9th International Conference of the European Society for Ecological Economics, Istanbul, June 14-17, 2011

Analysis of the energetic transition: the electric car

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In this paper, the first step of the energetic transition to a non-carbon society is studied. A global energy-economy model built with system dynamics has been used for this purpose. The model uses variables and data from depletion forecasts (oil, coal-gas), world economic growth and energy demands. Under different scenarios, the results contribute to the choice of those energy policies that are suitable and physically possible. The results show that peak oil is going to be the first and most relevant restriction. Electric vehicles lead to interesting oil savings; however, if peak oil is to be avoided, the savings obtained with electric vehicles or biofuels are far from being a global solution, and, based on current battery technology, lithium is a very important constraint. On the other hand, the production of electric energy seems not to be a relevant problem in the short term compared to the oil decline. If the economic growth moderates and important oil savings are implemented, the transition to 100% renewable electricity does not seem an impossible task.

1. Introduction

Energy is one of the most important technological aspects of our society, and the transition to a non-carbon society is a major source of concern among researchers and activists interested in pursuing a sustainable society. But even in circles not related to sustainability, few doubt that we have an important energy crisis, as much from the point of view of the extraction of resources (peak oil, fossil fuels) as from the sinks (climate change).

Oil is the most studied resource and peak oil is widely recognized, although the dates and rates of decline vary (Campbell, 1998; Hubbert, 1956; Robelius, 2007; I REEL, 2008; Kopelaar, 2005; Skrebowski, 2008; Aleklett, 2008; Hirsch., 2005, ASPO2008, Skrebowski, C. 2010). Other energy resources are much less studied, but some researchers offer forecasts, even in the form of extraction curves similar to Hubbert's oil predictions (EWG 2007, Tao and Li 2007, Patzek and Croft 2010, EWG 2007).

On the other hand, it is also necessary to consider the uses, since all the sources of energy are not directly interchangeable, and some can be substituted, but only after important technological or social changes. In this article, we study two of the basic uses of energy: electricity and liquid fuels. The substitution of oil-based liquid fuels is very problematic, since at present only biofuels can replace them directly. Biofuel yields and EROEI rates have been questioned, although improvements in second generation biofuels are expected (Ballenilla 2007, WBGU 2008, Bowyer 2010, EU2010, Papong 2010, FTF 2011).

Oil-based liquid fuels can be replaced indirectly using electrical vehicles. This substitution has important limitations: the technical capacities of electric cars are smaller, not all transport can be replaced by them, the batteries need rare elements, the substitution increases the demand of electricity, etc. (Offer 2010, AISBL2009, EEA 2009, Hacker 2009, FFT2011). Other alternatives for petroleum substitution are based on the implantation of public transport, human based mobility or railways, all policies that require important social changes, and that we only deal with as a general saving policy.

It is much simpler to replace non-renewable fuels in electrical energy production. Quite acceptable technologies with good EROEI rates and competitive prices exist at present (wind, hydro), and some others have interesting perspectives (thermoelectric, off-shore wind, tidal wave). The problem of the lack of stability of renewable energy makes it difficult to obtain high percentages of these technologies and needs extra infrastructures. Nevertheless, this problem is not dealt with in depth in this study; it will be dealt with in more complex models which we are working on.

The present article studies the substitution of the energy derived from exhaustible fuels by means of a dynamic model. By using this model we can quantify all the aspects of the substitution and detect the weak points of the possible policies.

2. World model.

Several global energy-economy models have been developed over the last decades (IIASA 2004, IIASA 2001, IPCC 2001, WETO 2003), some based on system dynamics (Fiddaman 1997, Castro 2009, Castro 2008 -- developed by the authors). The one used here is a simple system dynamics model that uses data from the depletion forecasts (oil, coal, gas and uranium), the world economic growth, and the energy demands. Under different scenarios, the model tests the policies of substitution and shows whether those that compensate peak oil are physically possible.

The model we have developed is a global model (World estimations) and contemplates the following aspects:

- The economic growth and the demand of Energy (separated into liquid fuels and electricity).
- The depletion of energetic resources (oil, coal, gas and uranium, lithium, copper)
- The "electric car": partial removal of oil consumption by the introduction of battery-based electric vehicles
- Biofuels as oil substitutes.
- The electric energy, with two basic sources: renewable and non renewable.

The basic scheme of the model can be seen in figure 1. The World economic activity (GDP) is a stock of the model that is increased by economic growth. GDP determines the demands of oil and electricity. In the lower part of figure 1 are the stocks of natural resources: oil and non-renewable electricity (subject to physical limits of extraction); and biofuels and renewable electricity (finite but non-exhaustible). The difference between the supply of natural resources and the demand is what we have called shortage. It would be logical to think that this shortage has consequences on the economic activity, so the feedback lines drawn in figure 1 (dashed) should be part of the model. Nevertheless, that feedback has not been included in our model, because there are very few theoretical tools and experimental data from this type of energy-economy interaction. Instead, we present some scenarios and consider that those scenarios where the energy demand is not satisfied with the supply are impossible.

Finally the basic policies of the model are in the ellipses of figure 1: the economic growth, the oil saving, the change to electrical transport (electrical car) and the investment in renewable electricity. In spite of the little existing feedback, this model is a fully system dynamics one, since it uses a holistic approach, characteristic of system dynamics models. Our interest concentrates on offering a panoramic and global view, establishing the relations between all the basic aspects of energy. The model is described in more detail in the following sections.

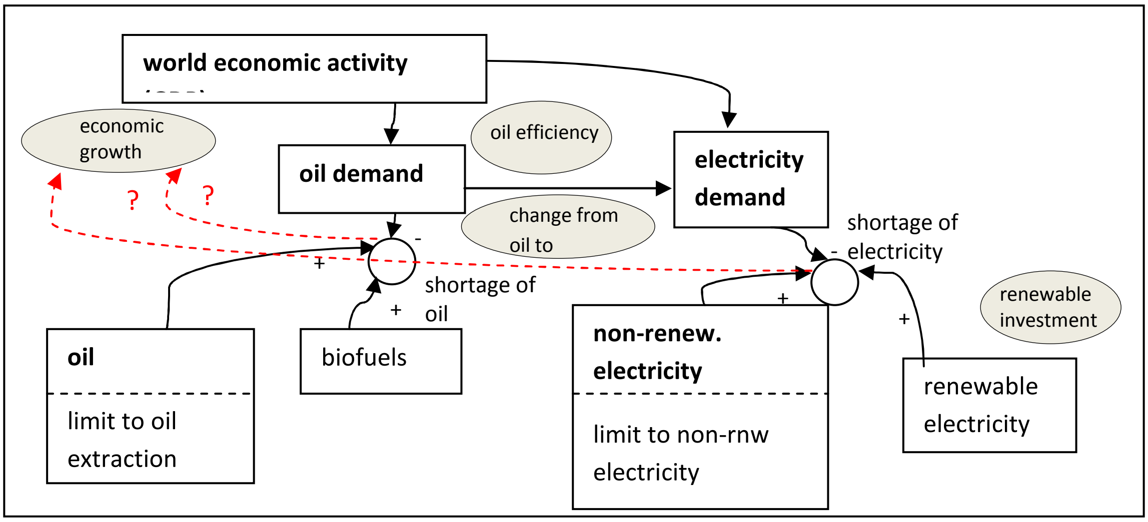

Figure 1: Basic elements of the system dynamics model used.

2.1 The depletion of natural resources.

We model the natural resources decline forecasts based on several experts' estimations, and modify their data (that are normally presented in curves of maximum extraction versus time) so that they are compatible with our dynamic models. For oil, we took the estimations from ASPO (ASPO 2008, which assumes the peak oil of conventional and non conventional oil around 2005-2015). For coal, gas and uranium we used the curves of maximum extraction of EWG 2006, EWG 2007 and ASPO 2008 and, for simplicity, we put them together in a single stock of non renewable resources for electricity. This we can do because it is possible to see that, for these three resources (based on the estimations of EWG 2006, EWG 2007 and ASPO 2008), the maximum ceilings of extraction are 20-30% higher than present consumption, while the total reserves are estimated to be of the size of 100-120 years of extraction at the present rate. This allows us to jointly deal with these three fuels with an acceptable precision (in previous works, the authors have used more detailed models, Castro 2009). The copper and lithium reserves have also been modelled in agreement with Hacker 2009.

2.2 Global economic growth and the demand of energy.

In this model, the demand of oil and electric energy is driven by the economic activity, which is measured with the GDP. It is easy to observe an evident historical correlation between consumption of energy and GDP, which is why we use it in our model as the stock that generates energy demand, assuming that the GDP-oil pattern of past decades holds, unless saving policies are applied.

The historical data of oil and electricity demand versus GDP are plotted in figure 2. The figure shows that the relation electricity-GDP is practically linear, whereas petroleum-GDP presents a clear rupture of tendency in the oil crisis of the 1970s. The graph also shows, if we use the linear pattern of the period 1970-1980 and use it to extrapolate the data of the period 1980-2005 adding a 2% annual oil saving , that the historical data fit the extrapolation quite well, except for a gap of 4Gb of oil that were suddenly removed from the market in 1979. Therefore, a 2% oil saving is not an impossible task, although we must take into account that it is more difficult to save oil today, since, in the 1970s, part of the oil was used for electricity production, which was easy to substitute with other fuels.

In our model, the oil and electricity demand is estimated using these linear tendencies.

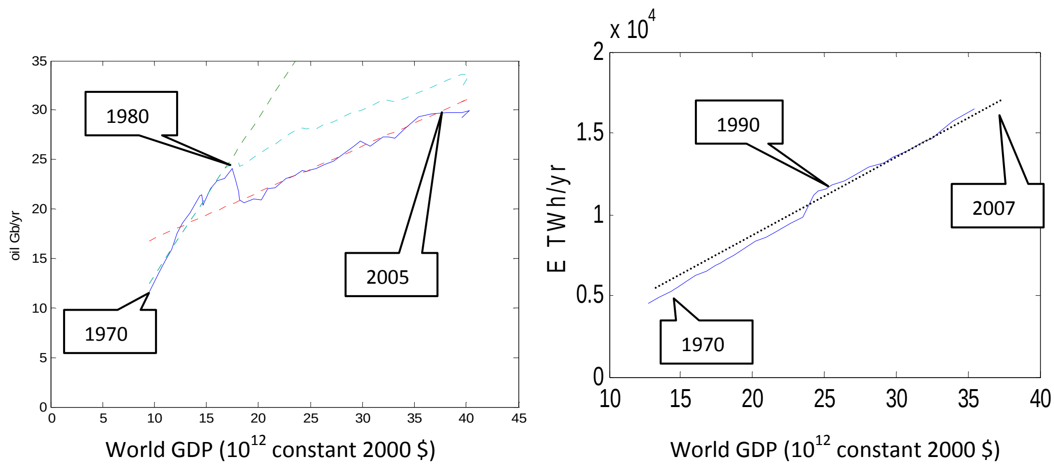

Figure 2: Oil- GDP relation. In the figure on the left, the World oil consumption versus GDP is plotted. The solid line is the historical data; the dashed lines are linear approximations. The blue line represents the observed tendency between 1970-80 extrapolated to the period 1980-2005, adding 2% of annual petroleum savings. In the figure on the right, the electrical consumption versus GDP is shown. It is basically a straight line.

2.3 Oil saving policies: the electrical car

The model contemplates the introduction of the electrical vehicle as a policy introduced in the year 2011. The penetration rate we use is the one that the car manufacturers propose for the UE market according to FTT2011 (extrapolated to the whole world): 10% share of electrical vehicles in 2020-25. More optimistic plans (Hacker 2009) propose 20% of electrical vehicles in 2020 and 90% in 2050.

One of the most important limitations of the electrical vehicle is the energy storage of the batteries, which, according to FFT 2011, makes the overall car-battery system 15 times less powerful in terms of energy storage than conventional cars (using the batteries that would be on the market in next 10 years and including the superior efficiency of the electric motor). This low storage efficiency limits electric vehicle substitution to light vehicles. Freight and public passenger transport consume almost half the oil destined to transport, therefore only half the oil used for transport can be substituted with electric cars, approximately 30% of oil.

Electrical vehicles increase electricity demand, but not very significantly. By comparing the needs of electric vehicles with the equivalent conventional vehicles, we can find the ratio of the oil-to-electricity substitution. In FFT2011, this ratio is set to 300 TWh/Gb (assuming 20 kWh/100 km of consumption). If we translate this ratio to equivalent energy units, it shows that the electrical car requires 5.3 times less energy than the conventional one (probably because of its optimized design). In addition, saving 20% of the oil consumed in the World today with electric cars would only increase electricity generation by 4%. Therefore, the substitution of oil with electric cars is very favourable in terms of energy savings.

The most important limitation of the electric car comes from the elements used to manufacture batteries. All the batteries that show high energy density today are based on rare elements such as lithium and cobalt. Lithium is considered the most immediate restriction to electric cars, and the results of our model validate this. We assume that each electric vehicle needs between 9 and 15 kg of mineral lithium, and lithium reserves are $11 \cdot 10^9$ Kg (according to Hacker 2009 they vary between $6.8 \cdot 10^9$ and $30 \cdot 10^9$ kg of lithium).

2.4 Biofuels

Biofuels are the immediate substitutes of oil-based fuels, but they have important disadvantages. Its EROEI has been widely studied and some researchers argue that it is even less than one for many crops (Ballenilla 2008, Papong 2010); but the most obvious limitation to biofuels is their land requirement (between $3.5 \cdot 10^7$ and $11 \cdot 10^7$ ha/Gb according to FFT2011), and the fact that they need arable and fertile land, not just any earth surface. We take the limits of biofuels compatible to land conservation, as they are considered in WBGU 2008, (50EJ/yr, which is the equivalent to 7.1 Gb/yr of oil). More optimistic studies (FFT 2011) consider a world-wide potential of 270 EJ (49 Gb/yr) which would need, with present yields, two times the present world's arable land for its production. Although second generation biofuels are expected to improve yields, we consider this second estimation far too optimistic, and set the limit at 50 EJ/yr. On the other hand, we do not consider second generation biofuels based on algae and other promising sources, since there is not enough data available to make an estimate.

2.5 Renewable electric energy.

Renewable energy is divided into hydro power, which is assumed to grow moderately and double by 2050 (IEO2010), and the new renewable (wind, solar photovoltaic, thermoelectric, etc) which is assumed to be capable of growth from 2010 on, until it stagnates when the physical limits are reached. The physical limits are based on some unpublished work of Castro et al., who establishes 11 TW as the limit for solar and wind, which is significantly lower than some other limits found in the literature, and is similar to that established recently by Kleydon et al (Miller 2011). We also assume that the land requirement of renewable electricity is $20 \cdot 10^6$ ha/TW (considering the TW of global energy produced per second, not installed capacity).

We estimate an average cost of renewable infrastructure construction $1 \cdot 10^{-4}$ T$/TWh, and multiplied it by two to take into account the necessary adaptations of power grids and other infrastructures. In the Spanish case, for example, the electric grid has suffered a great transformation since 2003, the year when wind energy began to be important, and whose cost is almost 50% of the investment in wind power. We do not know if all this new infrastructure is due to the introduction of renewable energies, but we use this gross approximation of taking $2 \cdot 10^{-4}$ T$/TWh, which is probably too pessimistic, since the technologies will probably improve and costs might get lower.

Our model also considers the EROEI rate, since all these new renewable power facilities require energy for their construction. As we cannot calculate what percentage of this energy is consumed in the form of oil and liquid fuels and which in the form of electrical energy, we take the worse case and assume that all the demanded energy is oil (the most scarce fuel). The EROEI we take is low (10), which is also pessimistic.

The policies of renewable energy introduction that we use are simple. We let renewable energy grow exponentially by a fixed percentage, as it has been doing over recent decades; but, from 2011 on, the growth is lower (15-11%), since it does not seem realistic to maintain 30% growth for long periods.

2.6 The model's policies and scenarios

We shall test three types of scenarios: scenarios with an economic growth similar to that of recent decades, scenarios of moderate growth and scenarios of stagnation-decline. In all of them, we will apply the policies of the electric car and biofuels, renewable electricity and oil saving.

The model will be able to answer such questions as:

- Will biofuels and electric cars be able to compensate for peak oil?

- Is it possible to continue the present path of economic growth despite peak oil?
- Does the electric car need an important increase in electricity generation?
- Are renewable energies impossible on a large scale because of the economic and energetic costs they require?

3. Scenarios and their results.

Scenario E1: continued growth

In this scenario, we continue the economic tendencies of past decades. GDP continues to grow by 3.2% per year, the electrical car reaches the objectives proposed by the manufacturers (10% of light vehicles in 2020 and 75% in 2050), biofuel production grows to 50 EJ/yr (compatible with the conservation of soil) and renewable energy grows by 15% per year, except hydroelectric, which grows by 2%.

Figure 3 shows the result of this scenario in oil production and demand. Before 2010, oil demand has already surpassed supply (in recent years the economic crisis and the stagnation of petroleum production has meant that we no longer follow the tendencies of past decades), and an enormous disparity between supply and demand is observed. This scenario is, therefore, impossible.

The oil saved by the introduction of the electric car (oil_saved_for_E) is important, but it cannot compensate for peak oil. Biofuel savings (oil_save_for_bio) are marginal. The energy cost of the renewable infrastructure can also be seen in figure 3, (cost_renew_in_oil) and is negligible.

Figure 4 shows the requirement of lithium and copper for electric vehicles, and they exceed their physical limits. The known-to-date lithium reserves will run out by 2025 and, by 2045, all the lithium will be in vehicle batteries; which means that, not even with 100% recycling, can that amount of electrical cars be maintained. The copper necessary to construct the vehicles also represents a considerable amount of present production, but it is not impossible. Despite the high material requirements and the fact that this policy is being implemented very fast, the introduction of the electric vehicle has no significant effect on oil demand.

Scenario 1, in conclusion, it is impossible, since electric cars and biofuels alone cannot compensate for the oil decline.

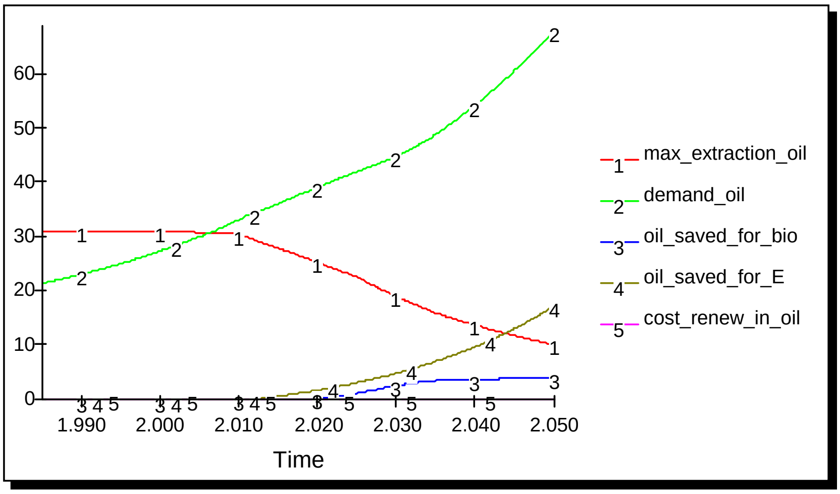

Figure 3: **E1.** Oil demand and extraction (Gb/yr). Scenario E1: economic growth 3.2%, no oil saving.

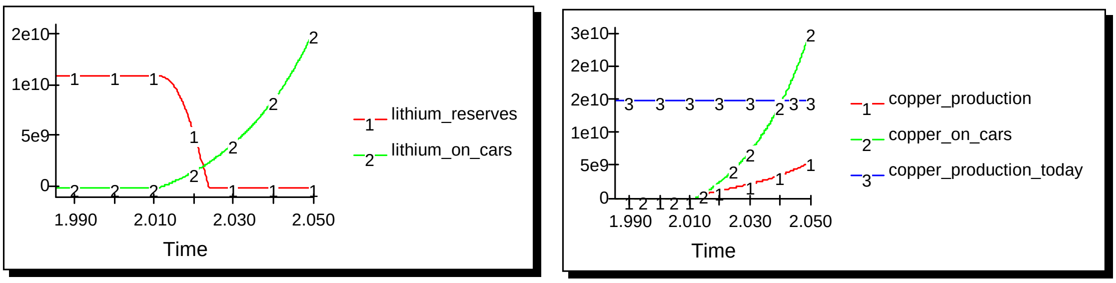

Figure 4: **E1.** Lithium and copper reserves and extraction (Kg) needed for the electric vehicles. Scenario E1: economic growth 3.2%, no oil saving.

The panorama of electrical energy, which can be seen in figure 5, also offers relevant results. It can be seen that electrical energy production meets demand until 2020, and after that date, it does not, but the gap between demand and supply remains small. The electricity generated with non-renewable sources (E_non_renew) stagnates from 2020 onwards, because we reach the ceiling of coal, gas and uranium extraction, but the growth of renewables rises and compensates for this stagnation to a great extent before reaching its physical limits (which are far greater than present consumption).

The economic cost of the construction of renewable infrastructure reaches 15% of the economic growth (three times the present cost). The increase of electricity due to the introduction of the electrical vehicle (increase_E_EV) does not mean a significant increase in the demand for electricity.

All these data show us that the problems related to electrical energy are far less complicated than the one of oil. If renewable energies continue to grow as they have been doing, they can play a very important role, although they cannot compensate for peak oil, since the technical substitution is not immediate.

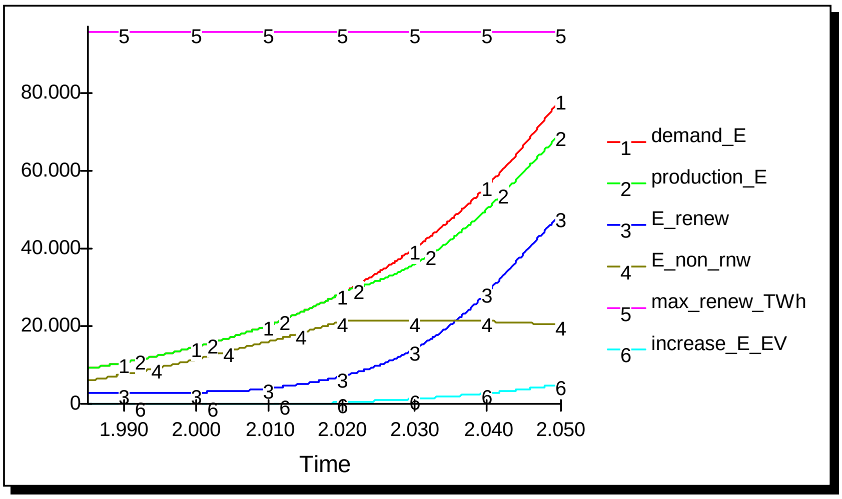

Figure 5: **E1** . Electrical energy demand and extraction (TWh/yr). Scenario E1: economic growth 3.2%, no oil savings.

Figure 6 offers two other interesting viewpoints. In the left hand graph, the GDP-oil relation corresponding to scenario 1 can be seen. This graph is basically an ascendant straight line from 1985 to 2008, and it suddenly changes to a descending line, since we have to generate more GDP using less and less energy. This change is substantially superior to the one observed in the graphs of figure 2, relative to the oil crisis the 1970s. On the other hand, the right hand graph compares the land occupation of bio combustibles and renewable energy. The fertile land required for biofuels is much greater, although its contribution is much smaller than the contribution of all the renewable electricity.

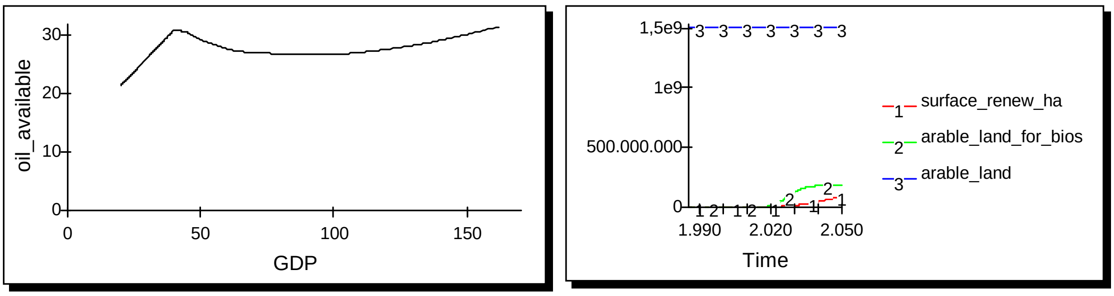

Figure 6: **E1** . Left: oil (Gb/yr) versus GDP (T$ constant 2000) needed to meet scenario E1. Right: arable land needed for biofuels and surface needed for renewable electricity compared to the arable land in 2007 (arable_land). Scenario E1: economic growth 3.2%, no oil savings.

The results of scenario E1 show that it is not possible to continue with the growth and consumption patterns of recent decades, since biofuels and electric cars are not enough to compensate for peak oil. They also show clearly the most evident aspect of this study: the energy crisis is essentially a problem of liquid fuels, due to the decline of oil. Electricity generation is a much less pressing problem, for which the alternative of the renewable energies already exists and is relatively easy.

Scenario E2: growth with energy saving

In this scenario, we tried to look for the amount of oil saving that would compensate for supply decay if economic growth continued as in past decades (3.2%). For this, we use electric vehicle, biofuel and renewables policies, such as those of the E1 scenario. Figure 7 shows that an annual saving of 3% of petroleum every year could compensate for the decline for some years. Nevertheless, in 2020, the decline becomes sharper (according to the predictions of ASPO 2008) and greater savings are needed. A 3% saving is greater than what was achieved in the 1970s, (as seen in figure 2) and doubles the 20-20-20 objectives of the European Union, since in 2020 it would be necessary to consume 40% less oil for the same amount of GDP, and 73% less in 2050.

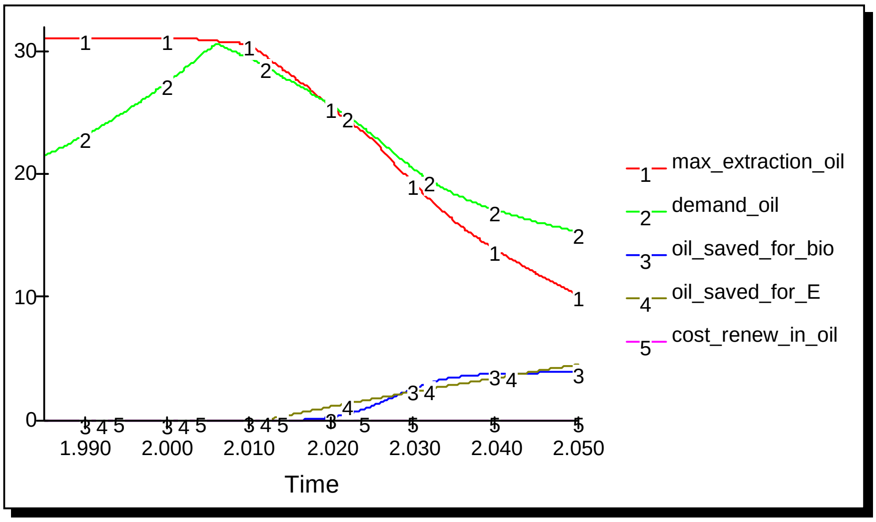

Figure 7: **E2.** Oil demand and extraction (Gb/yr). Scenario E2: economic growth 3.2%, 3% annual oil saving.

E3 scenario: moderate growth with energy saving

In this third scenario, we used a smaller economic growth (0.9%) and 2% saving of oil, (similar to the 20-20-20 UE strategy). The electric vehicle, biofuel and renewable electricity policies stay the same as in the previous scenarios. Figure 8 shows the results, which show that it is possible to compensate for peak oil reasonably well and there are no problems with electrical energy supply. In 2050, the renewable energies surpass fossil fuel production, but 100% renewable electricity has not been obtained because we limited the investment to 20% of the world's economic growth (four times today's investment). If we do not limit this growth and reach 100% renewable energy for 2050, we would need to dedicate around 50% of the growth in the GDP to renewable energy, as can be seen in figure 9. This would only need 15% growth of renewables and would allow contaminating energies such as coal, uranium and gas to be abandoned, and, although 50% of the economic growth is a significant amount of money, this is only 0.35% of the global GDP in absolute terms, dedicated to a productive activity.

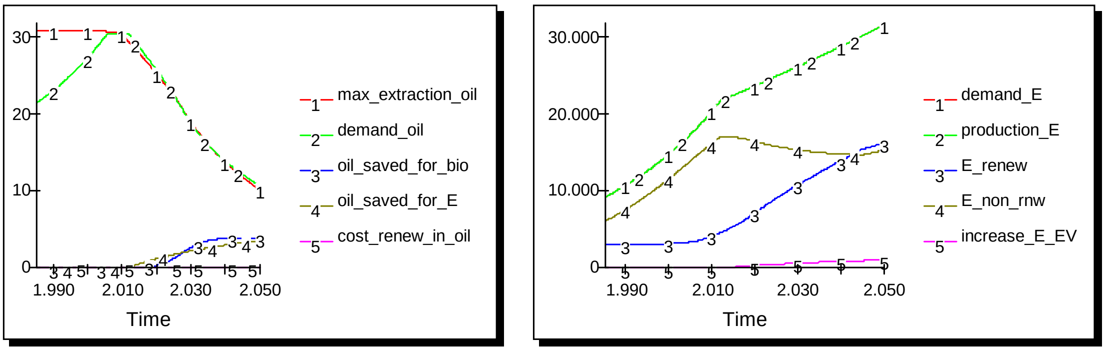

Figure 8: **E3.** Left: oil demand and extraction (Gb/yr). Right: electricity demand and extraction (TWh/yr). Scenario E3: economic growth 0.9%, 2% annual oil saving, renewable investment limited to 20% of GDP growth (4 times today's).

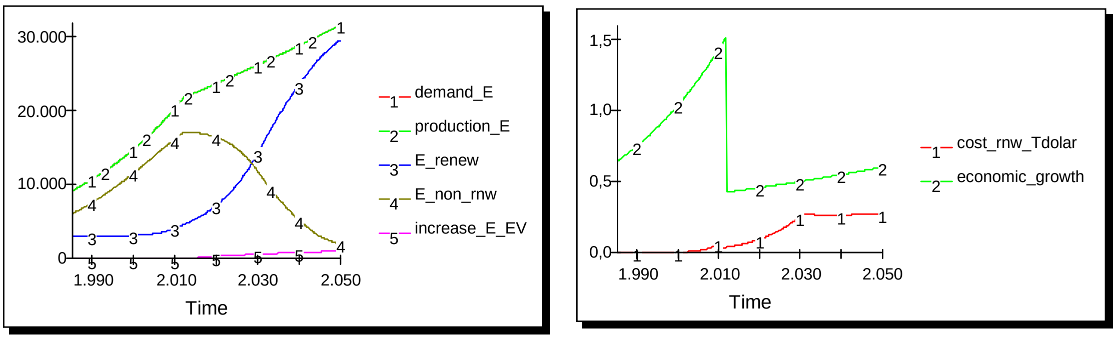

Figure 8: **E3-2.** Left: oil demand and extraction (Gb/yr). Right: electricity demand and extraction (TWh/yr). Scenario E3-2: economic growth 0.9%, 2% annual oil saving, renewable investment not limited.

The scenario E3 shows a quite realistic panorama, with savings similar to those of past crises. As in previous scenarios, the gross oil saving cannot come from the electric car and biofuels, but from more global oil saving measures. The electric energy supply is met and it is possible to reach a 100% renewable electricity generation with moderate growth rates.

Scenario E4: degrowth and 100% renewable

In the fourth scenario we shall draw a panorama of degrowth and a radical turn towards sustainability. We assume that the economic growth becomes slightly negative from 2011 on (- 0.1% of growth), while finding the rate of growth of renewable electricity that would lead to 100% in 2050. We allow the biofuel and electric car policies to grow until, in 2050, 60% of lithium reserves are in the vehicles (assuming that it is 100% recycled and that the number of cars can be maintained). Figure 9 shows the results.

We have had to use a 1.5% annual saving of oil to compensate for the decline, a percent much smaller than in Scenario E2. Figure 9 shows the electricity demand keeps growing because of the needs of the electric car, but the growth is small, and the renewable electricity replaces fossil fuels in 2050 just by growing at a rate of 11%, much smaller than the growth observed in previous decades. Nevertheless, as can be seen in figure 10, since the scenario is based on a negative economic growth, the investment in renewable energy must produce a net decrease of the GDP. However, as can be seen in figure 10, in absolute terms, this investment is negligible compared to global GDP.

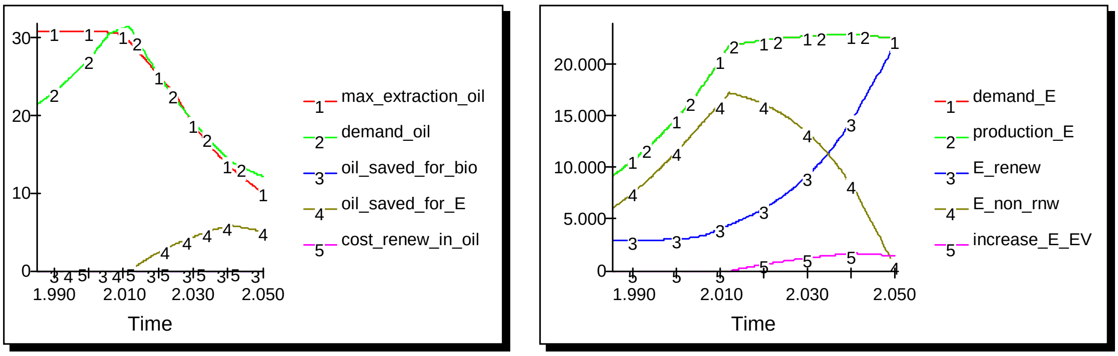

Figure 9: **E4.** Left: oil demand and extraction (Gb/yr). Right: electricity demand and extraction (TWh/yr). Scenario E4: economic degrowth -0.1%, 1.5% annual oil saving, renewable electricity 11% growth.

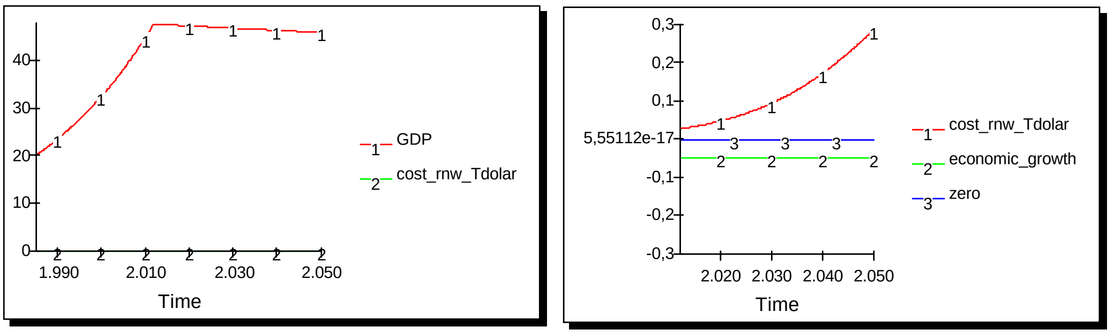

Figure 10: **E4.** Left: cost of renewable energy infrastructure compared to World GDP (T$ constant 2000). Right: cost of renewable energy infrastructure compared to GDP growth. Scenario E4: economic degrowth -0.1%, 1.5% annual oil saving, renewable electricity 11% growth.

Scenario E4 ratifies the conclusions of scenario E3, and, since the demand does not grow, it is easier to reach the objectives (100% renewable electricity and peak oil compensation). One question is posed, however, since the lack of economic growth might make the transition towards a renewable-energy based future more difficult in economic terms.

4. Conclusions

This paper presents a global energy-economy model built with system dynamics that allows us to see whether a world energy policy is compatible with the physical limits of natural resources. In spite of its simplicity, the model allows us to draw relevant conclusions.

In the next decades, it is not possible to continue with the tendencies of economic growth and the consumption patterns of previous decades; while policies such as the electric car and biofuels do not lead to the necessary oil savings. If we wish to continue a strong economic growth, similar to that of the previous decades, we must be able to save at least 3% of oil every year, which seems a very difficult task.

The electric car, however, is not a bad alternative to oil, and is far better than biofuels in terms of fertile land occupation and physical limits. In addition, the electric vehicle does not require a very high amount of electricity, but it has important limitations due to the elements of the batteries and the kind of vehicles that can be replaced.

Renewable energies can be an alternative to coal, gas and nuclear energy. They only need to continue growing at rates lower than those shown in previous decades, while the technical problems associated to their discontinuity need to be solved in 40 years. Their physical limits and land occupation pose no problem at the rates they are currently being used, although the challenge to get 100% renewable energy by 2050 might require an important economic effort.

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