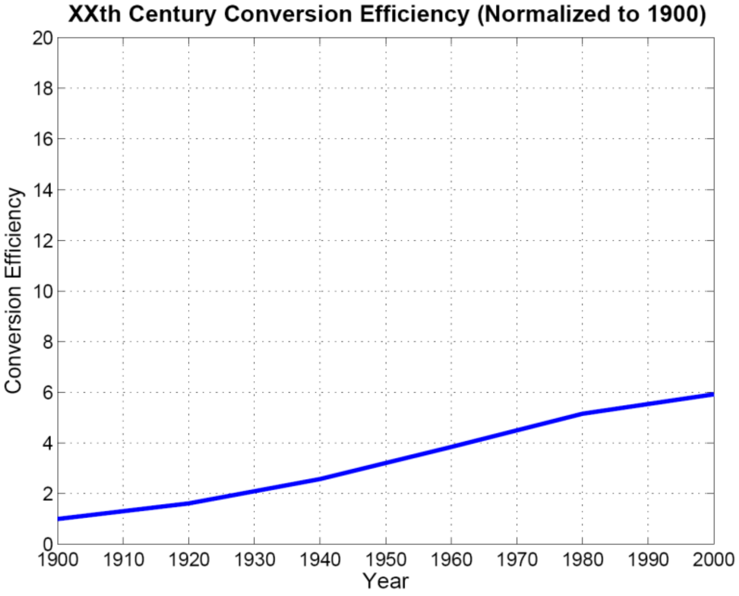
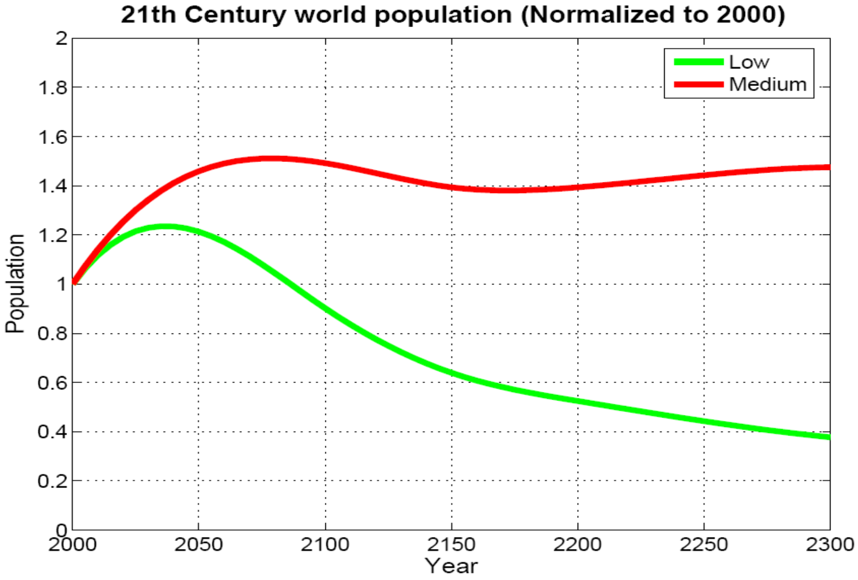


Figure 2. 20th Century conversion efficiency in the US economy, normalized to the 1900 value



The future evolution of an economy is investigated here using the parameters already set for the US economy, i.e. a=0.12 and b=3.78 and the statistical data of *L*, *K* and *U* in US compiled for Warr and Ayres (2006) for years 1900 to 2000. After year 2000, the labour force is assumed to be proportional to the curve of the world population evolution, as it has been predicted by the United Nations in its "medium" scenario (upper line of Fig. 3).

Figure 3. World population evolution, as it has been predicted by the United Nations in its "low" (green line) and "medium" (red line) scenarios.



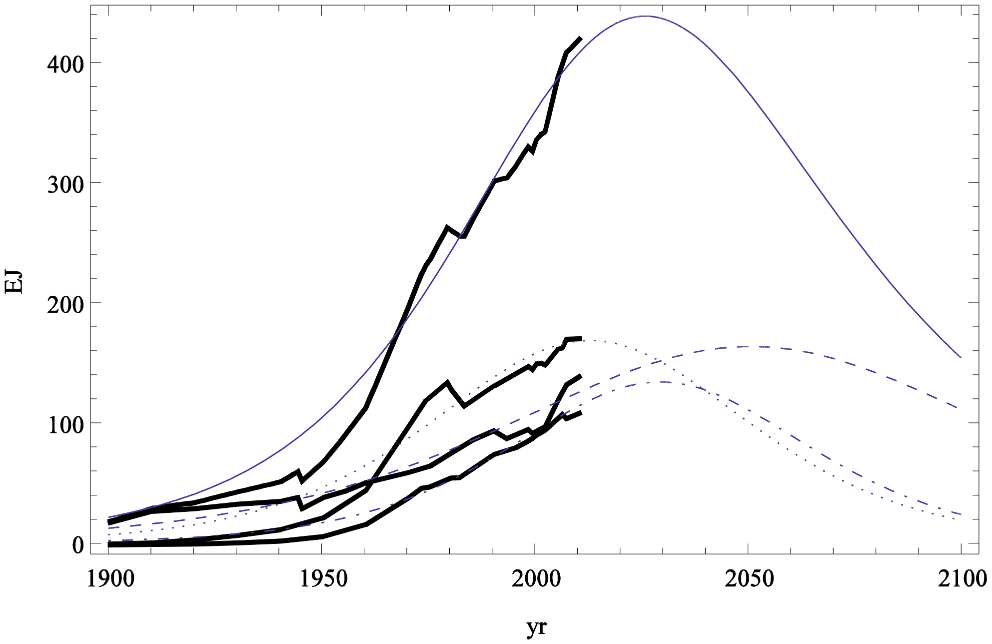
The amount of exergetic services consumed by the US energy comes from Warr and Ayres (2006) and the amount of energy consumed in the world is derived from the historical datasets of fossil fuel consumption collected from http://www.tsp-data-portal.org. For the future world consumption, every fossil fuel dataset has been adjusted to a Hubbert function with the following form:

$$P = \frac{ube^{-b(t-tp)}}{(1+e^{-b(t-tp)})^2} \qquad (2)$$

In equation (2), P is the annual production of a given fuel, u is its ultimately recoverable resource, b is the growth rate parameter and tp the year of the peak production. A key parameter in (2) is the ultimate recoverable resource. The following values have been reported by Laherrere (2007) in a detailed study country to country: 400 Gtoe (16748 EJ) for oil (conventional and non-conventional); 300 Gtoe (12561 EJ) for gas; and 600 Gtoe (25122 EJ) for coal.

Figure 4 shows the historical data and the corresponding fitted models for every fuel. The curve with the total fossil fuels consumption and the curve addition of all the separate fits are also displayed. As it can be observed, the predicted peaks take place at 2013 (oil), 2029 (gas) and 2051 (coal). The aggregated power produced by all the fossil fuels is expected to peak between 2026 and 2027. This prediction is in agreement with the study of Legget and Ball (2012) that analyzed 54 different published estimations and concluded that the expected year of the peak is 2028 with a standard deviation of 8.5 years.

Figure 4. Historical data of fossil fuels production and corresponding fitted models for every fuel: oil (dotted line), coal (dashed line) and gas (dot-dashed line). The curve with the total fossil fuels consumption (upper thick line) and the curve addition of all the separate fits (thin continuous line) are also displayed.



To obtain the total global consumption, 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/). As a first model, we assume that the consumption of the two first sources remains invariable after 2010.

The remaining fraction of a given fuel may be calculated from the area of the Hubbert curve already used in relation to the total area (equal to u). It is assumed that the EROEI of a given fuel decrease according to the following expression taken from García (2009):

$$EROEI\ (t) = c\ 100\ f_r(t)^2, \qquad (3)$$

where $f_r(t)$ is the fraction of fuel remaining and c is a constant to be adjusted to reproduce the reported value of the EROEI in the year 2000. The EROEI of the whole society at year *t* can be calculated as the following expression:

$$EROEIs(t) = \sum_i g_i(t) EROEI_i(t) \qquad (4)$$

Where $g_i(t)$ is the fraction of the i-th fuel in the mix at year *t*, and can be calculated from: $g_i\ (t) = P_i\ (t)\ /P_t(t)$, where P_i (t) is the production of fuel-i and $P_t(t)$ is the total power production, at time t. Both functions have been described above.

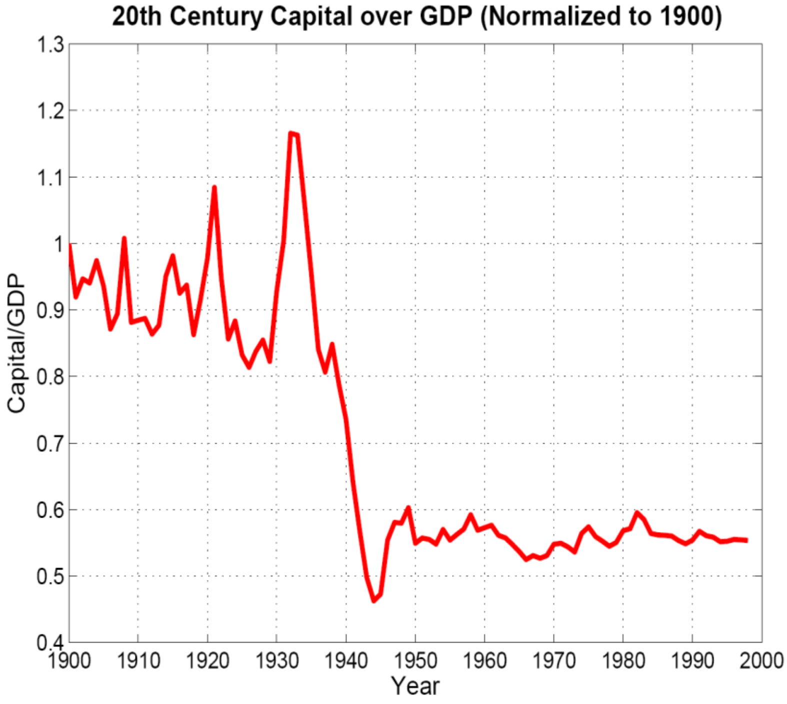
The ratio between the US primary production of useful energy ("exergetic services" in the Ayres denomination) and the global production of energy can now be obtained. The result shows that while such ratio has a tendency to decrease, between 1980 and 2000, it has remained approximately constant and equal to 0.39. As a first approach, it is assumed that this value will continue to decrease, exponentially, in the next two decades to a value of 0.33 to match the growth of emergent economies.

The capital *K* invested one year is assumed to be a fraction α of the GDP of the previous year. Warr and Ayres (2006) have obtained historical series of capital K and GDP observed in the US since 1900. The ratio α = K/GDP is displayed in Fig. 5 and it suggests that, after second world war, this ratio has decreased to 0.56 times the 1900 value. It is reasonable to assume that this ratio is not constant but depending on the capital available after discounting the capital invested in energy. We will assume that the fraction of capital invested in the energy sector (x) with respect to the GDP is the same fraction that the energy invested in energy production with respect to the whole energy consumed: x=1/EROEIs. And that the ratio $\alpha(t)$ is proportional to the fraction of GDP not used in energy production:

$$\alpha(t) = \alpha_0 \frac{1-x(t)}{1-x_0} \qquad (5)$$

Where $\alpha_o = \alpha(t=2000)$.

Figure 5. Evolution of the ratio Capital / GDP in the US economy during the past century



We assume that $K(t) = \alpha(t-1)\,Y(t-1)$, where t is the year, α is the statistical value if t<2001 and the value calculated with (5) if $t \geq 2001$.

Three evolution scenarios are investigated here. A first scenario, in which the energetic mix is to be composed of fossil fuels and a constant production of hydroelectricity, nuclear and renewable at the same level that in 2010 (scenario P or “Pesimistic”). The two additional scenarios assume a different growth for the relative weight of renewable sources. The second one (called hereafter M, or “Medium”) assumes that the useful energy in the US economy will be the one derived from the expected evolution of the fossil fuels (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 than in the last 10 years (about 0.48 EJ/yr globally). The last scenario (hereafter O, for “Optimistic”) assumes that the renewable sources worldwide will increase its growth slope in ten years to get the slope necessary to generate in 40 years 11.5 TW. This figure was considered enough to supply the global demand of energy in 2030 by Jacobson and Delucchi (2011). Such a power would add to the one provided by the fossil fuels that, even in decline from 2030, will not fall abruptly, but in a gradual way following the slope of the Hubbert’s curve. In every scenario we assume that the demand of energy in the US will be proportional to the growth of the global energetic demand.

To account for the higher efficiency expected in the conversion of a completely electric exergy to useful work, we estimated what could be the conversion efficiency of the current US economy if the primary energy were electricity alone. To this end, we 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 efficiencies of these 5 targets have been calculated from (Ayres et al. 2003, Supplementary material) and are given in Table 1. We have assumed five final destinations for energy: 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. The current losses of primary energy in the electricity production (currently 83% in the US) would not exist in an economy based on renewables, since the primary energy would come from origin in electric form.

Electricity has not a great advantage for high temperature heating, since a heat pump has almost the same efficiency than a resistance to produce high temperature heat. The efficiency of 0.31 reported by Ayres et al. (2003) for high-temperature heating is used here. Low-temperature heating and cooling by heat pumps is more efficient than using fossil fuels. However, the rate of installation of new heat pumps is slow and, to be conservative, it has been assumed that they would have the same efficiency than that observed in the present economy. The efficiency of chemical transformation with electricity was assumed to be similar to that made with oil in the present economy (0.5). However, mechanic drive production in industry is very variable and depends on the use of motion. Pumping uses, which shares 25% of industrial electric motion, have efficiencies between 31% and 72% (Fleiter et al. 2011), while traction with electric engines have efficiencies of 80-87% (Rosen and Bulucea 2009). We have assumed an average efficiency of 60% for all the industrial uses of motion.

Table 1. Weights and efficiencies in the energy transformation to useful energy of 5 economic sectors of the US economy.

Target Economic Sector	**Weight**	**Conversion Efficiency**
High Temperature	0.07	0.31
Low Temperature	0.27	0.03
Mechanic drive	0.38	0.6
Chemical Transformations	0.07	0.5
Animal Work Uses	0.21	0.04
Total	1	0.30

The difference with the current efficiencies, based on fossil fuels, is assumed to be the mechanic drive (calculated to be 0.12) and the existence of a conversion from fossil fuels to electricity, with an efficiency of 0.17 (Ayres et al. 2003). The current society efficiency is about 0.14 according to these assumptions and, as can be seen in Table 1, the current efficiency of an electrified society would be 0.3. However, this efficiency will be assumed to grow until 0.4 in the next two centuries, to take into account the plausible increase of electric technology efficiency. The future evolution of the social efficiency is assumed to be a weighted average of these two values, with weights given by the relative contribution of renewable and fossil fuel to the mix.

Fig. 6 shows the evolution of the efficiency of the electric technology conversion to useful work obtained by the model for Scenario O.

Figure 6. Evolution of the efficiency of the electric technology conversion to useful work obtained by the model for Scenario O.

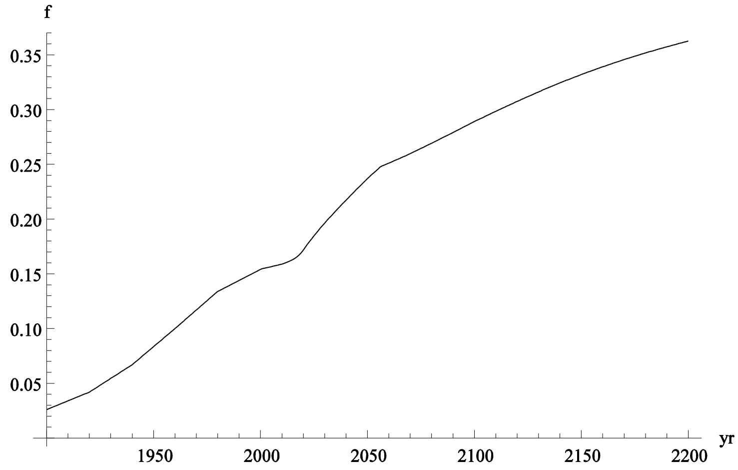
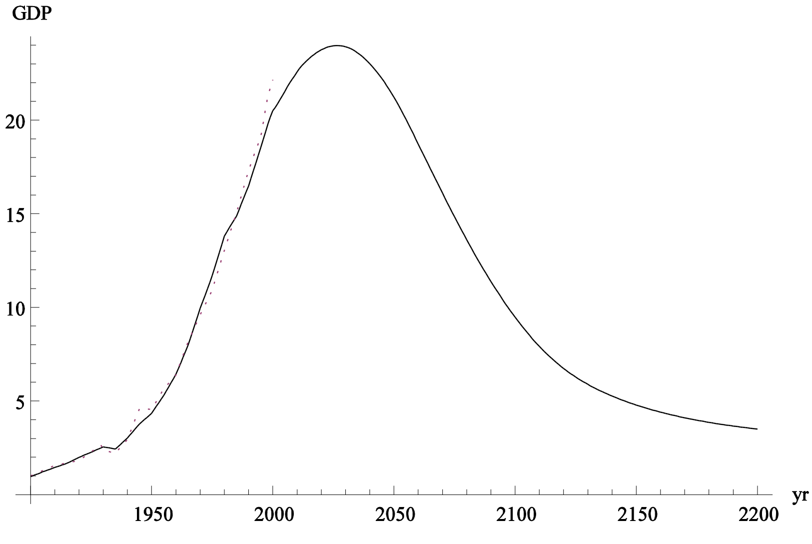


Fig. 7 shows the GDP evolution predicted for the P scenario. It portrays a production maximum about 2030 followed by a decline to an asymptotic steady state which derives from the constant power source assumed from nuclear and renewable origin. This curve is highly correlated with the evolution of U.

Figure 7. GDP evolution of the US economy (relative to 1900) predicted for the P scenario. The hystorical GDP until year 2000 is also displayed as a dotted line.



Regarding scenario M, Fig. 8 shows the evolution of the EROEI of the different fossil fuels and the social EROEI as a function of time. As it can be observed, the effective social EROEI falls to a minimum value of about 10 by 2100 and then going up to a steady value of 20 in the long term due to the dominance of the renewable sources in the mix.

Figure 8. 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).

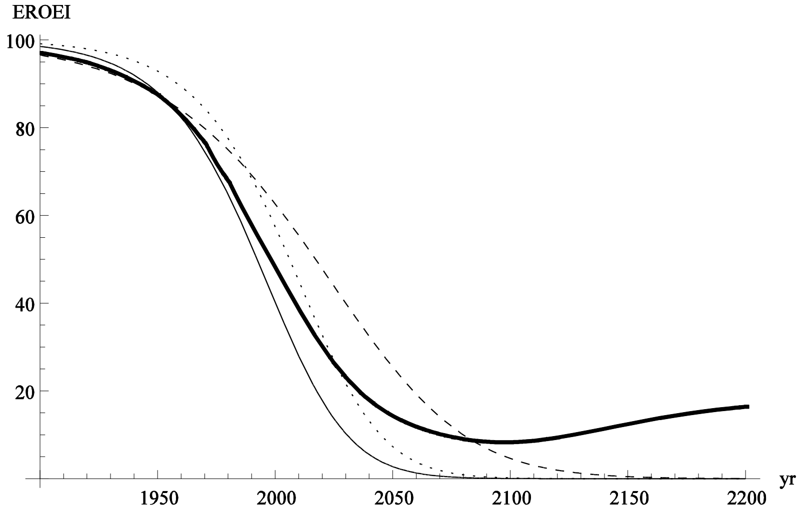


Fig. 9 shows the GDP evolution predicted for the M scenario. A maximum can be observed at 2030 followed by a decline to levels below the current ones and followed by a long term recover of the GDP. The cause of this rise is the improvement of the conversion efficiency to useful work in parallel to the rise of the renewable contribution to the mix.

Figure 9. GDP obtained by the model for Scenario M (continuous line) and historical GDP in the US economy (dotted line).

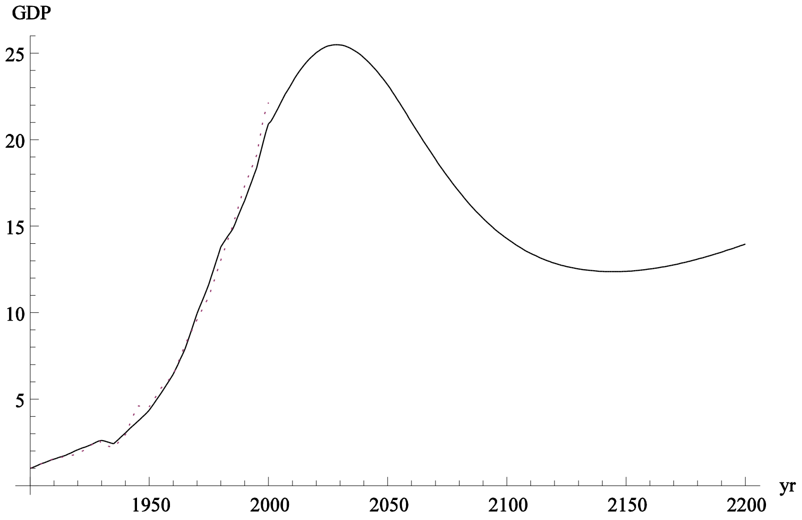


Fig. 10 shows the GDP simulated in the scenario O (massive installation of renewables in 40 years). A maximum can be observed by the end of the massive installation of all the renewables, and then a slow decrease (due to the decline of fossil fuels) to a steady state, which cannot be altered except by new improvements of the conversion efficiency. The final production level is approximately double than the present one. The ultimate cause of this high steady state is, as before, the high conversion efficiency to useful work that can be obtained, plausibly, in an electrified economy.
This curve is highly correlated with the evolution of the useful energy, which is shown in Fig. 11. Units are normalized to the useful energy consumed in the US at year 1900.

Figure 10. GDP obtained by the model for Scenario O (continuous line) and historical GDP in the US economy (dotted line).

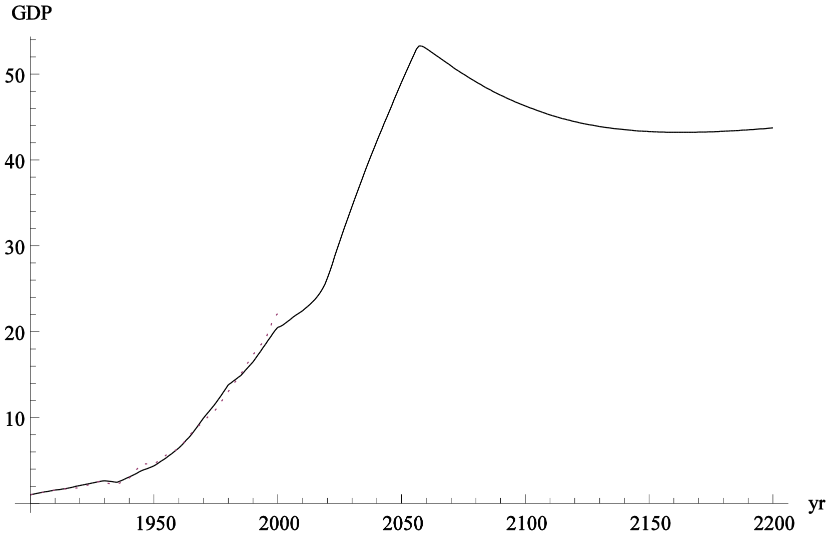
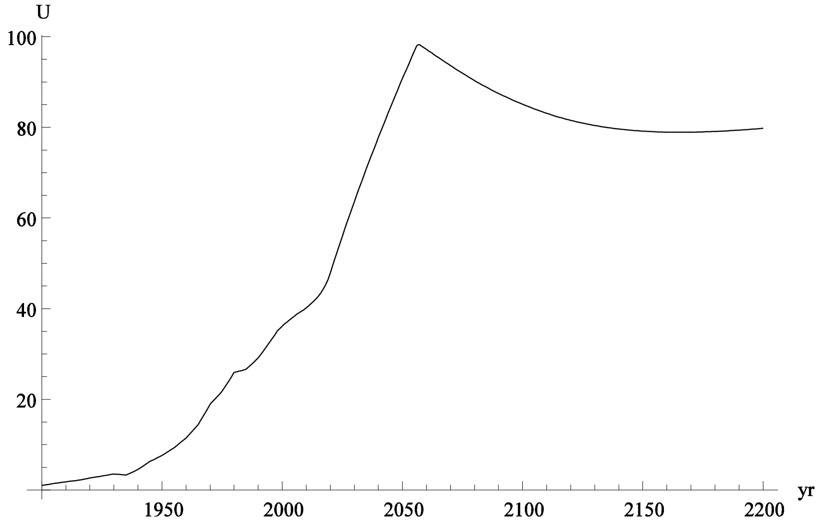


Figure 11. Evolution of the useful energy in Scenario O.



The Ayres model does not allow growing GDP with stationary exergy, and a steady state GDP is expected according to this model even in the most optimistic scenario (O). The use of the PL scenario for population does not change the qualitative behaviour of these curves, suggesting that labour has a smaller influence than exergy and capital in the GDP evolution of contemporary economies.

Marginal productivity of capital, work and energy can be obtained from the output elasticities of the PF:

$$p_k = \frac{\partial lnY}{\partial lnk} = a\left(\frac{l+u}{k}\right), \qquad p_l = \frac{\partial lnY}{\partial lnl} = a\left[b\left(\frac{l}{u}\right) - \left(\frac{l}{k}\right)\right], \qquad p_u = \frac{\partial lnY}{\partial lnu} = 1 - p_k - p_l$$

In scenario O these productivities take values that remain approximately constant since 1990: 40%, 1% and 59% for capital, labour and exergy, respectively. Historical substitution of capital for labour and increasing automation of industry have led to a marginal productivity of labour that is much smaller than the other two.

3. Discussion

The social consequences of scenario P, i.e. lack of further development of renewable energy sources, could be very hard because it would provoke a systematic decrease of the “energy intensity” of most of the economic sectors and de-growth of GDP. Up to now, no experience exists on an industrial economy with low (and always decreasing) inputs of energy, and it is not even known if it is viable. It is plausible that, in the conditions of Scenario P, the economy would become more rural and less industrialized.

What should we do? In the words of Winston Churchill, “Sometimes we have to do what is required.” We should start as quick as possible the transition to an economy of steady-state, in the line of the O scenario, because it is the best long-term scenario that we can reasonably wait for.

How to do that? Paraphrasing Kant we could also say: “Let us dare to think” (and not only repeating wishes). Bartlett (1996) suggests, first of all, getting serious about renewable energy. As a start, we ought to have a big increase in the funding for research in the development and dispersion of renewable energy. In a previous article (García-Olivares et al., 2012), we have shown that a renewable solution with proven technology which uses only common materials is, in principle, possible. However, if this solution has to be implemented in 40 years, this would imply a war economy, since most of the steel industry would have to be addressed to manufacture windmills and concentrating solar stations. Limitations to the supply of important minerals needed in batteries (Lithium and Nickel) and fuel cells (platinum) could demand a reduction of the current vehicles fleet of about 50%. Therefore, more emphasis should be done in the future in the public transport systems.

The future electrified society would be completely dependent on the safe and stable operation of the high voltage direct current (HVDC) transmission lines between subtropical sunny areas and high-latitude windy areas and the consumption areas. These transmission lines, which would have a typical length of 3000 km, would tend to press the states to integrate each other in energetically autonomous confederations. In the case of Europe, the natural confederation would be between the European Communities, Island and Norway and the Mahgreb states. The current *Desertec* project (Knies 2006) could be the germen of this integration.

Second, we have to educate people to acknowledge that growth of population and growth of rates of consumption of resources cannot be sustained. The implementation of the solution proposed by García-Olivares et al. (2012) does require the use 60% of the current resources of copper. Other minerals needed for an electric transport system would limit also additional future exponential growth of industrial consumption. Thus, if some solution exists, it requires necessarily a steady production and consumption, and sustainability means, in this context, a steady-state economy.

An exponential growth of population is not compatible with a steady state economy and, also, it undermines human value. Bartlett (2000) discusses this point by citing an interview of Bill Moyers to Isaac Asimov: “What happens to the idea of the dignity of the human species if this population growth continues at its present rate?” Isaac Asimov: “It will be completely destroyed. I like to use what I call my bathroom metaphor. If two people live in an apartment, and there are two bathrooms, then they both have freedom of the bathroom. You can go to the bathroom anytime you want, stay as long as you want, for whatever you need. And everyone believes in freedom of the bathroom. It should be right there in the constitution. But if you have twenty people in the apartment and two bathrooms, then no matter how much every person believes in freedom of the bathroom, there’s no such thing. You have to set up times for each person, you have to bang on the door, ‘Aren't you through yet?’ and so on.” And Asimov continues with a profound observation: “In the same way, democracy cannot survive overpopulation; Human dignity cannot survive (overpopulation); Convenience and decency cannot survive (overpopulation); As you put more and more people into the world, the value of life not only declines, it disappears. It doesn’t matter if someone dies, the more people there are, the less one individual matters.”

Time is crucial in our current energetic situation given that although a war economy could be possibly able to implement a global renewable solution, it would take 40 years starting now. However, to postpone the implementation of this global solution could take us to a scenario with increasingly high energy prices and inflation which is not the most appropriate to implement a global industrial mobilization.

Initiatives to save and promote an increase of efficiency would be of great help to facilitate the transition to a steady economy. Given that the only sustainable economy in the long term is a steady-state economy, it should be planned from now to avoid unmanageable ecological and economic surprises. As noticed by Kerschner (2008), the most classical economists agreed upon the possible existence of a steady state and many of them regarded it as desirable. The first to mention the concept was Adam Smith in 1776 (Smith 1776) but as a state equivalent to social poverty. For Malthus (1993 [1798]) was the inability of the human society to get a stationary state that condemned it to misery. John Stuart Mill (Mill 1888) had a very optimistic vision of the stationary state and he was convinced that humans would be content to be stationary long before necessity compelled them to it. However, the enormous technological innovation during the industrial revolution, fuelled by coal and oil, changed the economist’s vision of the stationary state, because growth started to appear as unlimited (Kerschner 2008). Only a few economists with a wider perspective were exceptions to this tendency during the 20th Century: Keynes (1936), Schumpeter (1993 [1942]), Georgescu-Roegen (1970), Boulding (1966), Meadows and Meadows (1972) and, more recently, Daly (1992), Martinez-Alier (2009) and many new economists related to the Ecological Economics school. This school and related research programs are contributing with important concepts that could be the base of the future economic paradigm.

Similarly to physical systems before a synergetic change, during a social crisiss many ideological and political patterns compete to become ordering patterns of the future society. In these situations, several future scenarios are possible and “the interaction between actors and relative power are as much decisive or more than the structural inertia or technological determinism” (FAST, 1986). For these reasons, in crisis moments, freedom, awareness, will and intelligence act as “precipitant factors” and “triggers” in the terminology of historians as Elliott, Stone and Mousnier, and become crucial to the final result. And, as emphasized by M. Harris (1977): “when a society has already chosen a concrete ecological and technological strategy … is possible that during a long time nothing can be done against the consequences of a little intelligent choice”.

Conflict of Interest

The authors declare no conflict of interest.

References

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

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

3. Cook, E., 1971: The flow of energy in industrial society, *Scientific American*, **224**(3): 134-48.

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. Mohr, S. H. and Evans, G. M. 2009. Forecasting coal production until 2100. Fuel 88, 2059-2067.

7. Heinberg, R., and D. Fridley, 2010: The end of cheap coal. Nature, 468, 367-369.

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

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

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

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

12. Grossling B.F., 1970. Future mineral supply. Econ. Geol., 65: 348-354.

13. Wright J.B., 1971. Affluence and future mineral supplies. Econ. Geol., 66: 676-679.

14. Duncan, R. C. (1989). Evolution, technology and the natural environment. Proceedings of the ASEE Conference, Binghamton, New York.

15. Latour, B. 2005, Reassembling the social: An introduction to actor-network-theory, Oxford University Press, USA

16. Law, J., Hassard, J. 1999, Actor Network Theory and After, edited by: Blackwell Publishing

17. Callon, Society in the Making: The Study of Technology as a Tool for Sociological Analysis, in W. E. Bijker, T. P. Hughes and T. Pinch (eds.), The Social Construction of Technological Systems, The MIT Press 1989, p. 84-103.

18. Law 1989, Technology and Heterogeneous Engineering: The Case of Portuguese Expansion, in Bijker, W. E. Hughes, T. P. and Pinch, T. (eds.), The Social Construction of the Technological Systems, MIT Press, Cambridge, MA, p. 111-134.

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

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

21. García-Olivares, A., Ballabrera, J., García-Ladona, E. and Turiel, A. 2012. A global renewable mix with proven technologies and common materials. Energy Policy *41, February 2012, p. 561-574.*

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

23. Tintner, G., Deutsch, E. and Rieder, R. (1974) “A Production Function for Austria Emphasizing Energy” in Altman, FL, Kyn, O and Wagener, HJ (eds) On the Measurement of Factor Productivities, Vandenhoek & Ruprecht, Göttingen, pp. 151-164.
24. Hudson E.A. and Jorgenson, D. W. 1974. US energy policy and economic growth, 1975-2000. Bell J. Econ. Manage. Sci. 5: 461-514.

25. Kümmel, R. 1989, Energy as a factor of production and entropy as a pollution indicator in macroeconomic modelling, Ecological Economics 1, p. 161-180.

26. Warr, B. and Ayres, R. 2006, REXS: A forecasting model for assessing the impact of natural resource consumption and technological change on economic growth, Structural Change and Economic Dynamics 17, p. 329-378.
27. Laherrere 2007, Fossil fuels: what future? Workshop “Global Dialogue on Energy Security”, The Dialogue International Policy Institute, China Institute of International Studies. http://hubbertpeak.com/laherrere/Beijing20061009.pdf (06/06/2011).
28. http://www.tsp-data-portal.org

29. García, D. (2009). 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

30. Jacobson, M. Z. and Delucchi, M. A., 2011. 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), 1154-1169.

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

32. Fleiter, T., Eichhammer, W. and Schleich, J. 2011. Energy efficiency in electric motor systems: Technical potentials and policy approaches for developing countries. United Nations Industrial Development Organization, Vienna.
33. Rosen, M. A. and Bulucea, C. A. (2009). Using Exergy to Understand and Improve the Efficiency of Electrical Power Technologies. Entropy 11, p. 820-835. Doi: 10.3390/e11040820.

34. Bartlett, A. A. (1996). The New Flat Earth Society, The Physics Teacher 34, No. 6 , pp. 342-343.

35. Knies, G., 2006. Global energy and climate security through solar power from deserts. Trans-Mediterranean Renewable Energy Cooperation (TREC) in co-operation with The Club of Rome. Report available at: /gerhard.knies@trec-eumena.orgS.

36. Bartlett, A. A. (2000). Democracy Can Not Survive Overpopulation. Population and Environment 22 (No. 1), p. 63-71.

37. Kerschner, C. (2008). 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, p. 125-130. Paris, April 18-19 2008.

38. Smith, A. (1776). An Inquiry into the Nature and Causes of the Wealth of Nations. Oxford Clerendon Press.
39. Malthus, T. R. (1993 [1798]). An Essay on the Principle of Population. Oxford/New York, Oxford University Press.
40. Mill, J. S. 1888. Principle of Political Economy with some of their applications to Social Philosophy. London, Longsmans, green & Co.

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

42. Schumpeter, J. A. (2003 [1942]). Capitalism, Socialism and Democracy, Taylor and Francis.

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

44. Meadows, D. H., Meadows, D. I. Et al. (1972). The limits to growth: a report for the Club of Rome’s project on the predicament of mankind. New York, Universe Books.

45. Daly, H. E. 1992. Steady-State Economics: Concepts, Questions, Policies. Ecological economics, GAIA I, Nº 6, p. 333-338.

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

47. FAST 1986. “Europa, 1995: Nuevas Tecnologías y Cambio Social” (“Informe FAST”). Comisión de las Comunidades Europeas. Ed. Fundesco.

48. Harris, M., 1977. Cannibals and Kings: The Origins of Cultures, Fontana. ISBN 0006356036.