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

Margarita Mediavilla ^{a,*}, Carlos de Castro ^a, Iñigo Capellán ^a, Luis Javier Miguel ^a,
Iñaki Arto ^{b,1}, Fernando Frechoso ^a

^a Escuela de Ingenierías Industriales, Paseo del Cauce s/n, University of Valladolid, Spain

^b Institute for Prospective Technological Studies, DG Joint Research Centre, European Commission, Spain

HIGHLIGHTS

- ▶ We study world energy demand and resources with a systems dynamics model.
- ▶ We find that peak oil cannot be overcome 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.

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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; Laherrère, 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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* Corresponding author. Tel.: +34 983 423545; fax: +34 983 423490.

E-mail addresses: marga@eii.uva.es (M. Mediavilla),
inaki.arto@ec.europa.eu (I. Arto).

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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 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

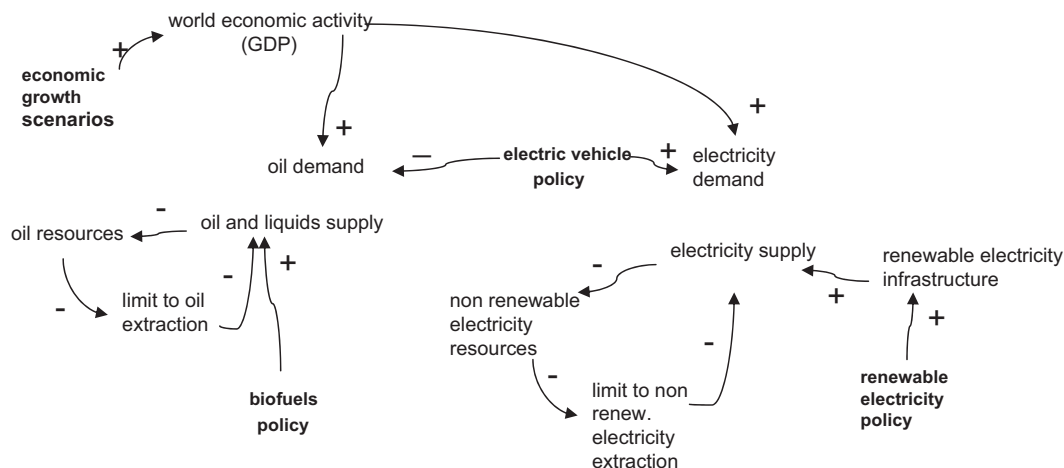


Fig. 1. Causal loop diagram of the model with its basic elements. The policies are in bold font.

extraction), biofuels and renewable electricity (not exhaustible, but finite).

The relationship between economy and energy in our model can be described as dual, as it acts as a supply-driven model if there is a shortage of resources, and demand-driven otherwise. The logic underlying this approach is that, given a scenario of economic growth, the demand for liquid fuels and electricity would be determined according to the oil and electricity intensities. On the other hand, by taking into account the depletion curves of reserves and the different policies for foresting renewable energy, the maximum potential of energy supply at any given time can be determined. Then,

- if the energy demand associated with our scenario of economic growth is less than the maximum potential of energy supply, the prices will be fixed in such a way that the energy demand will be totally satisfied. In this case, the supply of energy will adjust to the demand of energy resulting from the economic scenario analysed (demand-driven model);
- if the demand for oil is greater than the supply, we will face an energy shortfall. In such a case, energy demand will exceed supply, and energy prices will increase until demand matches the maximum potential of energy supply (supply-driven). In this way, the model detects the scenarios of economic growth and the policies that are incompatible with physical limits.

Therefore, this is a model without energy–economy feedback, which makes it simply a model of maximum physical restrictions. As it omits energy–economy feedback (through prices) we disregard the dynamics that tend to make the economy contract because of the energy shortfall. Many of these feedback patterns emphasise economic depressions: the lack of oil, for example, might cause economic depression and lack of investment in new oil fields, which would worsen the oil crisis and cause more economic depression. Our model is, therefore, a “framework” which defines the physical limits.

Finally, the basic policies in the model are shown in the bold face in Fig. 1: economic growth scenarios, electric vehicle policy (which includes hybrid cars) and investment in renewable electricity (renewable electricity policy). Appendix B gives a simplified diagram of the model used here.

3. Study of world energy resources

In order to make an estimate of the availability of fossil fuels, we have gathered together the main studies to date on this issue, only seeking those that not only refer to resources and reserves, but also take into account the limits to production rates (such as “peak oil”). These studies (ASPO, 2009; Höök, 2009, EWG, 2007, 2006; Mohr and Evans, 2011; Mohr and Evans, 2009; Patzek and

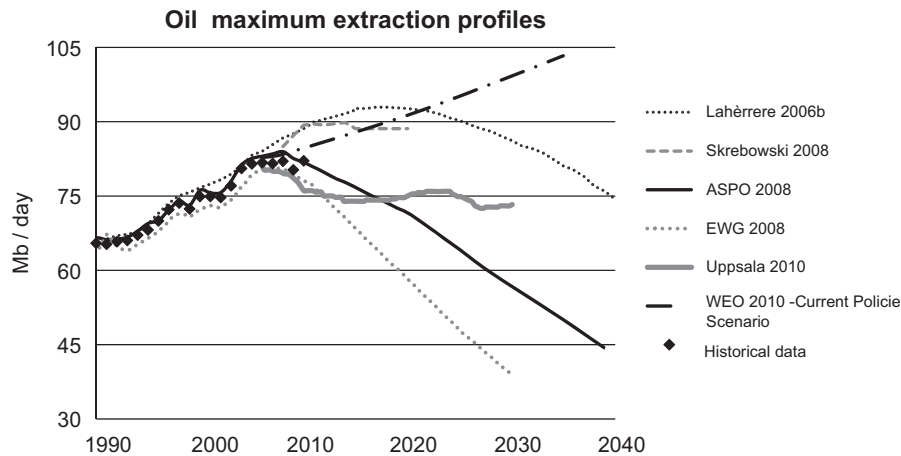


Fig. 2. Summary of curves of oil maximum extraction by different authors and historical data of extraction (source BP). Million barrels of oil per day.

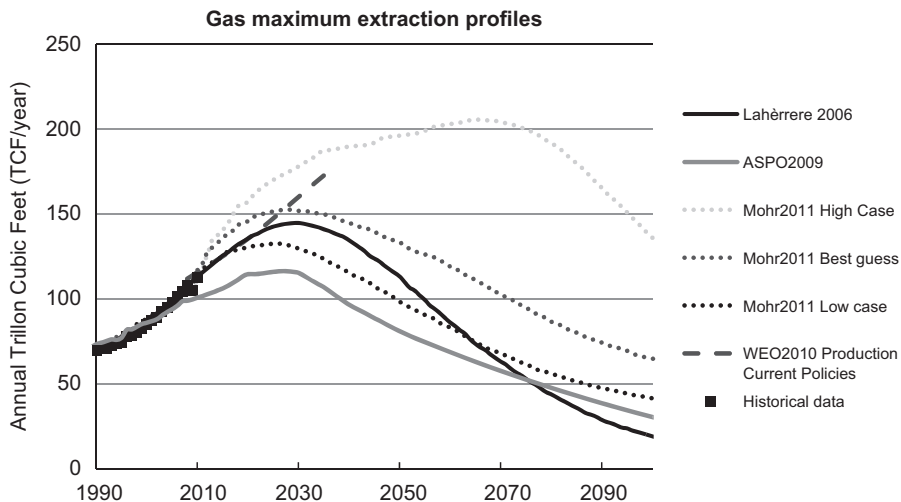


Fig. 3. Summary of curves of gas maximum extraction by different authors and historical data of extraction. Trillion cubic feet per year.

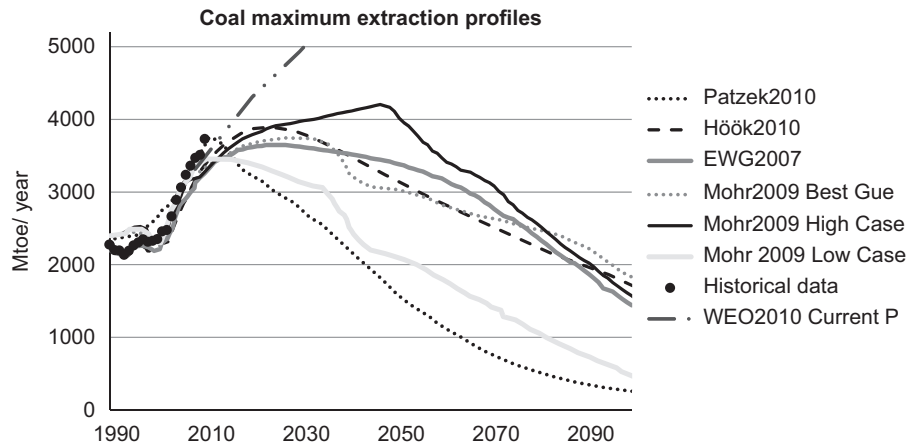


Fig. 4. Summary of curves of coal maximum extraction by different authors and historical data of extraction (source BP). Mtoe per year.

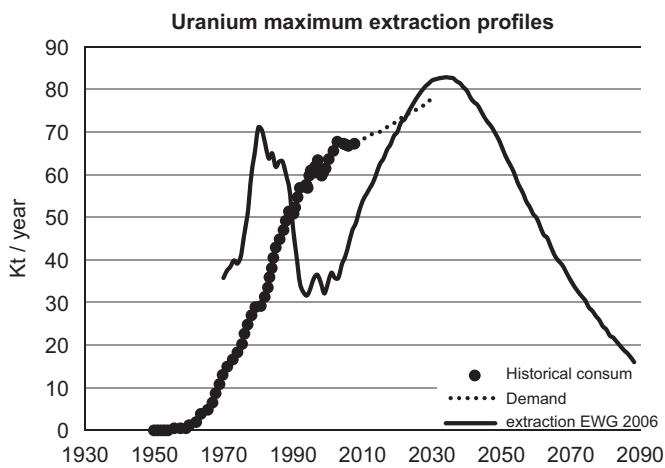


Fig. 5. Curves of maximum extraction of uranium (EWG), demand and historical extraction. The figure shows that part of the demand has been met with the uranium stocks extracted in previous decades. Thousand tonnes per year.

Croft, 2010; Lahèrre, 2006) provide production curves as a function of time, as in Figs. 2–5, based on estimating the annual decline in wells and mines and supposing that, while the limits are not reached, production will tend to increase due to demand.

To be able to use these data in our model we must transform them, since it is a dynamic model that considers demand. Production depends on this (if the world economy goes into crisis and does not demand gas, for example, it will not be produced). Production will therefore be the minimum between the demand and the maximum production. To do this, we have integrated the curves of maximum production as a function of time and we have converted them into maximum production curves as a function of resources (see Appendix A).

In this model, we are only going to study the resources that provide liquid fuels (oil), since over 90% of transport depends on them and they are used for electricity. Consequently we do not consider energy resources such as natural gas and oil for heating and industry (which will be studied in future models).

3.1. Oil

In Fig. 2 we can see a summary of different authors' predictions (ASPO, 2009; Skrebowski, 2010; WEO, 2010; Höök, 2009; EWG, 2008; Lahèrre, 2006) for oil production. It can be seen that ASPO (2009) and EWG (2008) estimate maximum production

curves (as a function of time) with a peak, whereas the estimation of the University of Uppsala (Höök, 2009) and the one in Skrebowski (2010) give curves in the form of a plateau (although they only give data until 2030). The estimate of Lahèrre (2006) is very high and much larger than the production data for the last five years (BP), which display quite a clear stagnation since 2005 (although the fall in demand due to the economic crisis does not appear until 2009).

We have not considered the estimates for future production given by the International Energy Agency in their “business as usual” scenarios (shown in Fig. 2 as WEO, 2010 Current Policies Scenario), as we believe these scenarios (which allocate a major role to not-found or not-developed crude) are unrealistic, as the group of Uppsala has criticised in Aleklett et al., 2010 (and as the historical data of the last five years appear to confirm). Instead, we believe that the estimation of the group of Uppsala, which is based on the Agency's own data but eliminates the discoveries incoherent with geological restrictions, is more accurate.

Out of all the estimates in these studies, we have chosen for the model those that seem most appropriate for each fuel. Therefore, for conventional and non-conventional oil we have taken as most accurate the estimates of ASPO (2009) and the group of Uppsala (Höök, 2009); the former estimates a decline of 2% from the present time and the latter a production plateau until 2030. In scenarios 4a and 4b “more oil” and “less coal” of Section 7.4 the estimates of Lahèrre (2006) have been taken too, although the historical data of the last five years appear to invalidate it. It should be remembered, however, that the exact data for oil production are difficult to compare between studies due to the different criteria that each author uses to define what is regarded as oil. Slight disparities between the real data and estimates (like those shown in Fig. 2) are therefore inevitable.

3.2. Non-renewable electricity

3.2.1. Natural gas

Fig. 3 shows the results of collecting estimates for natural gas (ASPO, 2009; Mohr and Evans, 2011; WEO, 2010; Lahèrre, 2006). In the graph for natural gas, it seems that ASPO's estimate is surpassed by historical data of production (probably due to it not being updated in recent years). Mohr and Evans (2011) offers a wide range between “low case” and “best guess”, while we have ruled out their “high case” as it is exaggeratedly higher than the other forecasts. Lahèrre's estimate falls between Mohr's two cases. We are going to take Lahèrre's estimate as the most appropriate, ruling out the ASPO (2009) estimate and considering an average between Mohr's two cases.

3.2.2. Coal

Fig. 4 shows the different estimates for coal production that have been collected from the literature (EWG, 2007; Patzek and Croft, 2010; Höök, 2009; Mohr and Evans, 2009). We took the coal estimation of Mohr and Evans (2009) “high case” because their work takes into account the nature of coal as a mined resource better than other studies. Other studies (Patzek and Croft, 2010; EWG, 2007; Höök, 2009) are based on logistic curves similar to the ones used for oil. The liquid nature of oil makes fast extraction in mature fields impossible, no matter how much infrastructure is used. Coal is a mineral and, therefore, more infrastructure and extraction effort can replace the low quality of the resource. If the maximum extraction is higher, this means that, with the same amount of resource, the curve goes up more and then goes to zero faster. The curve that best fits this is the one we choose: the “Mohr high case”. In addition, we choose this curve because the historical data seem to support our argument: we have already passed the maximum production that some studies established (EWG, 2007 and Mohr best guess). Therefore, the maximum extraction seems to be higher than the one set by other estimations. In any case in scenarios 4a and 4b “more oil” and “less coal” of Section 7.4 the estimates of Höök (2009) have been taken too.

Uranium: finally, Fig. 5 shows the uranium production curve that we have taken into consideration, which is the only study on uranium to be found in the literature, by Energy Watch Group (EWG, 2006). We do not believe that the technologies that claim they could increase the fisible material by 50–100 times, like fast breeders and the so-called fourth generation reactors, will be available during this decade (Celier, 2009). Therefore, they are not taken into account in this model. We also assume in our model that there are enough reactors to use all the available uranium, which may be a bit optimistic, since Schneider et al. (2009) conclude that the current trend of the buildup of new reactors is too low to even maintain present nuclear activity.

The estimates chosen for these three forms of fuel (coal, gas and uranium) have been aggregated into a single maximum production curve, depending on the reserves. This curve, which can be seen in Appendix A, shows the results in terms of usable electrical energy. To calculate this we have used the conversion of primary energy in EJ to electrical TWh, using present efficiencies: 0.33 for nuclear (IEA, 2009), 0.35 for coal (WEO, 2010) and 0.5 for gas (de Castro et al., 2009). In the case of natural gas and coal, we have ruled out the non-electrical uses of the fuels taking the data of past years’ consumption (IEO, 2010): 33% of the gas and 63% of the coal was used for electricity generation. In the model this proportion is maintained.

4. Oil substitution

As seen in the previous section, oil is the energy resource whose decline is nearest in time, and it is quite likely that we have already reached the peak of production. The data of oil production (BP, 2011) show an evident stagnation from 2004, as the historical data of Fig. 2, some years before the 2008 economic crisis lowered the energy demand. The effects of this reduction in the supply of oil on the world’s socioeconomic system will be framed by the importance of oil in the economy and by the difficulties in implementing adaptation or mitigation policies contributing to reducing the demand.

In the 1970s, after the oil crises, it was possible to considerably decrease the oil intensity of world’s economy. This was achieved in part by replacing the oil used to generate electricity with other forms of fuel, and this step cannot be taken now, as the amount of oil used to produce electricity is small at a global scale.

The most immediate technological substitutes for the consumption of oil in transport are biofuels and electric and hybrid

cars, as these are technologies that are already being utilised. Greater efficiency may also be expected, through improvements in the engines and the change to lighter vehicles. This is similar to the introduction of hybrid vehicles, as it simply represents a smaller consumption per vehicle. Cars using hydrogen, synthetic fuel, biogas and similar alternatives will not be introduced in the model as they are still in a developmental stage. Other ways of saving energy, such as railways and changes in mobility patterns require more profound social transformations and costly infrastructures and for the moment will not be included in our model.

4.1. Biofuels

Biofuels are the most immediate replacement for oil derivatives, but suffer from some serious disadvantages. Their energy return on energy investment (EROEI) has been widely researched and some studies say it is extremely low or even less than one (Field et al., 2007; Pimentel et al., 2009; Ballenilla, 2007; Papong et al., 2010). In addition, they occupy large areas of fertile land (estimated at between 35 and 110 Mha/Gb, FTF, 2011). However, if we take the hectares used to grow biofuels in 2008, according to UNEP (2009), 36 Mha, and the 0.305 Gb of oil equivalent produced, the real productivity today is 118 Mha/Gb, which is slightly more than the highest estimate. Although improvements might be expected with technological advances, the fact is that the present biofuels are grown on some of the planet’s best land, and the biophysical limits of photosynthesis mean that a drastic reduction in this occupation will be very hard or impossible to achieve.

A basic analysis of the data shows that, with this performance, biofuels cannot become a global alternative to oil. The replacement of all the oil currently consumed by biofuels with the present performances would require 3540 Mha of land, which represents 232% of all the currently available arable land on the planet. This is obviously not feasible. Even if we only aimed to substitute 60% of the oil, the one used for transport, we would need some 140% of the arable land.

The International Energy Agency proposes, in its 450 Scenario (WEO, 2010), an increase in the production of biofuels from 1.1 Mb/d in 2009 to 8.1 Mb/d in 2035 (from 0.433 Gb/yr to 3.18 Gb/yr). We take this figure as the maximum level in our “high policy” for biofuels.

For the biofuels “low policy”, we use Field et al., 2007’s estimate, which claims we can devote 386 Mha of marginal land to growing biofuels, with lower productivity than at present (due to the poorer quality of the land). This results in 27 EJ/yr of gross heat content as the limit of net plant production. Assuming that the efficiency of the conversion into liquid fuels is 0.2 (based on the data of Brazilian ethanol by Triana, 2011), and assuming that the EROEI rate is 6 (a value between the 2.63 and 8.86 of the Brazilian ethanol—Triana, 2011), the resulting energy in the form of liquid fuels would be 4.5 EJ/yr, which is 2.53 Gb/yr.

4.2. Electric vehicles

The introduction of electric and hybrid vehicles is another of the possible ways to replace oil. One of the most important limitations of electric cars is their low functionality, above all in terms of the capacity of accumulation of energy: 15 times less storage, according to FTF (2011), even taking into account the greater efficiency of electric motors and battery technology that can be expected in the next decade. Owing to this low accumulation capacity, only lighter vehicles are normally considered as candidates to be purely electrical, and even in those texts, where purely electric vehicles are considered for freight transport, such as IEA (2009), the goals are very low and are restricted to “light commercial and medium-duty freight-movement”. The consumption of light vehicles takes

up practically half the oil used for transport (IEA, 2009). This means that around 30% of the world oil consumption can be substituted by electric (or hybrid) cars.

Despite this, electric vehicles enjoy some positive aspects. Their consumption of electricity, for example, is acceptable. If we compare the energy needs of electric vehicles with petrol vehicles of equal weight and power, EABEV (2008) gives a relationship of 1:3 favourable to electric vehicles (tank to wheel). According to this ratio, the necessary electricity consumption is 530 TWh for each Gb of oil that is replaced (5.71 EJ/Gb).

Another limit that should be taken into account when studying electric cars is that of the materials needed for the batteries. The most promising batteries at the moment are lithium-ion batteries, and it is thought that each electric vehicle will need between 9 and 15 kg of lithium mineral per vehicle. Lithium reserves are estimated as being 4.1 Mt, although some authors claim that 11 Mt could be exploited (Hacker et al., 2009). Angerer (2009) estimates 6 Mt of global reserves and, according to his data, if lithium consumption for applications unrelated with electric vehicles continues to rise at the present rate, by 2050, 2 Mt of lithium will have been consumed. Assuming that this lithium will not be recycled, this would leave between 2 Mt and 9 Mt for electric vehicles, which could maintain a total of between 222 and 1200 million vehicles, assuming 9 kg lithium per vehicle (current fleet size is 800 million), which would be sustainable if the lithium in electric vehicles could be recycled at rates close to 100%.

This shows that a number of electric cars higher than the current number of light vehicles could be beyond the reach of this particular technology, although some 50–60% might be possible with serious recycling policies. Obviously, this is not an absolute limit to electric vehicles, since other types of batteries could be developed (maybe at the cost of lower efficiency), or lighter vehicles such as motorcycles could be opted for. In any case it is important to be conscious of the finite nature of valuable minerals like lithium and the need to implement strong recycling policies.

However, it should be borne in mind that electric technology finds it very difficult to replace heavy vehicles, and synthetic fuels, hydrogen vehicles or major changes in machinery and mobility will be needed in order to cover these needs.

In their IEA (2009) report, the International Energy Agency proposes a “Blue EV Success” scenario which foresees 57% electric cars, 37% hybrid vehicles and 5.7% internal combustion vehicles by 2050. We shall propose this scenario as the “high policy” for electric vehicles, as it is the most favourable from the point of view of the replacement of oil that has been proposed by the IEA. We place a limit of 900 million electric cars in circulation (lithium restriction) and suppose that hybrid vehicles consume 40% less than petrol cars (currently the figure is 30%).

We regard this policy as optimistic because electric cars are finding serious problems in entering the market due to their high price and low autonomy (Querol, 2012). We (arbitrarily) establish the “low policy” in half the number of electric cars (27%) by 2050, and the same proportion of hybrid vehicles as before.

5. The replacement of electric energy

The replacement of electricity generated with fossil fuels is possible through technologies that are already in use, and some of them are now mature technologies. In our model we have considered, on the one hand, that hydroelectric energy is a technology that is near to saturation and is only capable of a moderate growth (double output by 2050, as WEO, 2008 estimates); whereas the new forms of renewable energy (wind, solar photovoltaic and thermoelectric) are capable of greater growth (as they have been implemented less).

We have fixed the physical limit of the implementation of these forms of renewable energy at 2.7 TW of average power (not installed power), based on the studies in De Castro et al. (2011) and De Castro (2012). This limit is significantly lower than that of other authors, for example, Schindler and Zittel (2007) forecast 500 EJ/yr (16 TW) (for 2100), Greenpeace (2010) 273 EJ/yr (8.64 TW) in 2050, the IEA (IEO, 2010) forecast from renewables 125 EJ/yr (4 TW) in 2035, and Jacobson and Delucchi (2011) 360 EJ/yr (11.5 TW) electricity from renewables. De Castro's studies show that obtaining more than 3 TW of renewable electricity might be an extremely difficult and costly task that would require too much land, materials and capital, and it is likely that energy efficiency and saving will be considered before taking too much space and capital. In any case, this limit does not change the conclusions stated in this paper. We therefore decided to keep this limit low, because it makes the conclusions more evident: the oil peak and time restrictions (substitution rates, oil decline rate, etc.) are much more important in the short-medium term than the final limit of electric renewable energy.

We take a high estimated mean cost of the installation of new renewables, as we agree with Trainer (2012)'s approach, which points out that their intermittence increases the costs and also because, in the long run, prices might tend to grow because of the saturation of locations and the rising cost of minerals that can be expected after oil's decline. In Krewitt et al. (2009), it refers to the current cost of 1370 \$/KW for wind energy, 3480 \$/KW for off-shore wind and 6340 \$/KW for solar-thermal energy. We take a cost of 6000 \$/KW with 2000 h in use per year, and estimate that the new infrastructures needed to accumulate the energy means that the costs must be multiplied by four (Trainer, 2012). If we took a lower estimation for the cost of the renewable energy, such as 1370 \$/KW, the resulting cost would be divided by 3.5.

We also take into account the EROEI rate, as these new installations use energy to be built. We assume that all the energy comes from oil and liquid fuels, as this is the worst scenario (since oil is the scarcest source of energy). The EROEI rate we have taken is eight (Heinberg, 2009; Hall et al., 2009, for example, estimate higher EROEI rates, but without the energy to build additional storage infrastructures).

It is necessary to highlight that the data we are using for land occupation, cost, energy EROEI rate and physical limits of these technologies are among the lowest in the literature. We are therefore being much more pessimistic about the possibilities of these technologies than about electric vehicles and biofuels. Thus, the basic results of the model are more revealing, as will be seen in the next section.

The policies for the implementation of renewable energy that we have taken are simple. We take a percentage of fixed growth (8–10%) which is similar to that of recent years (BP, 2011). For simplicity, the growth of renewable energy is made independently of demand and shortfall, and we give priority to renewable forms of energy in consumption compared with non-renewable energy.

6. World economic growth and energy demand

Energy is such a vital element in the functioning of society that any restriction in the available amount can have significant socioeconomic effects. GDP is an aggregate indicator of the market value of goods and services produced and therefore, given the close relationship between energy consumption and economic activity, in our model we shall use GDP as a proxy variable for the level of economic activity and thus estimate the demand for energy.

One way of analysing the relationship between the economy and oil is through oil intensity (amount of oil consumed per unit

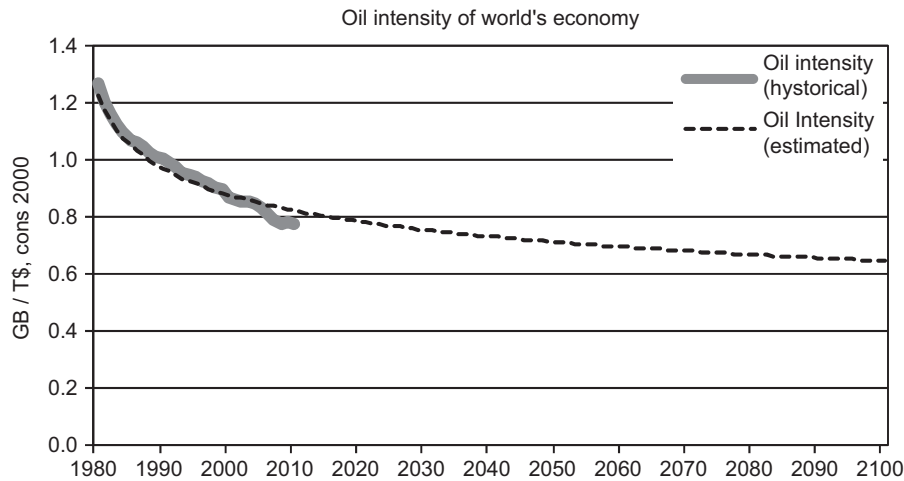


Fig. 6. Oil intensity of the world's economy, historical and estimated by Eq. (2). Gbarres of oil per T\$ (constant dollar 2000).

of GDP). In recent decades, the introduction of improved technologies and substitution with other energy sources has resulted in a reduction in the oil intensity of the economy (see Fig. 6). It is possible that this trend will continue in the future, although it is also foreseeable that it will become increasingly difficult to reduce it further.

In our model, the future demand for oil is determined by the interaction between the potential level of economic activity (exogenous in our model) and oil intensity in the economy. We suppose that world oil intensity has the form of a curve that decays exponentially with time. This means that over time, technological progress makes oil intensity in the economy decrease, but the reductions in energy intensity are increasingly small.

The equation for oil intensity in the economy would be determined as:

$$oil_intensity = a \times t^{-b} \quad (1)$$

where $oil_intensity$ is the intensity in the world economy in Gbarrels of oil per US trillion dollars GDP at constant 2000 prices; t is the time in years; a the initial value of the intensity; and b the intensity decay rate.

To estimate parameters a and b in Eq. (1) we have used the world GDP (World Bank data) at constant prices in T\$/yr (10^{12} \$/yr), and the world oil production in Gb/yr (BP, 2011). The equation for estimated energy intensity based on these data would be:

$$Intensity_{(oil/GDP)} = 1 \times 10^{-3} \times e^{[7.3698 - 0.1869 \ln(t - 1978)]} \quad (2)$$

In this model, the evolution in oil intensity in the economy depends only on time. It would be an improvement to refine the model so that other variables can be included, such as prices, which have not been taken into account, as it would make the model much more complex. The historical data for oil intensity in the economy, with the estimation of Eq. (2), can be seen in Fig. 6.

7. Scenarios and results

All the data explained in the previous sections have been introduced in the dynamic model. In addition, for after 2011, we should introduce the policies we have left as entries to be chosen by the user. These are:

- *Economic growth* (as a per cent of GDP, GDP expressed in T\$/yr constant 2000).
- *Introduction of electric and hybrid cars*. This is expressed in terms of the per cent of the cars in the fleet that are electric/

hybrid, and the Gb of oil they save. Notice that the number of electric cars depends on the total number of cars, which depends on the GDP, since the demand of oil for transportation is a fixed amount of the total oil demand (which is a function of GDP). The introduction of electric cars is linear in time and meets the final goals described in Section 3.2.

- *Maximum limit of biofuels* expressed in terms of Gb/yr of oil equivalent. Biofuels grow using present rates before the maximum is reached.
- *Rate of growth of renewable energy*. The installed potential of renewable electricity grows exponentially, a fixed per cent each year of the installed capacity in TW, while the hours of production per year are constant. We measure electricity in terms of the electric energy delivered per year, TWh/yr.

By varying these policies, we will create the different scenarios. The model will thus help us cast light on such issues as:

- Is it possible to continue with the economic growth and consumption patterns of recent decades, trusting in an adaptation of peak oil based on technological replacement?
- What economic growth will be possible if we do not change the oil–economy relationship, and what changes would we need to make to overcome peak oil?
- When will we encounter problems with the electric energy supplies?
- What limitations exist in the transition towards the generation of 100% renewable electricity?

7.1. Scenario 1: “Business as usual”

In the first place, we shall see how the model behaves if we attempt to continue with the economic growth of recent decades (2.9%) without any significant change of consumption patterns (energy intensity continues its downward trend) and with large investments in biofuels and electric vehicles.

In this scenario we suppose the “high policy” for biofuels and electric cars, whereas the growth of renewable electricity is 8%. We use two estimates for oil: by ASPO (ASPO, 2009) decline, and Uppsala (Höök, 2009) plateau until 2030, and give priority to renewable energy over non-renewable in the generation of electricity.

The results in Graphs 7, 8 and 9 clearly show that *this scenario is impossible* as the demand for oil is much greater than the supply. In Fig. 7, we can see the oil demand, the oil maximum extraction according to the estimates of ASPO and Uppsala and

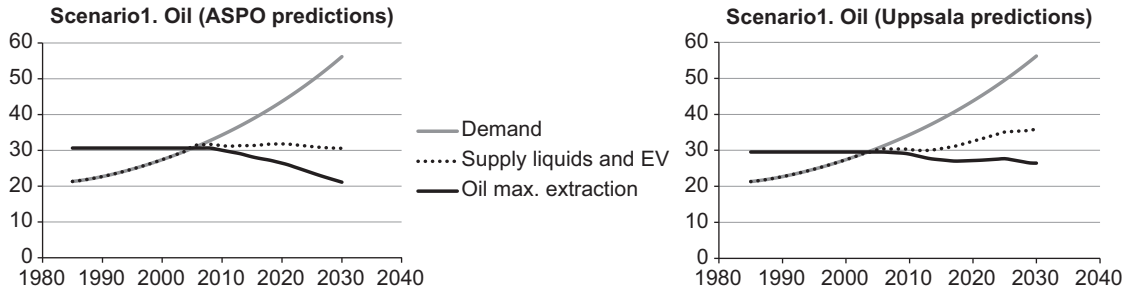


Fig. 7. Scenario 1, “business as usual”. Oil. The economic growth and the oil intensity trend of past decades continue. Electric car and biofuels with high policies. Demand is the oil demand as driven by GDP growth, Offer liquids and EV is the offer of oil plus biofuels plus oil saved by electric and hybrid cars, Oil max extraction is the oil extraction estimated by ASPO or Uppsala. All data in units of Gbarrels of oil equivalent per year.

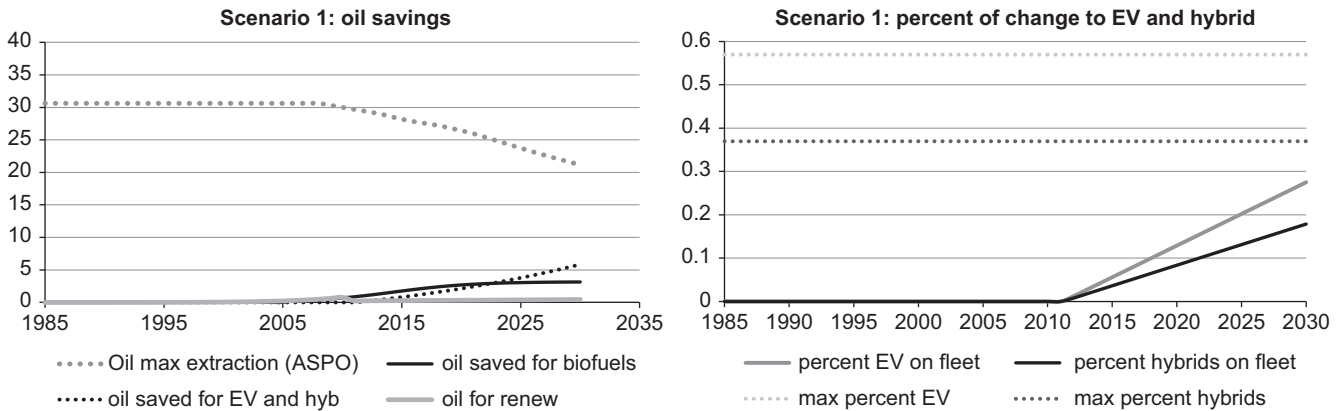


Fig. 8. Scenario 1, “business as usual”. Oil savings. Left: oil saved by electric vehicle and biofuels (high policies) as compared to oil maximum extraction (ASPO). Oil for renew is the oil necessary to build the infrastructures for renewable electricity. Right: per cent of electrical and hybrid vehicles in the fleet (percents expressed from 0 to 1).

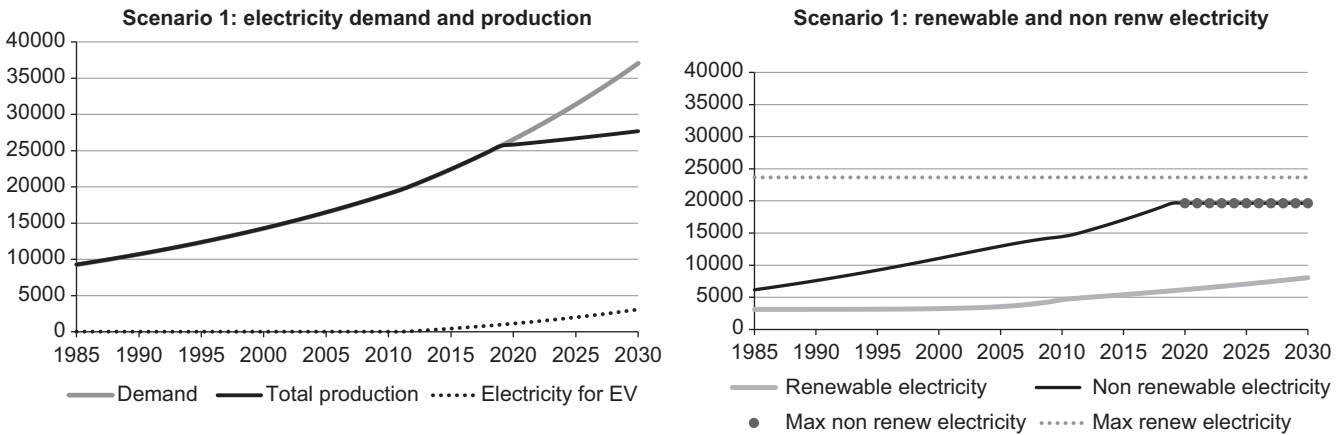


Fig. 9. Scenario 1: “business as usual”. Electricity. The economic growth and the oil intensity trend of past decades continue. Electric cars and biofuels with high policies. Moderate growth of renewable electricity (8%). Left: demand and total production of electricity (renewable and non-renewable). Electricity for EV is the demand of the electric vehicles (this is also included in the curve of demand). Right: production of renewable and non-renewable electricity. Non-renewable electricity reaches its maximum extraction plateau by 2020. Max non-renew electricity is the curve of maximum extraction that combines gas, coal and uranium peaks. All data in TWh/yr.

the total amount of oil equivalent that can be obtained with biofuels and the saving of electric and hybrid cars (considering the oil not spent as fuel added to the line liquids and EV+hyb). Fig. 7 shows that, even with all these substitutes, the offer is much lower than the demand. According to the estimates for peak oil we have used, and using the most optimistic policies for biofuels and electric vehicles, supply cannot meet demand with the economic growth and consumption patterns of the last few decades.

In Fig. 8 (left), the amounts of oil saved can be seen in more detail. The oil saved by biofuels soon stagnates (reaches the

maximum), while that of the electric car still grows. In Fig. 8 (right), the per cent of electrical and hybrid vehicles in the fleet is shown, by 2030 their introduction is half way to the objective of the policies (set for 2050).

Electricity generation does not exhibit such immediate limitations. In Fig. 9 (left), the demand of electricity and the offer (production) can be seen. They meet until approximately 2020. In Fig. 9 (right), the electricity production is separated into renewable and non-renewable. The non-renewable electricity grows until 2020, when it finds the limits of the combined peak of gas, coal and uranium and becomes stagnated (ends up being a plateau, instead of

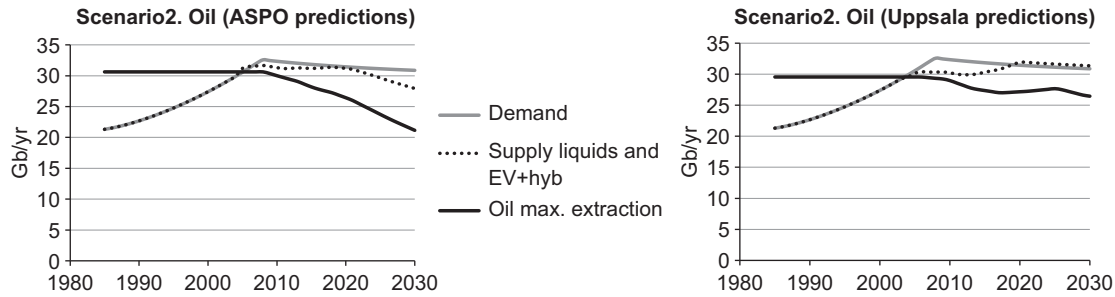


Fig. 10. Scenario 2, “high estimates”. Oil. The economic growth is set to 0.2% and the oil intensity trend of past decades continue. Electric car and biofuels with high policies. Demand is the oil demand as driven by GDP growth, Offer liquids and EV is the offer of oil plus biofuels plus oil saved by electric and hybrid cars, Oil max extraction is the oil extraction estimated by ASPO or Uppsala. All data in units of Gbarrels of oil equivalent per year.

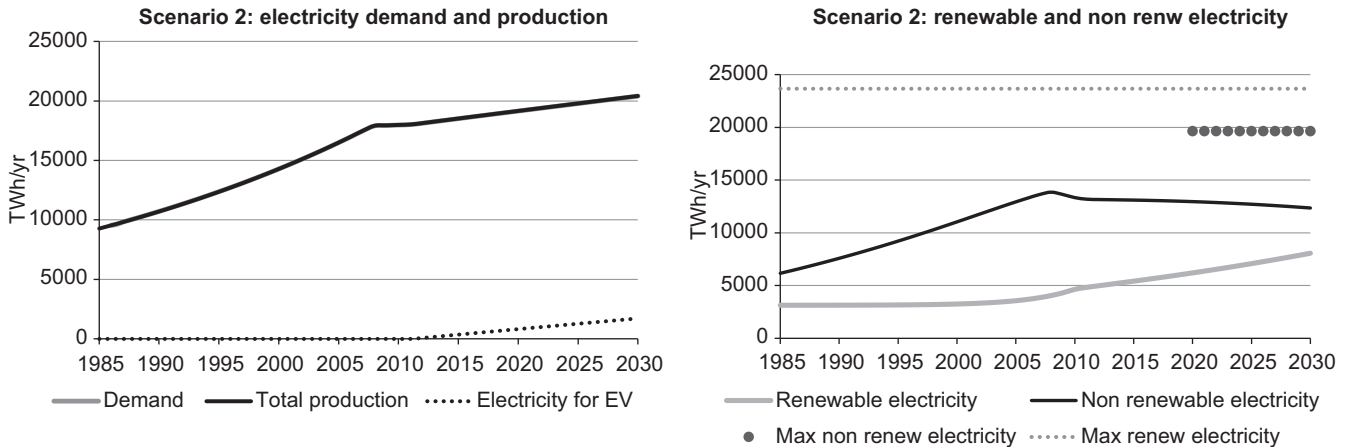


Fig. 11. Scenario 2: “high estimates”. Electricity. The economic growth is set to 0.2% and the oil intensity trend of past decades continues. Electric cars and biofuels with high policies. Moderate growth of renewable electricity (8%). Left: demand and total production of electricity (renewable and non-renewable). Electricity for EV is the demand of the electric vehicles (this is also included in the curve of demand). Right: production of renewable and non-renewable electricity. Non-renewable electricity reaches its maximum extraction plateau by 2020. Max non-renew electricity is the curve of maximum extraction that combines gas, coal and uranium peaks. All data in TWh/yr.

a sharp peak). After 2020, the growth of renewable electricity (8% in this scenario) is not big enough to compensate for the growing demand and the stagnation of the non-renewable electricity. In Fig. 9 (left), the electricity demanded from the electric cars is shown (although the demand of electricity shown in this figure is the total electricity demand, including the electric car). Electric vehicles represent an important (but not huge) increase in the consumption of electricity.

In this scenario, the investment in renewable energy reaches 0.14% of the GDP in 2030 (110 G\$/yr) and the energy invested in new renewable installed capacity, derived from its EROEI rate, is shown in Fig. 8, left (oil for renew). This figure shows that the energy cost of building renewable energy power stations is small compared to the global consumption.

The conclusion of this first scenario is clear: if the estimates for the decline in resources that we have used are correct and energy intensity does not decrease much more steeply than it has been doing, it will not be possible to continue with the economic growth of previous decades. In present and coming decades, some very significant savings in oil would be needed, much greater than the technical substitution we have proposed.

7.2. Scenario 2: High estimates

We shall now see how the model behaves with economic growth capable of adjusting oil supply and demand, using the highest policies. To achieve this, in the second scenario, we have fixed economic growth at 0.2%.

We have supposed a high policy for biofuels and electric vehicles, and fixed growth (8% annually) for renewable energy, and shall use two estimates for oil: ASPO and Uppsala.

In Fig. 10 it can be seen that, by fixing economic growth at 0.2%, the curves of demand and offer of all liquids coincide for some years. Using the data of ASPO (left), they stay together approximately until the oil decline gets more severe around 2020. Using the curve of Uppsala, there are some years of deficit, but offer meets demand around 2020.

It should be noted that the curve of liquids and EV of this scenario (Fig. 10) gets a much lower value than the equivalent curve of scenario 1 (Fig. 7), since the policies of electric and hybrid vehicles are set as a per cent of the total amount of cars and, if the economic growth is smaller, the demand for transportation and the number of electric cars is smaller too. We think this makes sense, since the growth of the economy drives the sales of new cars and, in any case, the policies of the IEA that we take as reference are set as a per cent of the transportation demand (which is proportional to the total demand).

The perspectives for electrical energy can be seen in Fig. 11. Both renewable and non-renewable electricity grow at a moderate rate and there are no supply problems, most of the growth of the demand of electricity is due to the electric vehicle. In fact, the growth of the demand is so slow that, in this scenario, even if the investment in renewable energy stops suddenly, difficulties in meeting demand would not arise before 2100 (not shown in the figures). On the other hand, as economic growth is lower than in Scenario 1, the investment in renewable energy reaches 0.26% of world GDP in 2030 (110 G\$/yr).

In Fig. 11 (right), the curve of non-renewable electricity goes down after 2011 since, in our model, we give preference to the renewable electricity generation over the non-renewable (for simplicity) and, in this scenario, there is no need to increase non-renewable electricity (although it might not be very realistic to assume that, in a economic crisis, humankind would decide not to burn the remaining coal and gas and invest in renewables).

This scenario tells us that, even with optimistic replacement policies and economic growth near to stagnation, it will be difficult to meet the demand for oil. If ASPO is right, and oil production is going to peak and not reach a plateau, even very high policies of biofuels and electric cars will only be able to postpone the problem.

In this scenario, by 2030, the oil replaced by electric cars and biofuels is similar (3.2 Gb/yr), but if we calculate the hectares occupied by biofuels, the result is 371 Mha, compared with the 7.6 Mha needed to generate the electricity for electric cars using solar photovoltaic energy. *Biofuels occupy almost 50 times more land than electric vehicles fed with solar power, and not just any land, but fertile farmland.*

7.3. Escenario scenario 3: Low estimates

We shall now see how the model behaves with low policies for electric vehicles and biofuels, while renewable energy follows a higher growth rate (10%). We seek economic growth that can match oil supply and demand, and we have had to fix negative economic growth (approximately -0.5%). With this degrowth, Fig. 12 shows that, after a few years of transition, in which the demand is higher than the supply (because in the last four years oil production has

stagnated and we have abandoned the trends of previous decades), supply and demand match up approximately. *This scenario shows that it is possible that the world economy will have to suffer a severe decline if we are not capable of overcoming peak oil.*

The perspectives for electricity can be seen in Fig. 13, where we have prolonged the time scale until 2050. It shows that in this scenario, in which the demand for electricity decreases significantly and is less than the present consumption in 2050, an annual growth of 10% in renewable energy is sufficient to cover all the electricity demand in 2050. In this scenario, the non-renewable electricity decreases since we gave preference to the renewable one in our model.

Investment in renewable energy would, in this case, reach a maximum of 271 G\$/yr by 2050 (0.84% of GDP) and 180 G\$/yr in 2030 (0.5% of GDP), and a total accumulated in 40 years of 7070 G\$. If we assume the low cost of renewable infrastructures (as described in Section 5), these numbers would be: 77 G\$/yr by 2050 (0.24% of GDP) and 51 G\$/yr in 2030 (0.14% of GDP). In any case, a detailed economic analysis would be necessary to conclude whether these costs are a heavy burden on the world's economy, which is beyond the objectives of this study.

7.4. Scenarios 4a and 4b: "Less coal" and "more oil"

Previous scenarios have been done with the extraction curves for oil, coal, gas and uranium elected in Section 3, which were based on a relatively low estimate for oil (rejecting high curves such as Lahèrre, 2006) and a high estimate for coal (electing Mohr and Evans, 2009 high case). The results of our simulations

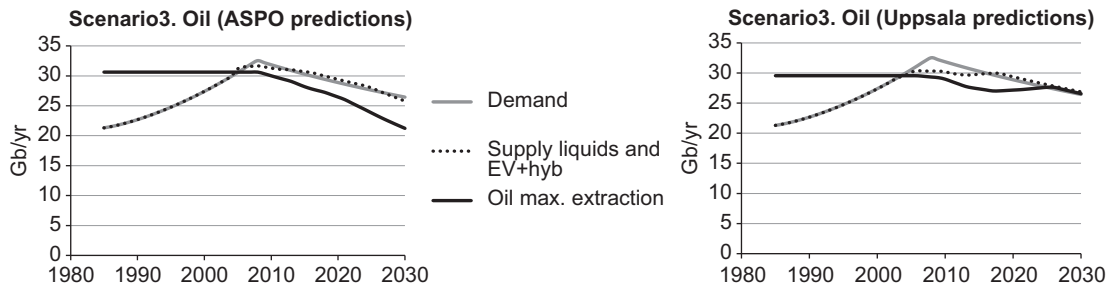


Fig. 12. Scenario 3, "low estimates". Oil. The economic growth is set to -0.5% and the oil intensity trend of past decades continues. Electric car and biofuels with high policies. Demand is the oil demand as driven by GDP growth, Offer liquids and EV is the offer of oil plus biofuels plus oil saved by electric and hybrid cars, Oil max extraction is the oil extraction estimated by ASPO or Uppsala. All data in units of Gbarrels of oil equivalent per year.

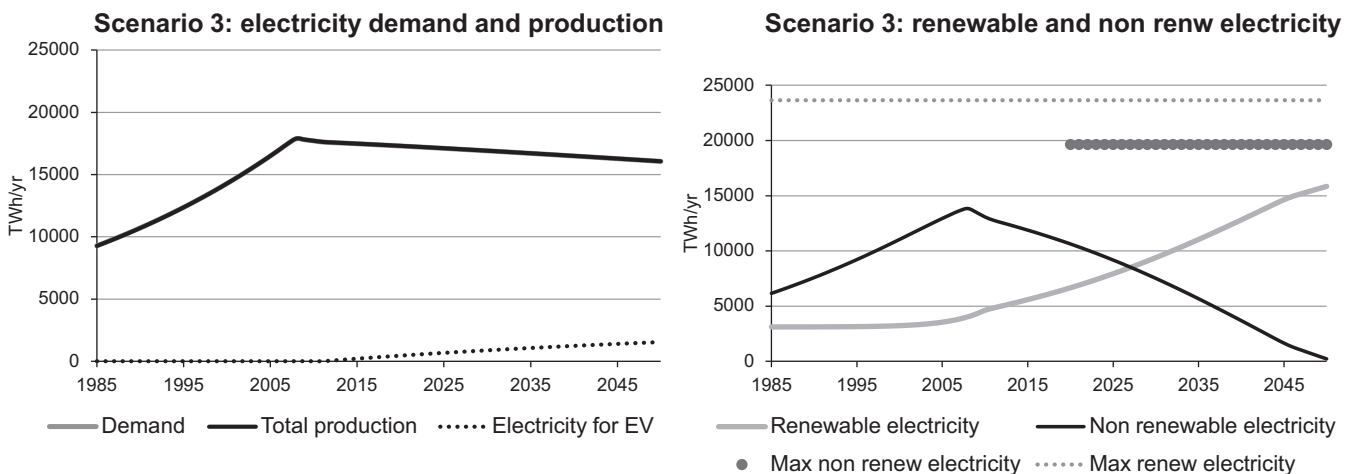


Fig. 13. Scenario 3: "low estimates". Electricity. The economic growth is set to -0.5% and the oil intensity trend of past decades continues. Electric cars and biofuels with low policies. High growth of renewable electricity (10%). Left: demand and total production of electricity (renewable and non-renewable). Electricity for EV is the demand of the electric vehicles (this is also included in the curve of demand). Right: production of renewable and non-renewable electricity. Non-renewable electricity reaches its maximum extraction plateau by 2020. Max non-renew electricity is the curve of maximum extraction that combines gas, coal and uranium peaks. All data in TWh/yr.

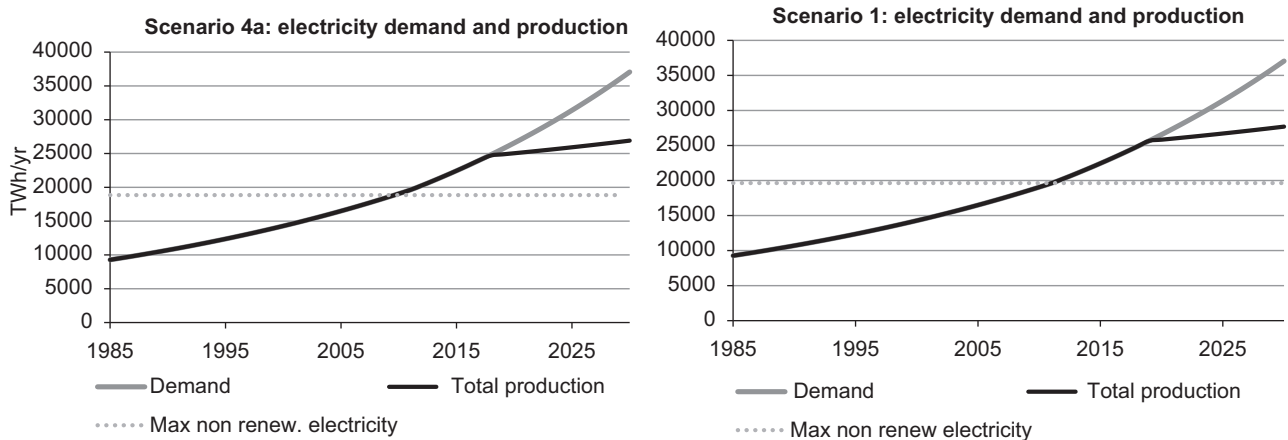


Fig. 14. Scenario 4a, “less coal”. Electricity. Demand and total production of electricity (renewable and non-renewable). The economic growth is set to 2.9% (“business as usual”), high policies for biofuels and electric vehicles, growth of renewable energies is set to 8%. Right: scenario 4a (with low estimates for coal); left: scenario 1 (with high estimates for coal). All data in TWh/yr.

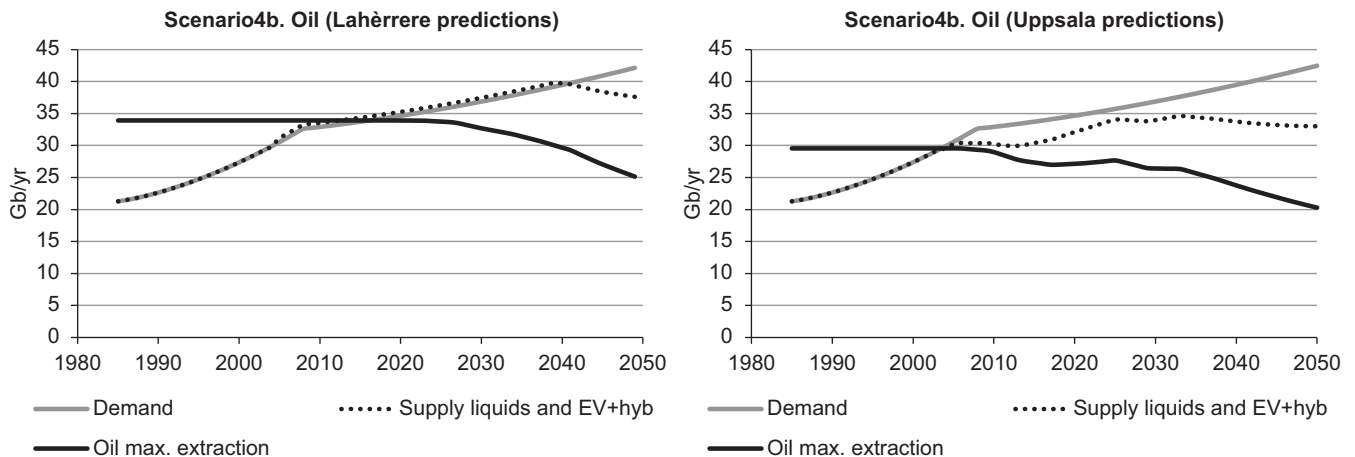


Fig. 15. Scenario 4b, “more oil”. The economic growth is set to 1% and the oil intensity trend of past decades continues. The oil prediction is set to the highest estimate, that of Lahèrre (2006), in the left; and that of Uppsala's in the right. Electric car and biofuels with high policies. Demand is the oil demand as driven by GDP growth, Supply liquids and EV is the supply of oil plus biofuels and oil saved by electric and hybrid cars. All data in units of Gbarrels of oil equivalent per year.

conclude that oil is going to be an important restriction while electricity is a lot less important. Both conclusions might change if we elect a less restrictive curve for oil and a more restrictive curve for coal. In this section we check these two cases.

7.4.1. Scenario 4a: “Less coal”

This scenario is based on a lower estimate for coal, the one of Höök (2009). The estimates for gas and uranium remain unchanged (as elected in Section 3) and we use ASPO estimates for oil. We assume a “business as usual” economic growth (2.9%), high policies for biofuels and electric vehicles and 8% growth of renewable electricity. The results of the electricity overview can be seen in Fig. 14 (the oil results are equal to those of scenario 1) and they are compared with the equivalent results of scenario 1. Fig. 14 shows that the difference between those two runs is very small. Choosing the lower estimation for coal does not change the main results of our model.

7.4.2. Scenario 4b: “More oil”

This scenario is based on a high estimate for oil, that of Lahèrre (2006) (the highest found in literature), while the estimates for gas, coal and uranium remain unchanged (as elected in Section 3). We use high policies for biofuels and electric vehicles and 8% growth of renewable electricity and find the economic growth that adjusts oil supply and demand, which ends up being 1%.

The results of the oil overview can be seen in Fig. 15 and they are compared with the results of the same scenario but using Uppsala estimates for oil.

In Fig. 15 one can see that, using Lahèrre's estimates and an economic growth of 1%, the production and the demand meet until almost 2040. This indicates that the election of Lahèrre's estimate does change substantially the results of our model. The high economic growth of past decades cannot continue if the energy–GDP relationship does not change abruptly, as in previous scenarios, but an important economic growth is possible (1%), clearly different from the stagnation of scenario 2.

The main difference between ASPO's and Lahèrre's predictions is in the amount of non-conventional oil that can be extracted, and it is well known that most unconventional oil has got very important ecological impacts. Scenario 4b, therefore, might envision a future where economic growth is still possible with the same energy–oil evolution of past decades at the cost of high ecological damage.

8. Discussion on the model

All models are a simplification of reality and this one, which attempts to give an overall perspective of energy, logically includes some very significant simplifications.

The model is intended to study whether or not a short-term reaction is possible in the face of the exhaustion of fossil fuels, and it has therefore focused on the best policies and technologies available at the moment. However, to study the energy transition in greater detail, it would be necessary to analyse all kinds of mid-term and even long-term policies. Among these, as the most immediate technologies, we could highlight the use of natural gas in transport, biogas produced from waste, substitution of fuels for heating and savings and efficiency policies.

This model does not study in depth many policies involving the electrification of energy consumption that currently depends on oil. As a result, in our model, the consumption of electric energy does not increase significantly. With the decline in oil, it is foreseeable that the consumption of electric energy will rise more than we have estimated, which would change some of the model's results significantly (but not others). If the demand for electricity increases, the peak of non-renewable electricity would be reached earlier and the role of renewable energy would be much more relevant. It would also be preferable to include the variability and storage problem of renewable energy in the model.

In this study, we have simplified the world economy greatly, only using an aggregated function of energy intensity. A regional or sectorial-based study would have advantages, as it is possible that growth will be unequal, and some countries and regions will still be capable of economic growth while others do not, and the result might be a net GDP global growth of those less oil-dependant economies. The oil-GDP relationship might also change abruptly

and we might see higher economic growth than the one predicted in these scenarios while oil declines, but predicting such social and economical changes is beyond the reach of this paper. This paper only states that the trends of previous decades cannot continue if only the proposed technological changes are taken. It would also be interesting to introduce feedback between energy and the economy in future studies, as this is a very sensitive aspect of the model and deserves to be studied carefully.

The model is not intended to make long-term predictions, but there is one fact that can be observed with a longer perspective: between 2020 and 2100, there will be a period when fossil energy resources are still being used while renewable energy infrastructures are being developed to a greater or lesser extent. This may cause the demand for energy to grow above the possibilities of the generation of renewable energy, which would lead to another situation of shortfall and a possible collapse when the peak of all forms of fossil energy occurs. The world should plan for this transition by attempting to adapt to the limits of energy the Earth can provide in a sustainable way.

9. Conclusions

The model presented in this paper is based on a simple dynamic model which is able to take some of the relevant data for world energy and study their evolution together. Despite its simplicity, it enables some quite clear conclusions to be drawn.

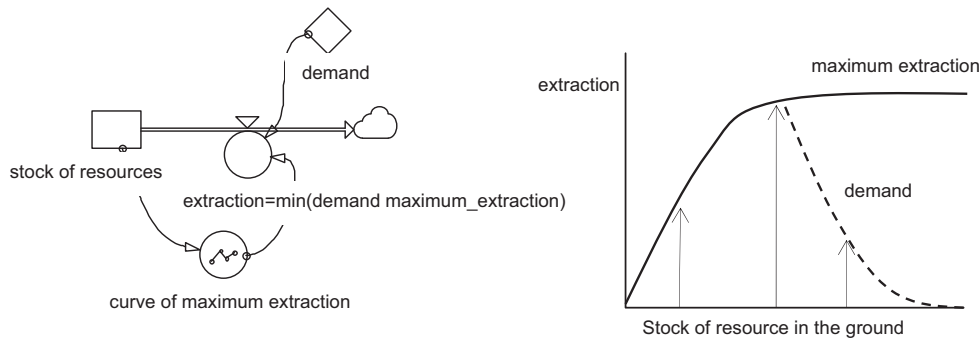


Fig. A1. Maximum extraction curves as a function of resources. Left: the systems dynamics model used to model extraction. Right: a curve of maximum extraction (solid) compared with the demand (dashed). Both curves meet when the peak of the resource is found.

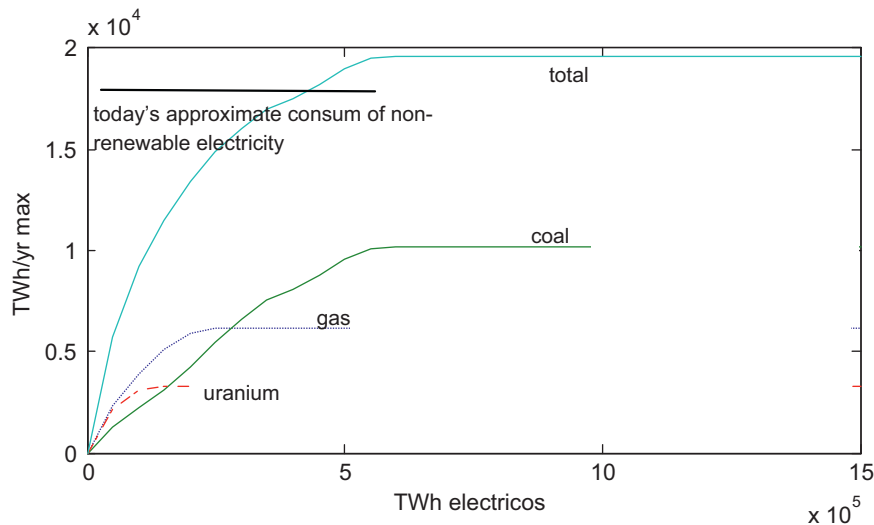


Fig. A2. Curves of maximum extraction for all the non-renewable resources for electricity. The x axis represents the stock of resource left in terms of the useful final electrical energy, the y axis represents the maximum extraction.

The main conclusion reached is that, according to the experts' estimates that have been used, peak oil will be the first restriction we shall have to face and it will not be easy to overcome it with the technology currently available. Neither biofuels nor renewable energy and electric cars offer satisfactory solutions on a large

scale and in the short term, to maintain the present trend in energy consumption and economic growth.

For this reason, the patterns of economic growth and decrease in energy intensity in previous decades cannot be maintained. If the hypotheses of "low policies" and the predictions about energy

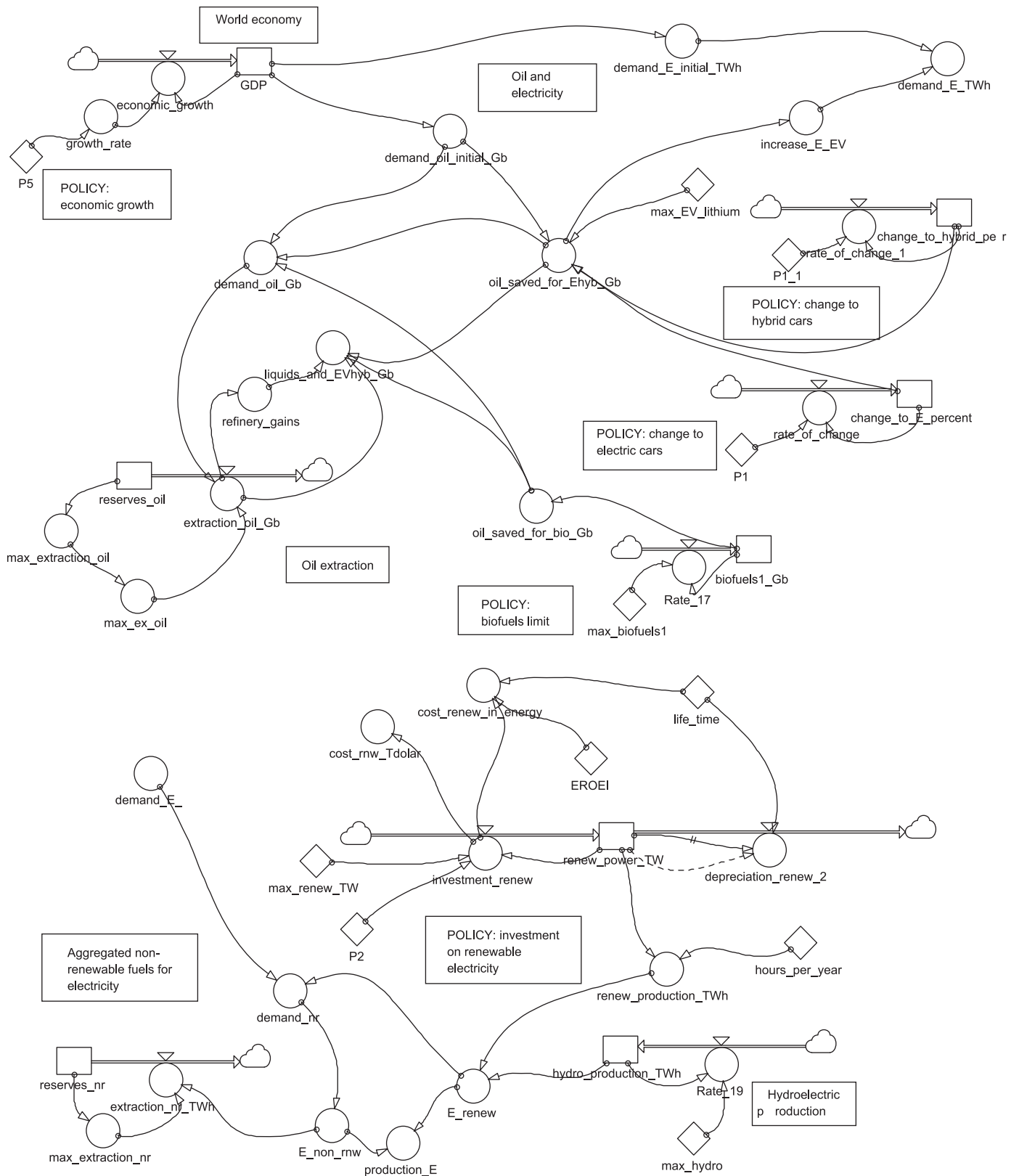


Fig. A3. Forrester diagram of the model with the most significant stocks and variables.

resources made by the most pessimistic experts are true, we might face continuous economic recessions. Overcoming the fall in oil production requires much greater changes in energy intensity than those achieved in recent decades.

Electric cars could be a partial solution to attenuate oil dependency, but are limited by the low performance. Biofuels are a much worse alternative, as the occupation of land is up to 50 times greater than the equivalent land needed by an electric vehicle powered with solar energy. As biofuels need fertile land, their large-scale use would result in competition for land with world food production.

In any case, our results show that the main problem related to peak oil is the rate of substitution. Peak oil is expected in this decade and even the most optimistic prospects of the international agencies related to electric vehicles and biofuels are not sufficient to substitute oil declines. Overcoming peak oil will probably need more structural changes: infrastructures for public transport, a change in the agrarian model, changes in production and consumption patterns, energy-saving policies, and so on. These are all policies involving very significant economic and social changes.

The replacement of electric energy produced from fossil and nuclear fuels with renewable energy seems easier, as the peaks of natural gas and coal are not so imminent and the technologies for renewable energy have been tried and tested. If world economic growth slows down because of peak oil and therefore the demand for electricity also falls, a moderate growth in renewable energy will be able to cover much of the demand and will help to reduce the emission of greenhouse gases.

The model is only intended to be an aid to understanding the feasibility of alternatives that may be able to adjust energy supply and demand on a world level, based on the experience of previous decades and the available information about resources and technologies. The model does not and cannot predict the energy or economic future because many aspects have not been taken into account. A much more complex model would be needed to study national energy policies and their interaction at a world level.

However, the model is complex enough to show that there are reasons to believe we are coming up against the first of the limits to growth (Meadows et al., 1972). This should make us face the problem of structural unsustainability of our society without falling into the temptation of applying quick fixes like the ones studied in this model, as they are far from being real solutions to the problems.

Acknowledgements

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Appendix A. Integration of resource curves

The maximum energy resource extraction curves as a function of time have been transformed into maximum production curves as a function of resources.

In these curves, as long as the resources are large, extraction will not be limited physically and we make it equal to the total maximum production. When the resources diminish, physical limits start to appear and production is reduced. In this way, the model uses a stock of resources (based on the URR taken by each author) and it studies how this stock is emptied depending on production, which is in turn determined by demand and

maximum extraction. Fig. A1 gives a hypothetical example of the dynamic model used and a production curve.

Fig. A2 shows the maximum extraction curve used in the model for all the non-renewable fuels involved in electricity generation. This curve gives the results in terms of usable electrical energy in annual electric TWh. The x-axis represents the stock of non-renewable electric energy available, according to the estimated resources of fossil and nuclear fuels and the equivalent electric energy these would provide. The y-axis represents the maximum extraction of this energy that could be obtained depending on the stock of the resource that was still unexploited. As can be seen, when the resources diminish, the maximum extraction decreases until it reaches zero when the resource is exhausted.

Appendix B. Simplified model

See Fig. A3.

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