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The transition towards renewable energies: Physical limits and temporal conditions ☆

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HIGHLIGHTS

- We study world energy demand and resources with a systems dynamics model.
- We find that peak oil cannot be overcomed with simple technological substitution.
- Past economic growth and energy intensity trends cannot be maintained.
- Electric vehicles are only a partial solution, biofuels are even more limited.
- Substitution of electric energy by renewables is much easier than oil substitution.

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ABSTRACT

The perspectives of the depletion of fossil energy resources, together with the consequences of climate change, have provoked the development of numerous national and pluri-national energy policies. However, there have been few overall studies on the evolution of these resources. This paper uses a dynamic model to study the exhaustion patterns of world fossil and nuclear fuels and their possible replacement by renewable energy sources. The results show that peak oil will be the first restriction and it will not be easily overcome. Electric vehicles can produce some interesting savings, but they are insufficient to avoid the decline in oil. Biofuels are even more limited, due to the enormous extensions of fertile land they require and their low productivity. This shows that overcoming the decline in oil will need much more ambitious policies than the mere substitution of technology. If the “oil–economy” relationship does not change substantially, world economic growth may be seriously limited or even negative. In contrast, the production of electrical energy is not such a worrying problem in the short and middle-term.

1. Introduction

The consumption of energy in its different forms is a key factor in the economic and social development of our societies and in our everyday lives. Technological and social evolution towards a society not based on fossil fuels is becoming a matter of the greatest interest, as it is increasingly clear that the energy consumption model of recent decades is not sustainable, due to the exhaustion of fossil energy resources and the effect of this consumption on climate change.

The evolution in fossil energy resources has been the subject of numerous studies in recent years, particularly in reference to oil. A peak in oil extraction is widely acknowledged, although the studies vary in the dates and nature of the decline (Campbell and Laherrère, 1998; Hubbert, 1982; Robelius, 2007; ASPO, 2008; Höök, 2009; Kopelaar, 2005; Skrebowski, 2008; Aleklett et al., 2010; EWG, 2008; UKERC, 2009; de Castro et al., 2009). Other energy resources have been studied less, but maximum extraction curves, similar to those for oil, have been proposed for gas and coal (EWG, 2007; Tao and Li, 2007; Patzek and Croft, 2010; EWG, 2006; Höök, 2009; Guseo, 2011; ASPO, 2009; Lahèrrere, 2006; Mohr and Evans, 2009, 2011).

From a global viewpoint of energy supply and demand it is necessary to separate the resources and their final uses, as not all energy types are directly interchangeable and, in some cases, a change in energy source might require major technological and even social adaptations. In this paper, two of the most important energy carriers have been studied: electricity and liquid fuels. The

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paper is centred on the substitution of oil in one of its main uses, transport; and in the substitution of non-renewable electric energy by renewable sources. A broader model with all types of uses is under development and, hopefully, its results will be described in further publications.

The substitution of oil in the production of liquid fuels is highly problematic, since currently only biofuels can replace oil directly in most of its uses. Biofuels display lower land use efficiency and EROEI (energy return on energy investment) rates than oil-based fuels, and have, therefore, been questioned. Although improvements are expected in second generation biofuels, the performances will have to improve greatly to be a large scale alternative to oil (Papong et al., 2010; Field et al., 2007; Pimentel et al., 2009).

The replacement of oil as the primary source of energy in transport by using electric vehicles also has its limitations. The technical specifications are currently much inferior, mainly in terms of travel range, which means that not all transport can be replaced immediately. In addition, modern battery technology needs to use rare elements. These and other limitations, such as the need to increase electric energy production, have been noted in numerous studies and will be examined in detail in the present model (Offer et al., 2010; AISBL, 2009; EEA, 2009; Hacker et al., 2009; FTF, 2011). Other alternatives for the reduction in the dependence on oil are based on the use of public transport, natural gas, and ways of saving oil, such as an increase in non-motorised transport, improvements in heat insulation, town planning, and so on. They all depend on social changes and new infrastructures and are not included in this model.

The technological hypothesis accepted by most models is that it is easier to replace non-renewable fuels in the generation of electrical energy than in transport. There are currently forms of renewable technology with quite acceptable EROEI rates and efficiency (wind and hydro power), while others offer interesting potential (thermoelectric solar power, off-shore wind power, tidal power) (Heinberg, 2009; Gupta and Hall, 2011; Murphy and Hall, 2010). The problem of the variability of renewable energy hinders the introduction of these technologies and requires extra infrastructures. However, in the present study, we have not tackled this problem in depth and have left it for future more complex models, although some authors suggest that it could be a significant limitation (Trainer, 2012).

This study uses a dynamic model to analyse the replacement of oil and non-renewable fuels, similar to the one used in Mediavilla et al. (2011). It is, however, based on a more exhaustive data set. The model enables the quantification of basic aspects of the replacement and acts as a framework of the physical boundaries that economic policies cannot cross. *Thus, the objective of the model is not to predict the future behaviour of the world economy, but to establish which policies are not feasible, according to the predictions for the exhaustion of resources made by different experts and estimates for the demand.*

2. World model

In recent decades, different global energy-economy models have been developed (IIASA, 2004, 2001; WETO, 2003; D'Alessandro et al., 2010), some based on system dynamics (Fiddaman, 1997; Dale et al., 2012). However, few models explicitly recognise phenomena like peak oil and relate it to the demand created by economic growth (Meadows et al., 1972, 1992; de Castro et al., 2009; de Castro, 2009; García, 2009).

In previous studies (de Castro et al., 2009; de Castro, 2009), the authors have studied the extraction of energy resources based on dynamic energy–economy feedback system models. However, the current model is simpler than the previous ones in its dynamic aspect, whilst it gathers together and relates data of very different kinds. Compared with the other models, it has the advantage of allowing us to include the estimates of different experts and study the energy–economy relationship in a simpler way. The model can be used to obtain an overall perspective of the global energy problem. It includes the following aspects:

- Global economic growth/recession and demand of liquid fuels and electricity.
- The depletion of natural resources (oil, gas, coal, uranium, lithium).
- Technical alternatives to oil in transportation: electric cars and biofuels.
- The generation of electrical energy with two basic sources: renewable and non-renewable.

The basic structure can be seen in Fig. 1. World economic activity (GDP) is one of the main variables of the model, since it is used to estimate the world demand for oil and electricity. The value of GDP each year is estimated by taking the GDP of the initial year of the simulation and adding to it the economic growth year by year. For past values of GDP an average value of economic growth has been used, for future years a policy of economic growth is set. According to this, GDP is considered a stock of the model and the policy of economic growth is its flow.

The stocks of natural resources are found in the lower part of Fig. 1: oil and non-renewable electricity (subject to limits of

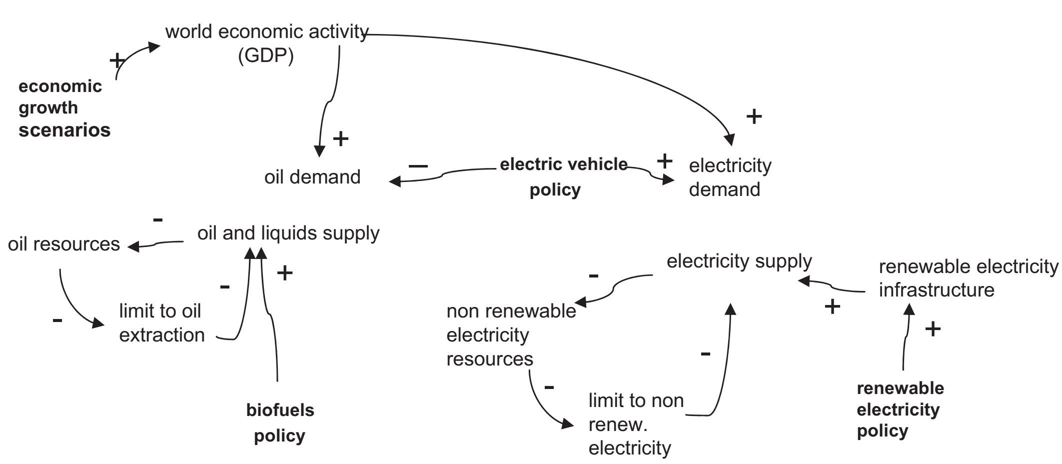

Fig. 1. Causal loop diagram of the model with its basic elements. The policies are in bold font.