From fossil fuels to renewable energies

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Abstract.
This paper describes the model of an industrial society based on fossil fuels whose supply decreases and the society is forced to develop alternative energy sources. It is conceived as an abstract model that captures the basic aspect of such a change, but in a simple and schematic way. Despite this, most of the important dynamics of this problem are included in the model. The results show interesting trends: the transition is possible but not straightforward. The technological change requires time and investment, and the dynamics of such investments are of vital importance. The system can also fall into a stage where no technological change is possible and the industrial ability of the society is lost.

1. Introduccion

Energy is becoming one of the most important problems at a global scale. The rising price of oil is threatening Worlds economies and, on the other hand, the pollution caused by fossil fuels, climate change, is becoming a major source of concern worldwide.

The World Energy Outlook published in 2007 by the International Energy Agency (WEO2007), estimated a continuous growth in the demand of energy that would, by 2030, require 55% more energy that today. On the other hand, 86% of the actual energy demand is now meet with fossil fuels. Although the theories about peak oil have not received much attention from public institutions and governments, they are gaining some attachment and social concern as the data confirm their predictions (ASPO2008a, ASPO2007, Annett 2005, Hubbert 1956, Hubbert 1993, Campbell 2006). Those theories predict an early scarcity of fossil fuels (especially oil) as the oil camps reach the decline. When the stocks of oil in a field fall, its extraction becomes slower, therefore the extraction curve has a bell shape, and once the peak is reached, yearly production is less every year.

The dependence of today's world economy on fossils fuels is, thus, evident. It is also evident that, if there would be an important problem of access to these fuels as the peak oil theory predicts, the World would not be able to react in an immediate way. The substitution of 86% of the energy by another sources such as renewables (of atomic fusion) would not only need technological discoveries, but a long and costly adaptation process of technological development, adaptation of industrial processes, machines and housing.

Most dynamic global models of energy-economy-and climate change (EECC) are oriented towards the political decision making (emissions market, energy/emission taxes, etc). The literature on this topic is very abundant (Tol 2006, Nordhaus 1989, Fiddaman 2002) and we could classify it into two groups: system dynamics models and integrated assessment models. Most models use with few feedback among these variables (energy, economy and climate change), even in the models of system dynamics (an exception could be the model of Meadows et al World 3). This way the models of energy/economy from a holistic point of view dynamic and with feedback are almost to be done.

This paper focuses on the very general problem of the energy and the economy. It has a very global view and is only a first trial; therefore our point of view is also very general. Our aim is to study the effects of energy shortage in a society based on a non renewable energy source that wants to change to renewable energies. How is this society going to make this transition? On one hand a person with a simplistic view of technology would say that a revolutionary invention will occupy the place as soon as needed, with no delays in between. On the other hand, some claim that this substitution is not possible, since renewable energies are not independent of fossil fuels: they need a complex technological network in order to be set and this network does not work without fossil fuels. Tainter 1996 claims that human societies tend to become more complex, but in doing so, the societies find decreasing benefits from each level of complexity, until it comes to a point where the increases in complexity have negative returns and the society collapses. Tainter fears that the shortage of fossil energy will mean that the complexity of our technology cannot be sustained any more, and the renewable energies will requite more complex technology which will tend to increase complexity, and therefore, lead even more rapidly to collapse.

The theory of Olduvai (Duncan 1996) is also another pessimistic view of society based on the correlation between historical data of population and energy consumption. It predicts that, when the fossil fuels are exhausted, the carrying capacity of the World would be that of a pre industrial society leading to a severe a decline in World population.

What can system dynamics say about that? We know that the story of the system is important. Fossil fuels are an input external to human evolution, but the actual state of a system is not only the result of its inputs, but also the result of its past behaviour. Those who say that, once this input is removed, we would go back to the previous stage of development, might ignore the dynamics of the human system and its ability to keep memory. Can the accumulated stock of technological knowledge and material capital serve as a basis to lead the society to an equilibrium point of higher energy consumption and population than pre-fossil society?

The model presented in this paper is an attempt to answer to these questions. It was only conceived as a sort of game, not a realistic model with estimated parameters. The idea is to capture the basic dynamics of this problem and gain insight into it, but never loosing the holistic view.

Section 2 describes the main variables and feedback loops of the model, section 3 describes the parameters used in the model, while results of the simulations and conclusions are given in sections 4 and 5.

2. Model description

The model has got three stock variables: material capital, non renewable resources and renewable energy infrastructure. Let us describe in detail the feedback loops associated with them.

Material capital.

We have considered the whole problem of a technological society that uses energy for all kinds of artefacts: industries, machines, housing, infrastructure…. All these artefacts are what we call *material capital* (see figure 1). Our material capital is not equivalent to the capital of economics, or GDP, it only covers the material aspects. If there is a shrink in the *material capital* it might mean, either that the society is becoming more austere while maintaining social stability, or that there is a complete social breakdown and industrial production is not possible. The social/economical or political aspects will not be considered so far, those aspects are too complex for this type of model.

If there is enough energy, the material capital tends to growth exponentially at a rate greater than the depreciation of old material goods, this loop imitates the exponential growth of today's economy, which is, to date, highly correlated to energy consumption (Hirsch 2008).

Energy consumption use is proportional to *material capital* (*consumE* constant). This relationship has been made constant, since it is not very clear weather it tends to increase or decrease. On one hand technological improvements tend to make a society more efficient in the use of energy, but, on the other hand, when the energy available decreases it is more difficult to find good materials for sophisticated technologies and the efficiency of technology could decrease.

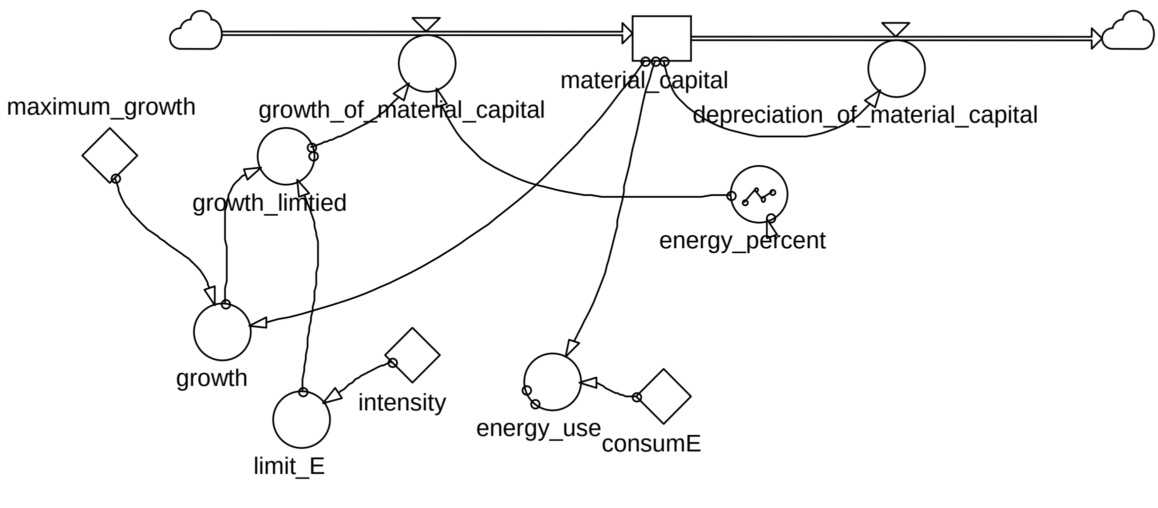

Figure 1: material capital part of the model.

The growth of the material capital is limited by the availability of energy, *limit E* is the variable that limits *growth* it depends on the physical availability of energy (called *energy abundance*).

Non renewable energy.
Initially, the energy to feed material capital comes from fossil sources that tend to get exhausted, except for a small portion that comes from renewable energies.

Non renewable resources (see figure 2) is a stock that gets depleted at the rate of *non renewable extraction*. This energy cannot be extracted at any rate, when the stock tends to get exhausted it is more costly to extract, and the rate of extraction declines. This behaviour imitates the peak oil theories of Hubbert (Hubbert 1956, Campbell 2006) in a simple way. The *non renewable extraction* is, thus, the minimum between the *demand of non renewable* energy and the *limit non renewable extraction*. *Limit non renew extraction* is a decaying graph, the more the ratio *non renew resources/non renew initial stock* decays to zero the lower the value of this graph is. This means that, when the stock of *non renewable resources* is high the energy extracted equals the demanded, but when the stock declines the extraction is limited by the *limit non renewable extraction* curve.

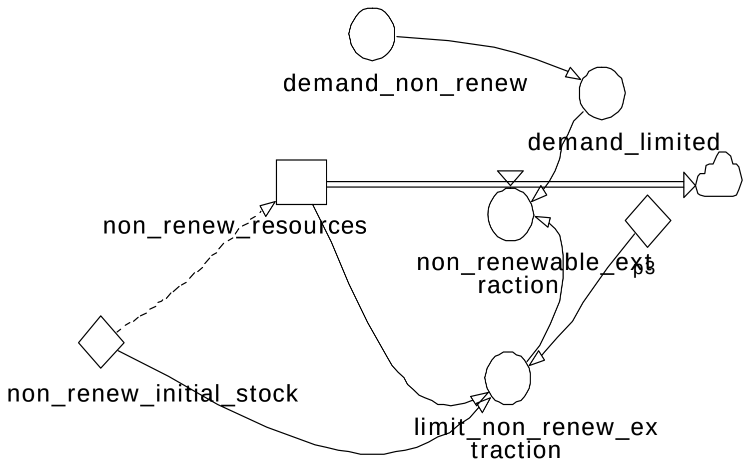

Figure 2: non renewable resources part of the model.

Renewable energy infrastructure.
Renewable energy cannot be produced at any rate either. It needs infrastructure (windmill, solar panels) that need time and inversion to be installed. *Renewable infrastructure* (see figure 3) is a stock that accounts for the amount of infrastructure set, which is proportional to the amount of energy extracted each year. The *increase of infrastructure* is the flow of *renewable infrastructure*, this flow requires an *energy investment*, which is the amount of material capital invested in them. There is also a physical limit to the amount of renewable energy that can be extracted (*max renew*). The more we approach this limit, the more material capital we need to invest to set renewable infrastructure, until further growth is not possible.
There is one important parameter in this part of the model: *renew return*. It is the amount of material capital needed to establish the infrastructure that produces a unit of energy. This is a crucial parameter, if the renewable technologies do not produce more

energy than they require, the collapse is assured. This parameter is similar to the EROEI (Energy Return On Energy Investment) concept.
Once this infrastructure is set it produces energy until its life cycle is completed, therefore the renewable energy is the first to be used, if the energy demand is not covered with it, non renewable energies are used.

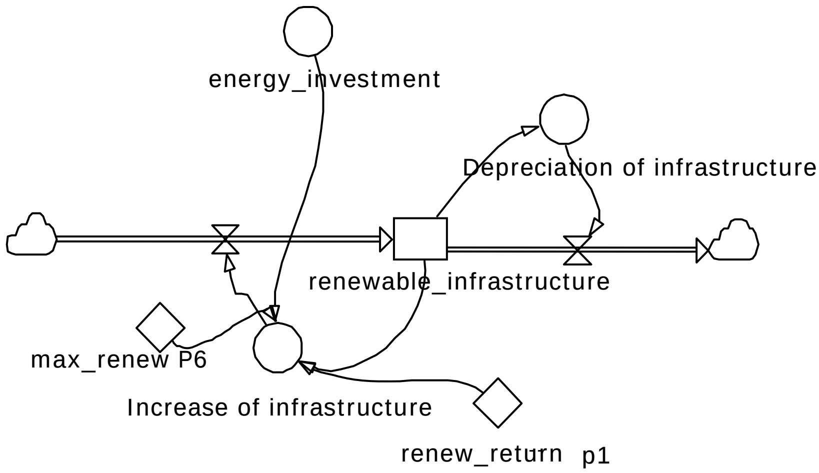

Figure 3: renewable energy part of the model.

Energy and growth.
This part of the model involves the policies and the possible interactions economy-energy. *Energy use* (see figure 4) is proportional to *material capital*, while energy available is the sum of the renewable plus non renewable energy that can be extracted. The variable *energy abundance* is *energy available* minus *energy use*, and account for the amount of energy available for growth. The energy abundance fixes the *limit E*, which is the variable that determines the limit to material growth, if the desired growth (*growth*), which is the product of the *material capital* times the *maximum growth* is higher that this limit, it cannot be done, therefore the *growth of the material capital* is the minimum between *growth* and *limit E*, minus *energy investment*, which is the share of the material growth dedicated to invest on renewable infrastructure.
If the energy abundance becomes low the actors tend to invest more in renewable energies; this means that a share of the *growth limited* is dedicated to *energy investment* instead of to *material capital* growth, which, in fact, tends to slow even more the growth of the material capital.

The complete view of the model is shown in figure 6.

3. Parameters and experiments

The parameters and functions of the model that we have found more relevant have been elected as variable parameters:

P1, *renew return*. It is measured in terms of units of energy per year divided by the units of material capital. It corresponds to the amount of material capital that needs to be invested in order to install an amount of renewable energy infrastructure. This parameter resembles the EROEI concept, the amount of energy necessary to produce energy. P1 takes values between 0.03 and 2, P1=1 means, for example that every year the equipment returns the energy employed in its fabrication, since we consider a 30 year life for the equipments this would be a EROEI of 30.

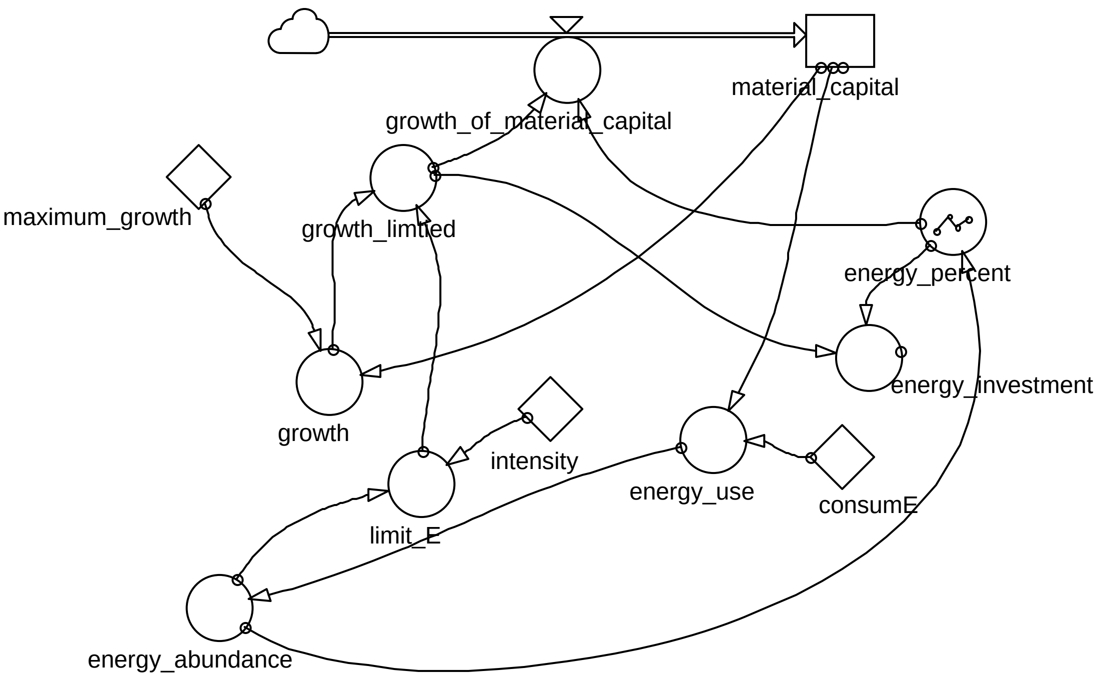

Figure 5: energy- growth part of the model.

P2, *non_renew_init*. Indicates the stock of non renewable energy left. The parameter is expressed in terms of units of energy. Since the initial energy spent in one year by the initial material capital is 1, this value expresses the resources left in terms of years with the initial consume, and takes the values between 30 and 80 (years at the initial level of consume).

P3, *limit non renew extraction*. Is a curve that imitates the Hubbert peak, it has been implemented with a polynomial function of a parameter P3, that takes the shape shown in figure 7. The parameter p3 takes values between -1.5 (plateau) and 1.3 (peak).

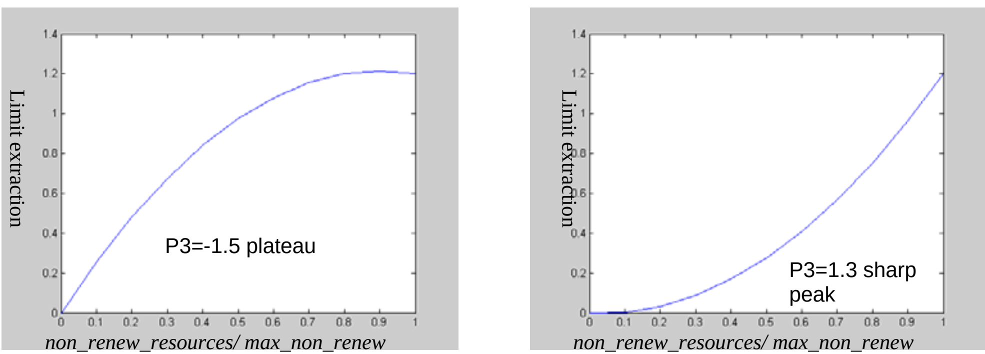

Figure 7: limit extraction of non renewable resources curves

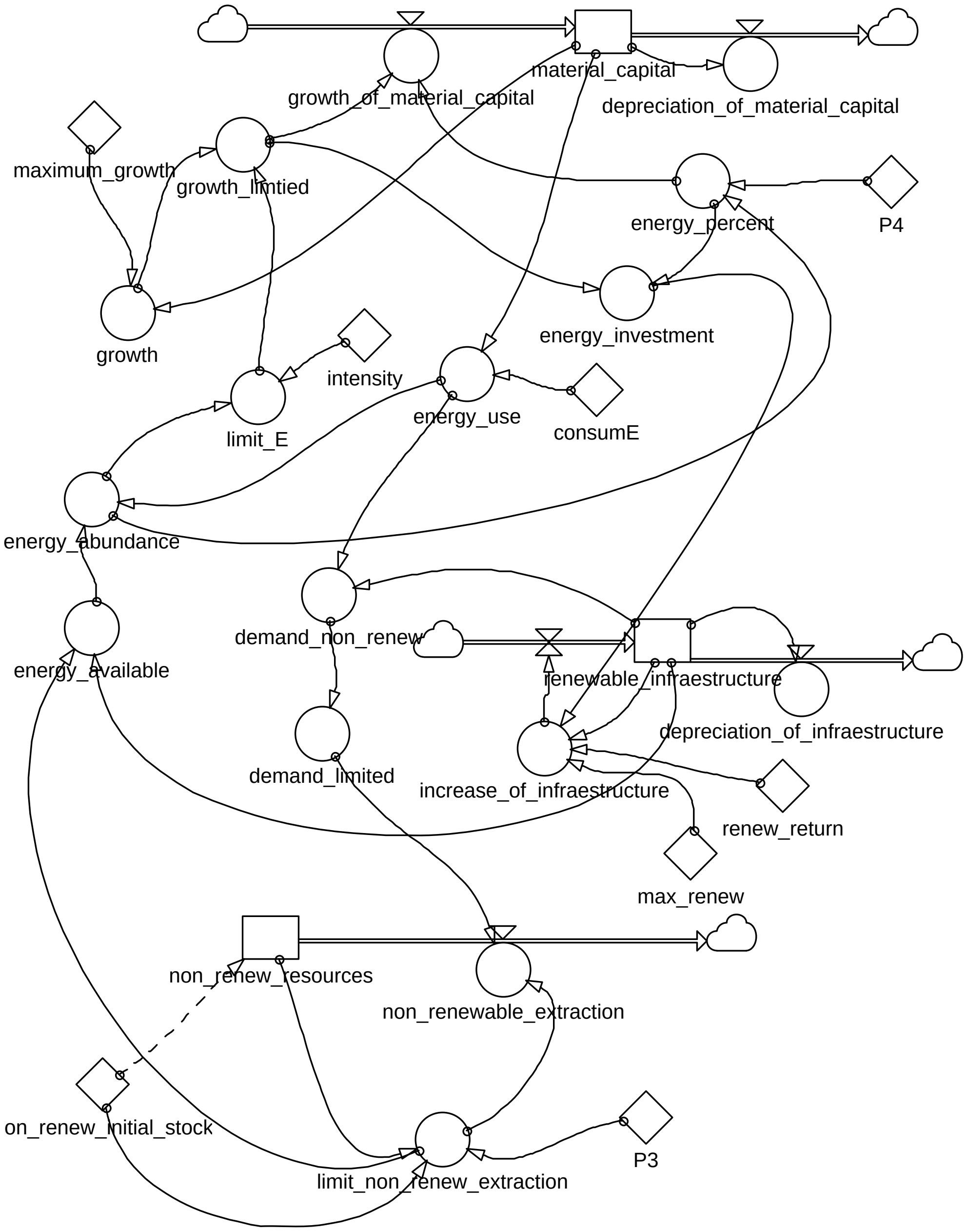

Figure 6: “enerfiction” model

P4, ***energy percent*** is the policy of the model. It indicates the percentage of the growth on material capital dedicated to build renewable energy infrastructure. It is implemented with exponential curves as the ones of figure 8:

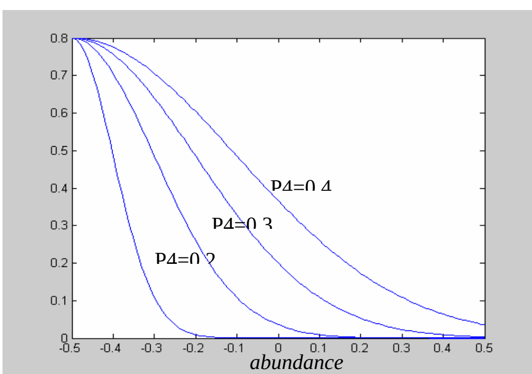

Figure 8: energy percent curves.

P4 equal to 0.4, for example, means that an early reaction to the energy crisis is attained and 10% of the economic growth is dedicated to renewable infrastructure when the abundance is 0.4. When abundance falls below 0.2 there are problems with the growth of the material capital, since, at that stage the depreciation of the material capital gets greater than the growth. Curves with parameter P4 lower than 0.3 are, therefore, slow reactions to the problem.

P6, max renew. This parameter indicates the physical limit of the renewable energies, the maximum renewable energy that can be obtained. It is indicated in terms of the initial energy use of the society and takes values between 0.6 and 1.3.

The initial value of material capital is 1 unit of material capital and the initial renewable energy extracted is 10% of the energy required.

4. Results

We have simulated this model using MATLAB in order to be able to run several simulations changing parameters, plot the results as desired and perform a screening analysis (as described in Ford and Flynt 2004). The results obtained for random values of parameters P1 to P6 and can be seen in figures 10 to 13. There are two types of results that can be classified as “crisis” and “collapse”.

“Crisis” runs are those where the material capital, when facing decreasing inputs of energy, decreases, but soon the energy investment grows to compensate the lack of energy, then renewable energy supply increases and the system reaches equilibrium. The equilibrium might appear at different levels of energy (20%, 50% of the initial consume of energy, for example). This is normally a state where the maximum amount of renewable capacity is not reached. This is an interesting result, it implies that the final value of renewable energy is not caused by the limiting factor of the physical maximum capacity, but by the effect of an stabilising loop. Increasing the material capital implies increasing the investment on renewable energy, and this, in turn, means a decrement of the material capital. Installing renewable energy costs, and that prevents material growth. Therefore, the limit on the renewable energy installed is determined by this stabilising loop not by the physical limits.

“Collapse” runs are those where the equilibrium cannot be reached and the material capital tends clearly to zero, the energy infrastructure cannot be maintained and the society loses its ability to use energy. This is also another interesting result of the model. If the investment on renewable infrastructure is slow, when the non renewable energy declines and the material capital decreases it is more difficult to obtain renewable infrastructure, since the energy available for growth is scarce. If no renewable infrastructure can be set, the energy supply is even lower. This reinforcing loop leads to the final state of zero material capital.

Notice that both of the results, what we call “crisis” and what we call “collapse” would be called collapses in the traditional sense, since the society reaches a maximum of material standard followed by a decline. In fact, we hardly found results where there is no collapse in the traditional sense; most times the material capital suffers a sharp decline at the beginning, but, since material capital is not a crucial variable such as population or food, we do not find our "crisis" results as negative to call them collapse.

Out of 100 simulations with different random parameters 26% have been "collapses". Some of the results are shown and commented in figures 10 to 13.

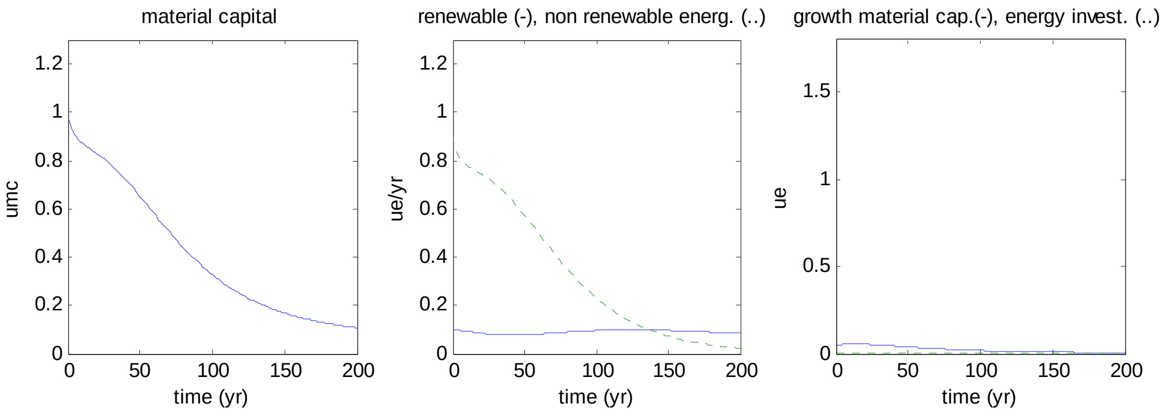

Figure 10. **Collapse.** The material capital suffers an slow but continued decline. The renewable infrastructure growth is very slow, when the renewable extraction equals the non renewable extraction the material capital is too low to allow for strong investments on new renewable infrastructure and the material capital tends to zero. In this simulation the energy return is high (0,97 almost an EROEI of 30) the remaining non renewable stock is high (66 years), the Hubbert curve is a plateau (-1.2) and the maximum renewable energy available is 0.73 of the initial, but the energy investment parameter is slow, the slow investment on renewable infrastructure leads to a collapse.

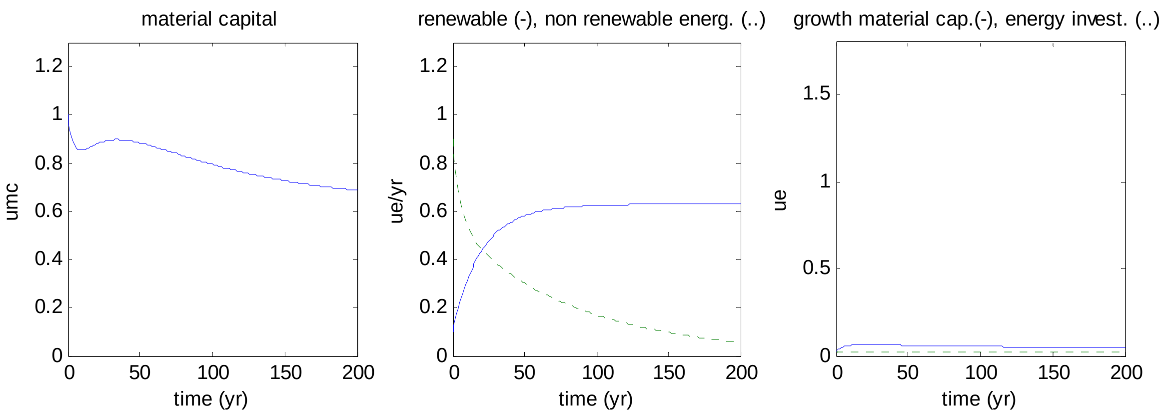

Figure 11. Fast reaction to crisis. The energy investment is fast and the renew return too. The initial decline of the material capital is sharp too, but the energy investment is very fast and the return is large, therefore the renewable energy soon becomes greater than the non renewable and the final material capital is high. Renew return = "high" (EROEI 50), non renew init =60yr, limit extraction="peak", energy percent = "fast", max renew = 0.8.

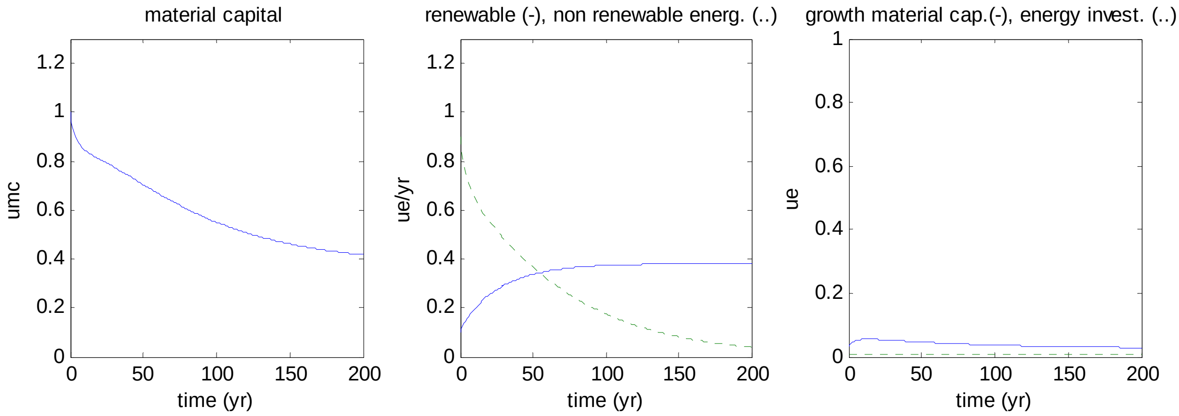

Figure 12: Slower reaction. The reaction to the crisis is not as fast as in previous figure and the final equilibrium is got less energy and material capital. Energy return is very high (almost EROEI of 50), initial non renewable stock is medium (62 years), Hubbert curve is a sharp plateau, but energy investment is medium (0.48) and max renew 0.7 of the initial energy.

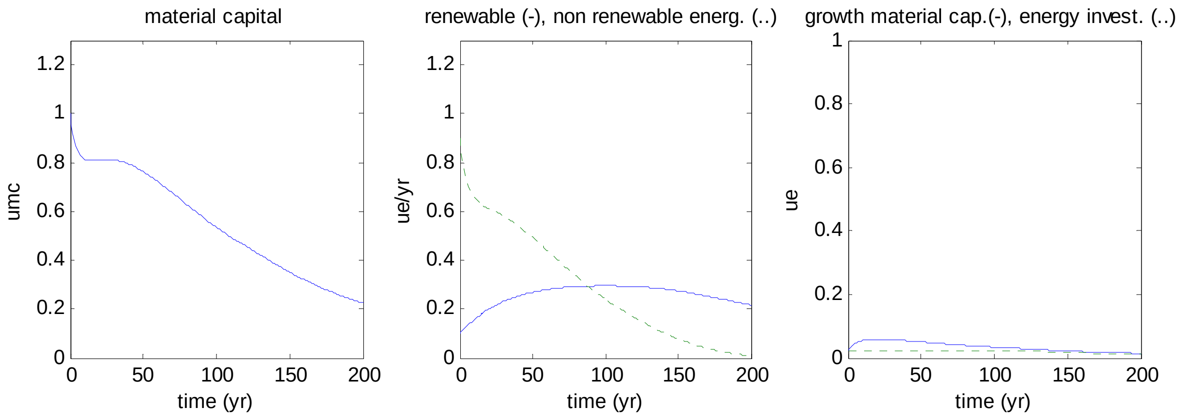

Figure 13: Two stage collapse. The reaction to the crisis is fast (0.7) and, at the beginning a small plateau is observed in the material capital, but the energy return is not high (EROEI 12) and the Hubbert curve is a plateau, while the max renew is 0.8. The energy investment is not enough and the material capital suffers a slow decline.

The parameter that seems to influence the results most is the *energy percent*, the rhythm of renewable investment, but let us see the correlation between the parameters and the final result in more detail. In figure 14 we can see the results of 100 runs where the parameters have been elected following a uniform random distribution in their intervals. The final value of the material capital is the parameter elected as indicator of the success. We can see that neither the initial stock of non renewable energy (the number of years of reserves left) nor the shape of the depletion curve seem to have much influence on the final result. Energy return (EROEI) seems to be important, since at low values no high final-energy simulations are obtained, but the parameter that seems to be most correlated is energy percent, the rhythm of investment on renewable energies.

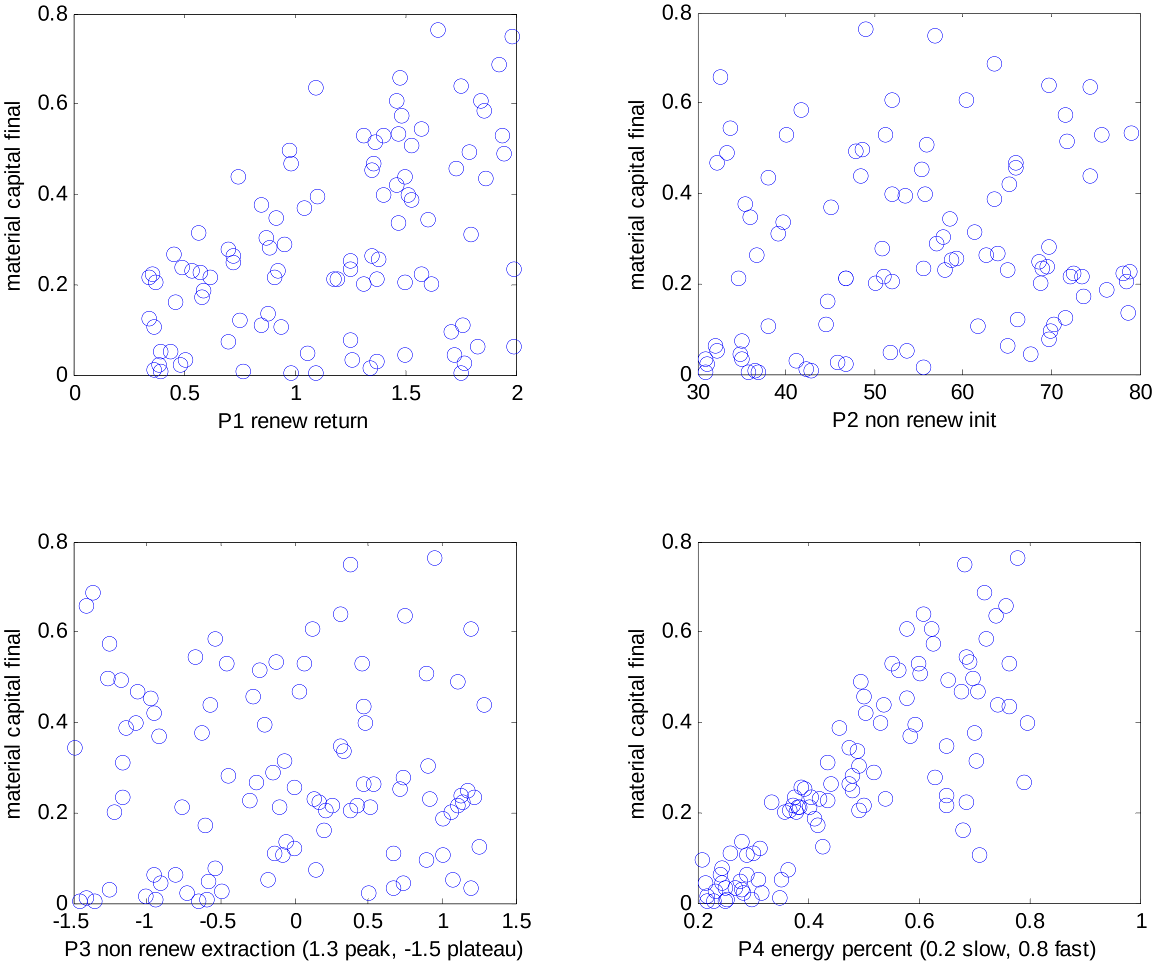

Figure 14. Correlation between parameters and the final value of the material capital. Results of 100 runs with random parameters. Neither the initial stock of non renewable energy (the number of years of reserves left) nor the shape of the Hubbert curve seem to have much influence on the final result. Energy return (EROEI) seem to be important, since at low values no high final-energy simulations are obtained, but the parameter that seems to be most correlated is energy percent, the rhythm of investment on renewable energies.

The plot of figure 15, of the product of the two parameters that have more influence on the final result versus the final value of the material capital show that the correlation of those two variables is evident.

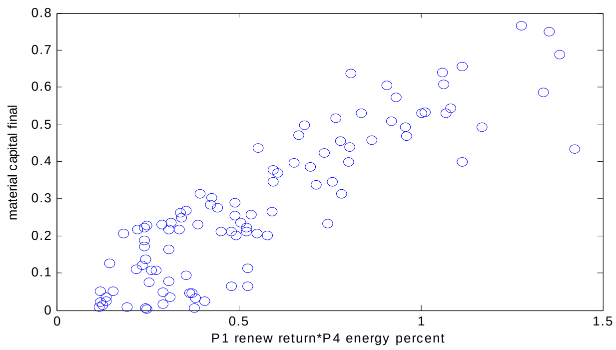

Figure 15: **Correlation between parameters and the final value of the material capital**. Results of 100 runs with random parameters Relation between the final value of material capital and the product of parameters P1 and P4 (renew return and energy percent).

Screening analysis.

Screening (Ford and Flynn 2004) is a technique that shows the relative influence of parameters on system dynamics models. It consists on calculating the correlation coefficients between the output variables of the model and the randomly changed parameters in each time instant. In our model we have calculated the correlation between the material capital and the parameters P1 to P6. In figure 16 we can see the results of those coefficients. P1 and P2, energy return and initial non renew both have a positive correlation with material capital. That seems coherent, and this correlation seems to be greater at the first years of the simulation. P3, the Hubbert curve parameter, has got negative values, since this parameter is negative for plateau shape and positive for peak, this means that more plateau-shape the bigger the material capital. That seems coherent too, and also the fact that at the end of the simulation the correlation is less important. Figure 16 shows the results of P4 energy percent and P6 max renew too. Max renew does not seem to have a strong correlation, but the most interesting result is the one of energy percent. The first years of the simulation the correlation between the material capital and the energy percent is extremely negative, not surprisingly, since the growth of the energy investment is subtracted from the growth of the material capital. The trend changes at the middle of the simulation and the correlation becomes highly positive. This is another of the interesting conclusions of the model, which repeats the idea of previous results. The early investment on renewable energy is very important for the final results but it has got to be done by sacrificing the short term material growth. This would make our energy policy difficult to sell to short sighted politicians!

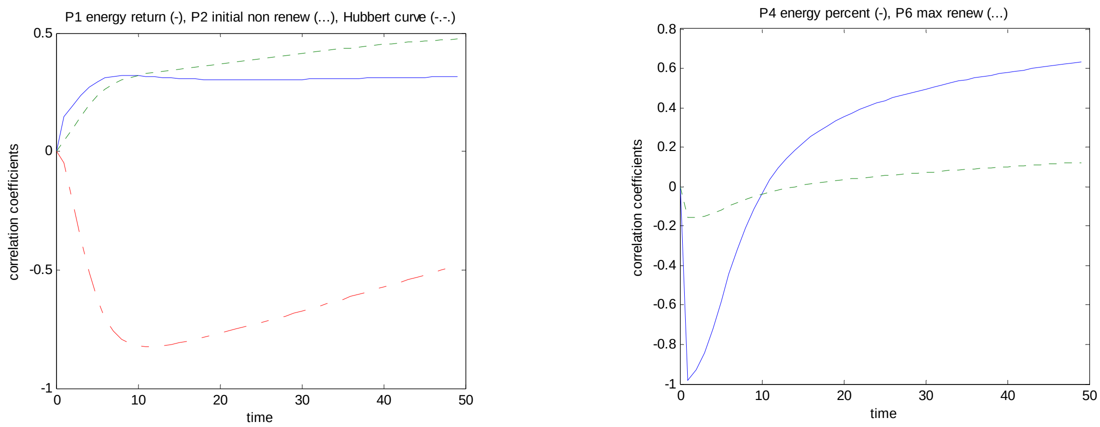

Figure 16: **Screening analysis**. Correlation coefficients between the value of the material capital and each one of the parameters.

Conclusions

This paper describes the model of an idealized transition from an industrial society based on fossil fuels to a society based on renewable energies. The model is simple but captures the basic dynamics of the problem: the reinforcing loop of economic growth, the delay in the setting of renewable energy infrastructure, the need to invest on this infrastructure, the depletion pattern of non renewable energies, etc. The results show that the dynamic aspects of the problem are of vital importance. There must be a fast investment on renewable energies in order to obtain a high value of the material standard of living of the society in the long run.

The results fall into two categories, “crisis” and “collapse”. In “collapses” the change between fossil to renewable is too slow and when the investments want to be done, the society is too poor to invest in renewable energy; the ending result is a non industrial society that cannot use renewable energies because of lack of capital to invest on it. In the crisis scenarios there is a transition period of decrease but the stability is obtained.
This is a first step into a complex and important problem. We are sure it can be the basis for more complete and realistic models.

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