Fossil fuel depletion and socio-economic scenarios: an integrated approach

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Abstract

The progressive reduction of high-quality-easy-to-extract energy is a widely recognized and already ongoing process. Although depletion studies for individual fuels are relatively abundant, few of them offer a global perspective of all energy sources and their potential future developments, and even fewer include the demand of the socio-economic system.

This paper presents an Economy-Energy-Environment model based on System Dynamics which integrates all those aspects: the physical restrictions (with peak estimations for oil, gas, coal and uranium), the techno-sustainable potential of renewable energy estimated by a novel top-down methodology, the socio-economic energy demands, the development of alternative technologies and the net CO2 emissions.

We confront our model with the basic assumptions of previous Global Environmental Assessment (GEA) studies. The results show that demand-driven evolution, as performed in the past, might be unfeasible: strong energy-supply scarcity is found in the next two decades, especially in the transportation sector before 2020. Electricity generation is unable to fulfill its demand in 2025-2040, and a large expansion of electric renewable energies move us close to their limits. In order to find achievable scenarios, we are obliged to set hypotheses which are hardly used in GEA scenarios, such as zero or negative economic growth.

Key-words: Renewable limits; Fossil fuel depletion; Global Warming; System dynamics; Peak oil; Global Environmental Assessment.

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[1] The opinions expressed in this paper are the authors' own opinions and do not necessarily correspond with those of the Low Carbon Programme.

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1. Introduction

In recent years, concerns about the depletion of energy and materials (e.g. peak oil), as well as limits to the ecosystem's assimilation capacity of residues (e.g. climatic change) have been raised in the social, political and business arena. All fossil fuels and minerals are finite and non-renewable on a human scale. These resources are thus limited physically and, more stringently, economically. However, different views about this phenomenon exist in the scientific discussion, opposing "geologists" (or pessimists) vs. "conventional economists" (or optimists). The first (Hubbert, 1956) argue that geological factors determine a peak in the extraction of each resource that technology can only slightly modify -see for example (Campbell and Laherrère, 1998; Laherrère, 2006; Sorrell et al., 2009) and the activity of ASPO in http://www.peakoil.net- and point out that these restrictions might have strong economic consequences (Brown et al., 2011; Hamilton, 2009; Hirsch, 2008; Murphy and Hall, 2011; Tverberg, 2012). However, the "conventional economists", applying the basis of neoclassical growth theory (Solow, 1974), claim that market mechanisms and human ingenuity will be able to both transform resources into reserves and find alternative energy sources to replace the scarce ones at a sufficient pace to avoid supply restrictions, and thus, not affect GDP growth (Adelman, 1990; Maugeri, 2012; Odell, 2004; Simon, 1996; Thielemann, 2012). This paper intends to shed light on this discussion by using a System Dynamics (SD) model that includes both the physical data of the energy resources and the economic data.

The fact that the peak of conventional oil has already occurred has been largely admitted in Academia (e.g. (Murray and King, 2012)) as well as by international institutional agencies -together with the acknowledgment of peak oil basic theory as an appropriate methodology - (Benes et al., 2012; WEC, 2010; WEO, 2012, 2010), representing government declarations (e.g. the European Energy Commissioner[2] in 2009) and even from some oil companies (Mosconi, 2008). In 2012, the ratio of oil in the global energy consumption mix fell to its minimum value in the last 50 years (BP, 2013). Annual oil discoveries peaked in the 60s and no oil price rise since then could invert or stop the tendency of declining discoveries thereafter.

[2] Original post deleted. A transcription can be found in < http://europe.theoildrum.com/node/5397 >.

Due to the close relation between natural gas and oil, the geological understanding of their deposits and depletion is very similar. Conventional wisdom has it that global coal and uranium reserves are ample and supply restrictions due to scarcity must not be expected within the next several decades or even this century, but this is disputed by several studies (Dittmar, 2013; EWG, 2007; Heinberg and Fridley, 2010; Mohr and Evans, 2009; Rutledge, 2011).

Consequently, renewable energy, and particularly solar and wind energy, are the two main sources of renewable energy which might substitute the decline in fossil fuel extraction (Smil, 2010). However, recent studies of their limits show that their potentials might be even lower than the current final consumption of energy by means of fossil fuels (de Castro et al., 2013a, 2013b, 2011). Thus, if a long-term structural scarcity in energy supplies in the next few years and/or decades occurs, as suggested in the past (e.g. Reports from the *Club of Rome* (Meadows et al., 1993, 1972), *Global 2000* (Barney, 1980), (de Castro, 2009; Maggio and Cacciola, 2012; Nel and Cooper, 2009; Valero and Valero, 2010)), this situation would be unprecedented in modern history. Moreover, the study of previous technological transitions shows that they are slow, in the order of decades (Fouquet, 2010).

On the other hand, energy consumption acts as a climatic change driver (IPCC, 2007a). But few studies have focused on the effect of energy constraints in climate scenarios, e.g. (Brecha, 2008; Höök and Tang, 2013; Ward et al., 2012)).

While depletion estimation for individual fuels following different approaches are relatively abundant (see (Maggio and Cacciola, 2012; Mediavilla et al., 2013) for an overview), few studies have centered on the objective of giving a comprehensive study, including estimates for all fossil fuels: (Aleklett, 2007; EWG, 2013; Laherrère, 2006; Maggio and Cacciola, 2012; Mohr, 2012; Valero and Valero, 2010) and even fewer have analyzed the whole system and fuel interactions (de Castro, 2009; Nel and Cooper, 2009; Zerta et al., 2008), as we propose with our WoLiM model.

This paper intends to shed light on these issues by describing and showing the results of the model we have developed, *WoLiM* (World Limit Model), which is a continuation of previous System Dynamic models developed (De Castro, 2009; Mediavilla et al., 2013). WoLiM is a structurally-simple and transparent model that compares data from many different sources and helps to view global panoramas. The SD approach allows the combination of different kinds of variables from different knowledge sources, such as socio-economic, geological and technological, so they can be managed and integrated. The model includes the exhaustion patterns of non-renewable resources and their replacement by alternative energies, the estimations of the development and market penetration of alternative technologies, the energy demand of the World's economy under different socio-economic scenarios, the sustainable potential of renewable energies, and the estimations of CO_2 emissions related to fossil fuel consumption, all of them viewed in a dynamic framework.

On the other hand, scenario methodology offers an approach to deal with the complexity and uncertainty inherent to these interrelated issues and has become very popular in recent Global Environmental Assessments (GEA), e.g. IPCC's Assessment reports (IPCC, 2007a, 2001; IPCC SRES, 2000), UNEP's Global Environmental Outlook (UNEP, 2012, 2007, 2004) or (MEA, 2005)). Each storyline entails the representation of a plausible and relevant story about how the future might unfold. We judge that this methodology is an adequate one for the design of the socio economic scenarios that are needed as inputs to our model. The paper, therefore, quantifies and implements five representative storylines identified in GEA studies (as described in van Vuuren et al., 2012) and use them as input policies of the WoLiM model. *By using this methodology, we replicate the usual visions of the future explored by these international agencies*, *allowing them to be confronted with the case of the energy development constraints. In fact, to date, these international scientific bodies have largely ignored these constraints* (Aleklett et al., 2010; Dale, 2012; Höök and Tang, 2013)[3].

The paper is organized as follows: Section 2 overviews the model and its main hypothesis and limitations. Section 3 describes the modeling of non renewable and renewable resources. Section 4 explains the estimation of energy demand and section 5 describes the calculation of CO_2 emissions. Scenarios and results are described in sections 6 and 7. Finally, conclusions are drawn in section 8.

2. Overview of the WoLiM model

In recent decades, many global energy-economy-environment models, most focusing on climate change analysis, have been developed (e.g. MESSAGE (Nakicenovic and Riahi, 2003), IMAGE (Bouwman et al., 2006), MERGE (Manne and Richels, 2004), etc.), some based on system dynamics (Bassi and Shilling, 2010; Davies and Simonovic, 2010; Fiddaman, 2002). However, most of these models tend to use (very) large resource

[3] For example, some international economic organizations such as (OECD, 2012) projects that global GDP will grow at around 3% per year over the next half century. It will almost triple in the years 2010–2060, although world GDP distribution among countries will be very different from now: China and India will together account for 46 % of global GDP in 2050, up from less than 13 % today. No mention, however, about how scientific knowledge on resources constraints, likely future scarcities and some other economic uncertainties may affect these forecasts.

estimates (e.g. (McCollum et al., 2014)) that are subject to high uncertainties and are strongly biased towards overestimation due to the preeminence of optimistic economic assumptions (Dale, 2012; Höök and Tang, 2013; Rutledge, 2011). Thus, few models explicitly recognize resource limits such as peak oil and relate them to the economic growth (de Castro, 2009; García, 2009; Meadows et al., 1993, 1972; Mediavilla et al., 2013). The WoLiM model does recognize such limits and adopts the approach of URR (Ultimately Recoverable Resources), which is an expert-estimate of the total amount of resource that will ever be recovered and produced.

The WoLiM model,[4] which continues previous work by (de Castro, 2009; de Castro et al., 2009; Mediavilla et al., 2013), includes the following trends in a dynamic framework:

- The exhaustion patterns of non-renewable resources (URR approach and maximum extraction curves).
- The replacement of non renewable by alternative energies.
- The energy demand of the World's economy under different socio-economic scenarios.
- The sustainable potential of renewable energies.
- The net CO2 concentrations.

WoLiM is based on a lineal structure (see Figure 1) which starts by choosing a scenario framework that consists of a set of socioeconomic and technological assumptions and policies that are integrated in a coherent and sensible way (this scenario methodology is described in Section 6). The projection of the socio-economic drivers establishes the world energy demand. This demand is then disaggregated by sectors according to the different end-use sectors (electricity, industry, transport, etc.), and the energy demand of each sector is disaggregated into the demand by resources (liquid fuels, gas, electricity, etc.). These demands are compared to the production of each particular resource, which is limited by the geology-based peaks and the rates of technological substitution. Finally, the net CO_2 emission and concentration levels are computed.

[4] For a full description of the WoLiM model see (Capellán-Pérez et al., 2014).

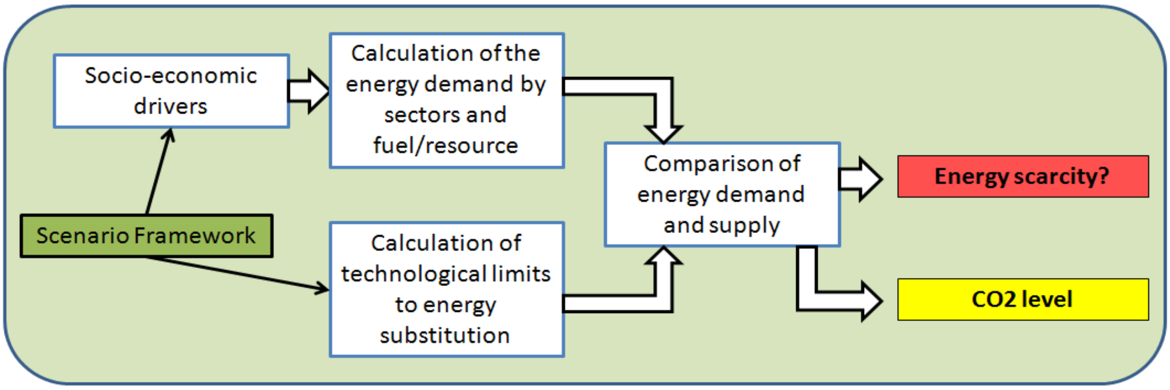

Figure 1: Basic logic functioning of the WoLiM model.

Although the model is based on System Dynamics (SD), this version is not a feedback-rich one as SD models tend to be. Some of the most obvious feedback loops are missing: e.g. it does not consider that the energy scarcity would influence the economy, i.e. the lack of energy would, for example, reduce economic growth (e.g. (Ayres et al., 2013; Hirsch, 2008)). This makes WoLiM, basically, a dynamic model of energy demand and technology trends versus physical restrictions.[5]

The reason for the simplification in this model version is the lack of consensus in the literature about the quantification of the impact of energy scarcity on the future economic growth. Although some authors analyze this relationship (e.g. (Hirsch, 2008)), there is no well-developed and widely accepted theory on this topic. Despite increasing criticism on this dominant view (Ayres et al., 2013; Bithas and Kalimeris, 2013), most macroeconomic models still pay very little attention to natural resources and, from our point of view, overestimate the capacity of technological substitution. Our studies are showing that the technological substitution, in particular the substitution of oil in this decade, is very difficult and does not seem possible in a demand-driven transition (Mediavilla et al., 2013; de Castro et al., 2009). On the other hand, the integration of this feedback tends to drive the system into collapse (de Castro et al., 2009; Nel and Cooper, 2009). Therefore, prior to modeling an inadequate feedback, we decided not to include it.

Therefore, the relationship between economy and energy in our model can be described as dual:

- **Demand-driven** if there is no restriction to the access of resources. In this case, the supply of energy is assumed to adjust to the estimated demand.

[5] Another significant feedback, such as the impact of climate change on the economy, is not considered either, but there are some important loops included which make WoLiM a feedback model, such as the fossil fuel extraction and the renewable energy dynamics. See Appendixes B and C for more detailed explanations.

- **Supply-driven** if the energy demand cannot be satisfied. In such a case, the estimated energy demand exceeds supply and an *energy scarcity* would appear. Of course, in reality there would be an adjustment through a price increase to reach a new equilibrium, but the model cannot simulate it because that feedback loop is missing, it only observes a discrepancy between demand and production.

Thus, the WoLiM model outputs are only valid while no important disequilibrium between demand and supply is reached in any sector. Afterwards, the system could in fact evolve in a variety of ways and the results shown are unrealistic. However, its main contribution is the fact that it enables the detection of those years and sectors (or "scarcity points", as they are called in Section 7) when the energy supply cannot meet the demand (under the given socioeconomic scenarios).

Key variables of the model

Exogenous variables are set by the scenario methodology, while endogenous variables are calculated within the model. The exogenous variables (or policies) are:

- GDP per capita growth
- Population growth
- Sectoral efficiency improvements (improvement of the energy intensity of the following economic sectors: transportation, industry, electricity and buildings).
- Non-renewable extraction curves for oil, gas, coal and uranium.
- Techno-sustainable potential of renewable energy sources.
- Growth of renewable energies for electricity production (wind, solar PV and CSP, hydroelectric, geothermal, biomass&waste and oceanic), and growth of nuclear power infrastructure.
- Growth of renewable energy for thermal uses and savings related to efficiency in industry and buildings.
- Market penetration of alternative transport by means of electric and hybrid vehicles and gas.
- Market penetration of alternatives to liquid fuels by coal to liquids, gas to liquids and biofuels (first and second generation).
- Afforestation programs.

The number of endogenous variables of the model is large (over 420), but the main ones are:

- Energy intensities of each economic sector: transportation, electricity, industry and buildings.
- Energy demands of each fuel (liquid fuels, gas, electricity, etc.) for each sector. In order to find out the share of each fuel, historical trends have been extrapolated (unless a specific policy is applied).
- Stocks and flows of non renewable resources (oil, gas, uranium, coal) whose depletion dynamics are described in Appendix B.
- Stocks that describe the infrastructure of renewable energies (solar, wind, hydroelectric, etc.) whose growth is determined by the policies applied (see appendix C for a detailed description).
- Stocks that represent the introduction of the alternative policies (biofuels, EV, efficiency, etc.), described in Appendix D.
- CO2 emissions and CO2 concentration levels related to fossil fuel use.

An overview of the model (Forrester diagram) can be seen in Appendix A, Figure A1.

Assumptions and hypotheses

The main hypotheses of the model are the following:

- Non-renewable resources extraction is subject to geological constraints (e.g. peak oil theory).
- Technological changes, such as the replacement of non renewable by alternative energies or efficiency, take time. The transition growth ratios are determined based on the tendencies observed in past decades (or accelerated under specific policies).
- The energy demand of the World's economy is determined by the sectoral energy intensities, whose evolution is considered to have inertia as well. Its variation is based on the tendencies observed in past decades and accelerated in some scenarios.

Trends of the key variables

The trends of the key variables are determined by a scenario framework, which sets the values of the exogenous variables (or policies) of the model (see Figure 2). A detailed description of these scenarios and policies is given in Section 6.

Once a scenario is set, the estimation of the energy demand is calculated as the product of the estimated GDP (determined exogenously) by energy intensity. Demand is organized into 3 aggregated sectors:

Transportation, Electricity and ***IB*** (Industrial and Buildings) without electrical demands. Each sector's energy demand is generated through sectoral energy Intensities (details in Section 4). These energy demands are divided into demands of different resources following past trends: electricity from different sources, liquid fuels, etc.

The non-renewable energy extraction (coal, oil, uranium, gas) is compared with demand, taking into account that it is restricted by their maximum extraction curves (see Appendix B). The model includes the estimations of expansion of several technologies (renewable electricity, bio energy, nuclear, CTL, GTL, etc. (as shown in Appendix C)). The policies of the different scenarios determine the expansion of each technology. Finally, CO_2 emission and concentration levels to 2100 are computed.

Priority is given to renewable energy (once the infrastructure is built, all the energy generated is used), and the rest of the demand is proportionally divided between the non-renewable sources, maintaining past ratios (20-year average values from *International Energy Outlooks*). In this way, the comparison of demand vs. production is done for each fuel. Since energy transitions have been shown to be slow (Fouquet, 2010), and past fuel ratios by sectors have happened to change smoothly in the recent past (e.g. (WEO, 2012)), we consider this analysis valid in the medium term (2050).

Limitations of the model

Appendix E discusses some other omissions of the model, such as the lack of some feedback loops, the non-inclusion of the EROEI, fuel competition or limits to minerals extraction. In this sense, we can say that our model is conservative and its results can be seen as optimistic. The development of a more sophisticated model with energy-economy-climate feedbacks would be desirable, and, at present, the authors are oriented towards Ecological Economics in order to find theories that describe the real importance of natural resources in the economic process.

Despite these simplifications, the main advantage of WoLiM is the *large amount of data it integrates and its structural simplicity,* which makes it very transparent. It is not a model that intends to predict the future, since it only says ***which future is not possible because of being not compatible with physical restrictions*,** but, in fact, the ultimate objective of SD and scenario development is not to predict, but to understand the system analyzed (Meadows et al., 1972; Sterman, 2001).

The following subsections describe the energy resources modeling (3.1 for non renewable and 3.2 for renewable), the energy demand estimation through sectoral intensities (section 4) and the estimation of CO_2

emission and concentration (section 5). In the model, we discuss the assumed potential of energy resources until 2050; therefore, nuclear fusion is not considered since the ITER and DEMO projects estimate that the first commercial fusion power would not be available before 2040.[6]

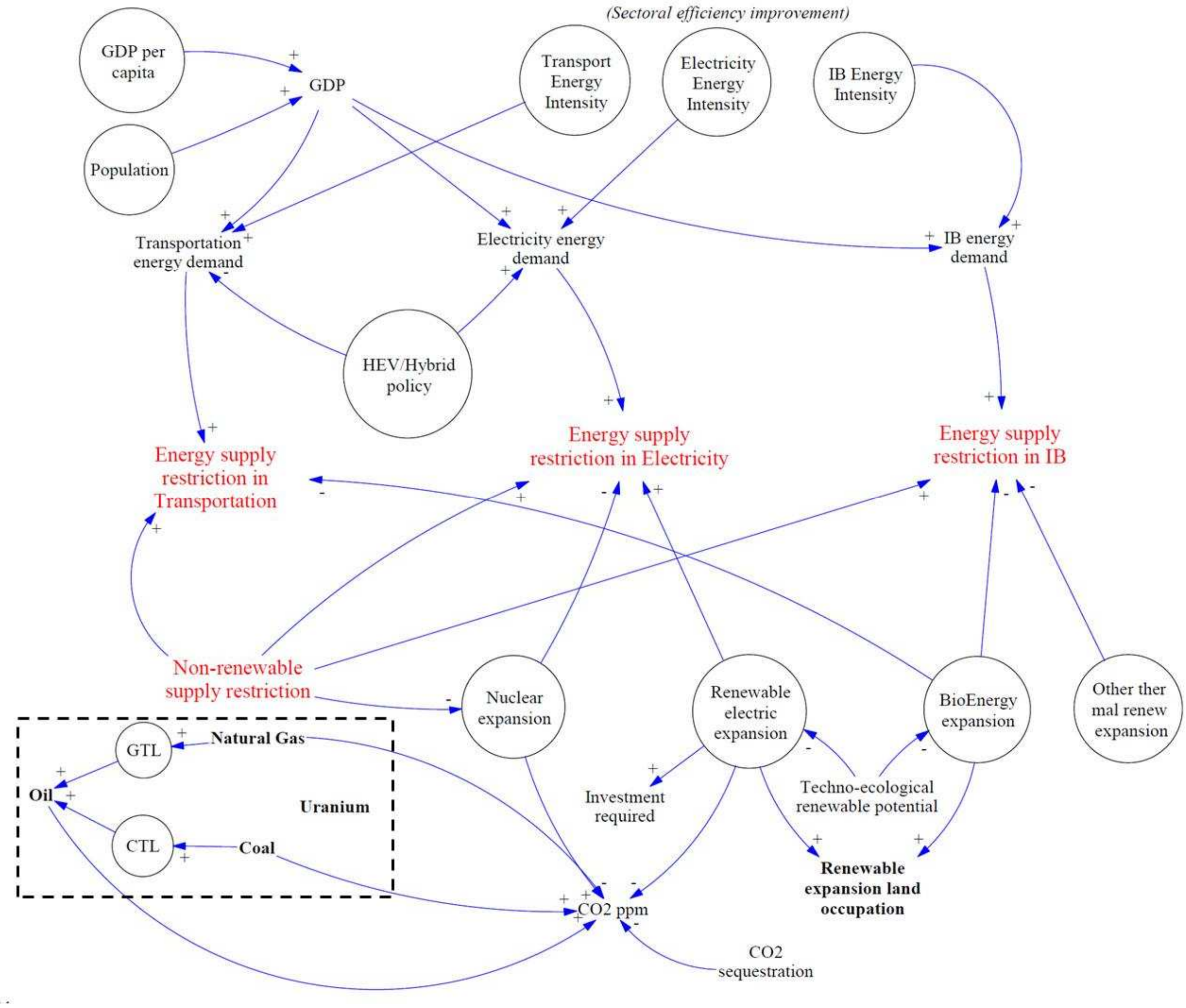

Figure 2: Causal loop diagram of the model with its basic elements. Scenario elements and policies are circled. IB is the acronym for Industrial and Buildings sector.

3. Energy resources modeling

3.1 Non-renewable resources

[6] < http://www.iter.org >.

The previous model, (Mediavilla et al., 2013), extensively discusses the different individual fuel extraction profiles proposed in the literature. Thus, we follow their discussion and select the same profiles (updating when new data is available). For some resources, we provide a "Best Guess" and "High Case" estimation based on the literature range ("Best Guess" the one considered most probable and "High Case" the one of highest resources).

Oil

The recent estimations for conventional oil of different authors tend to converge (de Castro, 2009; Maggio and Cacciola, 2012; Sorrell et al., 2009), and in order to reach stronger conclusions, the highest estimation for conventional oil found in the literature has been implemented (see Figure 3).

Unconventional oil extraction is modeled following the approach used in (de Castro et al., 2009) by extrapolating the 4.5% annual growth past trend and an optimistic 6.6% annual growth, as estimated by (Grushevenko and Grushevenko, 2012; Söderbergh et al., 2007). A URR of 750 Gboe is considered for non conventional oil after a review of other studies (ASPO, 2009; de Castro, 2009; Guseo, 2011; Laherrère, 2006).

Unconventional oil extraction is modeled following the approach used in (de Castro et al., 2009). We consider (1) a "Best Guess" case extrapolating the 4.5% annual growth past trend, and (2) an optimistic case of 6.6% annual growth as estimated by (Grushevenko and Grushevenko, 2012; Söderbergh et al., 2007).

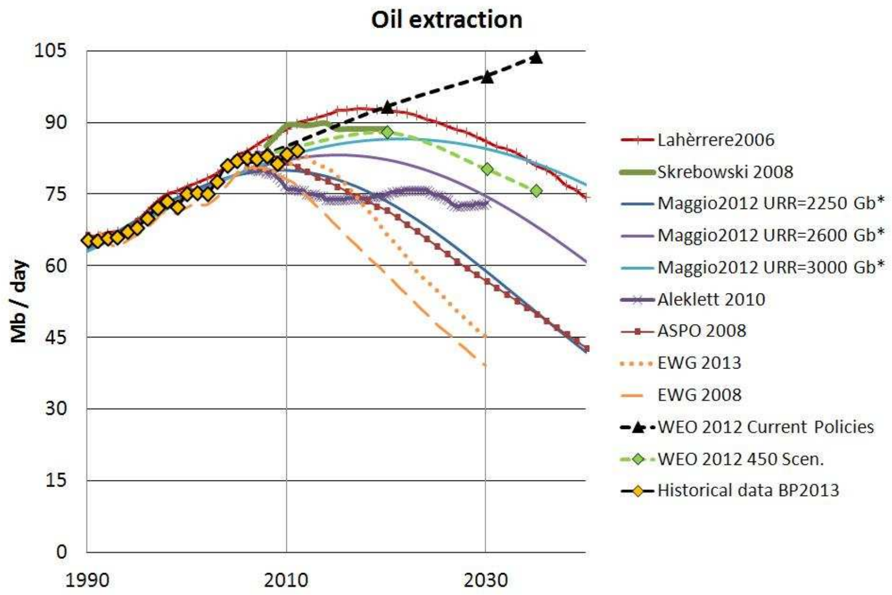

Figure 3: Estimations of oil extraction by different authors. There is a lack of standardization in the literature. For each study, "oil" refers to only crude oil (including NGLs) (Maggio and Cacciola, 2012); crude and unconventional (ASPO, 2009; EWG, 2013, 2008); crude, unconventional and refinery gains (Aleklett et al., 2010; Skrebowski, 2010; WEO, 2012); crude oil, unconventional, refinery

gains and biofuels (Laherrère, 2006); finally (BP, 2013) historical data include crude oil, shale oil and oil sands. (Aleklett et al., 2010) adjust the total volume to the energy content since 1 barrel of NGL contains in reality 70% of the energy of an oil barrel.

Natural gas

In (Mediavilla et al., 2013) the gas profile selected was from (Laherrère, 2006). In this paper the recent update of the author has been used for most scenarios (Laherrère, 2010), which assumes a combined URR for conventional and unconventional resources of 13,000 tcf (13.6 ZJ) (Figure 4). In some of the scenarios a higher case is taken, assuming that unconventional gas would expand significantly more under certain favorable conditions. In these cases, the "Best Guess" of (Mohr, 2012) that assumes almost 13,000 tcf of conventional gas and more than 7,000 tcf (7.3 ZJ) of unconventional gas are available is used (thus 50% more than the URR estimate of (Laherrère, 2010)).

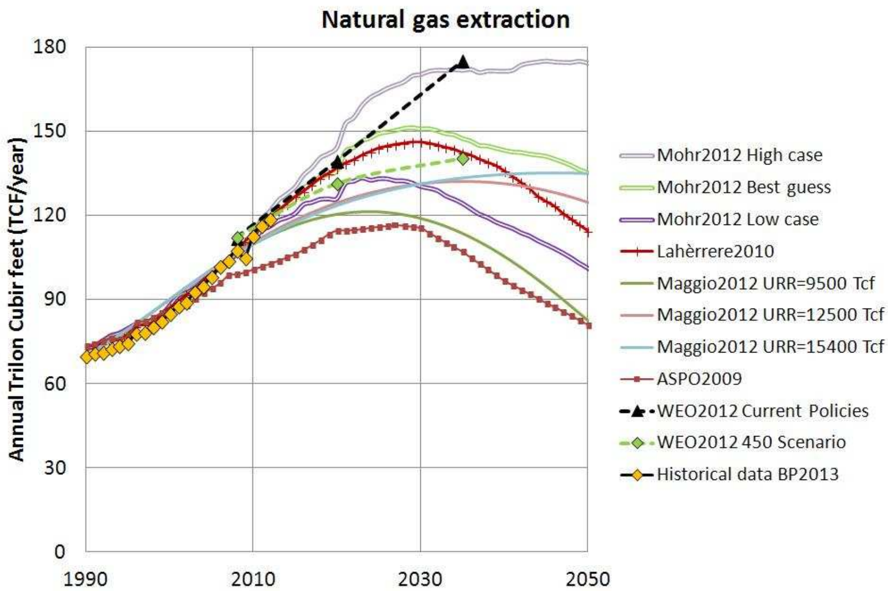

Figure 4: Estimations of conventional and unconventional natural gas extraction by different authors

Coal

Although there is a great interest in the phenomenon of peak oil and peak gas, very few research groups work with peak coal. Even fewer consider the fact that coal is a solid mineral, which implies different geological restrictions and different mining techniques (Hubbert's approaches being the most used). This is why the chosen extraction curve is the updated to the "High case" estimation by (Mohr, 2012; Mohr and Evans, 2009) (Figure 5), based on a mining model.

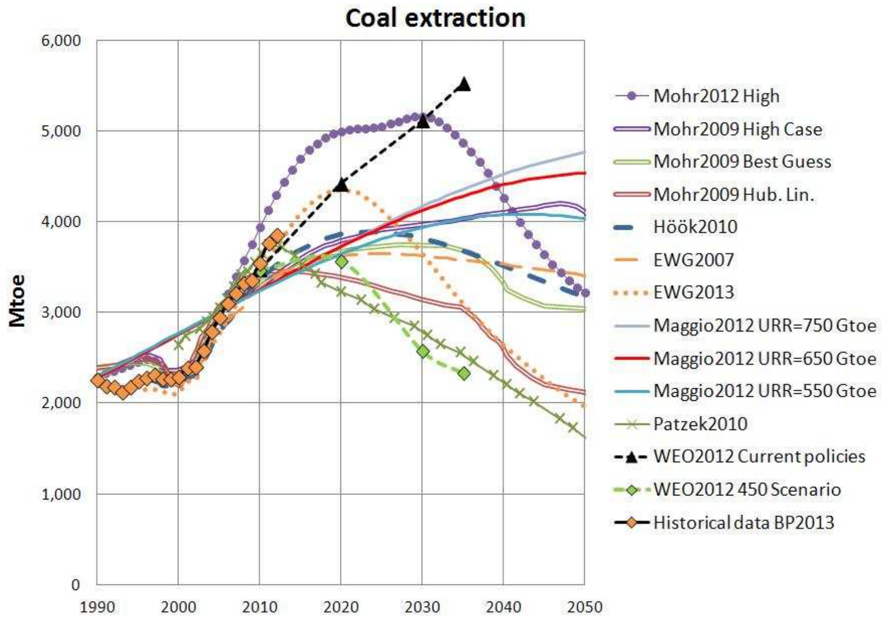

Figure 5: Estimations of coal extraction by different authors. (1 Mt = 0.482 Mtoe (Höök et al., 2010)).

Uranium

The estimation of uranium extraction taken is the one by (Zittel, 2012), which includes new (more costly) ore-reserves categories, as estimated by the *Nuclear Energy Association*, increasing the URR (see Table 1) and peak production until a maximum of 100 Kt of uranium mined is reached (Figure 6).[7]

[7] A recent paper is even more stringent, estimating that the peak will occur within this decade at 58 ± 4 ktons (Dittmar, 2013). The model does not include secondary resources of uranium (tailings, stocks and former nuclear weapons), since they will be exhausted within a few years (Dittmar, 2013; EWG, 2006).

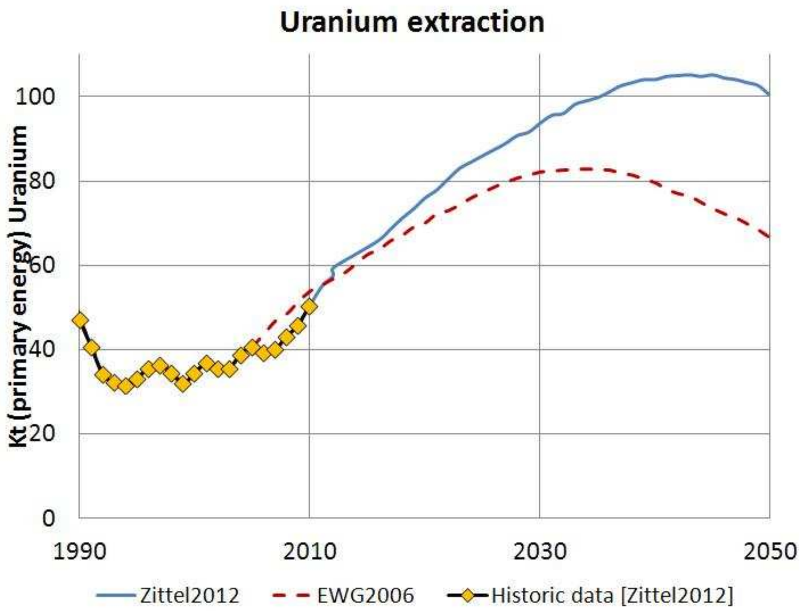

Figure 6: Estimations of uranium extraction by different authors.

A summary of all these estimations can be found in Table 1.

Resource		Reference	Description	URR	
Oil	Conv.	(Maggio and Cacciola, 2012) high scenario.	Hubbert method.	3,000 Gb	16.71 ZJ
	Unconv.	*Best Guess:* Own projection based on (de Castro et al., 2009)	Extrapolation of past trends deployment (+ 4.5 %/yr)	750 Gb	4.2 ZJ
		High case: (Grushevenko and Grushevenko, 2012)	High deployment rate (+ 6.6 %/yr)		
Natural gas		*Best Guess*: (Laherrère, 2010) Best Guess	Hubbert method: "creaming curve".	13,000 tcf	13.6 ZJ
		High Case: Best Guess from (Mohr, 2012)	12,900 tcf of conventional + 7,200 tcf of unconventional.	19,100 tcf	19.9 ZJ
Coal		(Mohr, 2012)	High Case, static. Mining model extraction.	670 Gtoe	27.8 ZJ
Uranium		(Zittel, 2012)	Hubbert method, considering RAR (<260 $/KgU) and IR of NEA.[a]	19,500 KtU	8.2 ZJ

Table 1: Non-renewable resources used in the model. (a)RAR: reasonably assured resources; IR: Inferred resources; NEA: Nuclear Energy Association**.**

Coal to liquids and gas to liquids

Other technologies for producing liquid fuels, such as CTL (coal-to-liquids) and GTL (gas-to-liquids), are also considered in the model. Different technologies exist, but all of them are characterized by low efficiencies (Höök et al., 2013; IPCC, 2007c). Their current production is exiguous: less than 0.3 Mb/d in 2011 (WEO, 2012) and their growth projections from international agencies are usually relatively modest (e.g. +11%/yr for GTL in the *New Policies Scenario* of (WEO, 2012)).

To be able to use all these data in our model we must transform them, since it is a dynamic model that considers demand. If the world economy goes into crisis and does not demand gas, for example, it will not be produced. The maximum extraction curves as a function of time have been transformed into maximum production curves as a function of the stock of resources (as in Figure 7), as explained in Appendix B. Production will, therefore, be the minimum between the demand and the achievable maximum extraction.

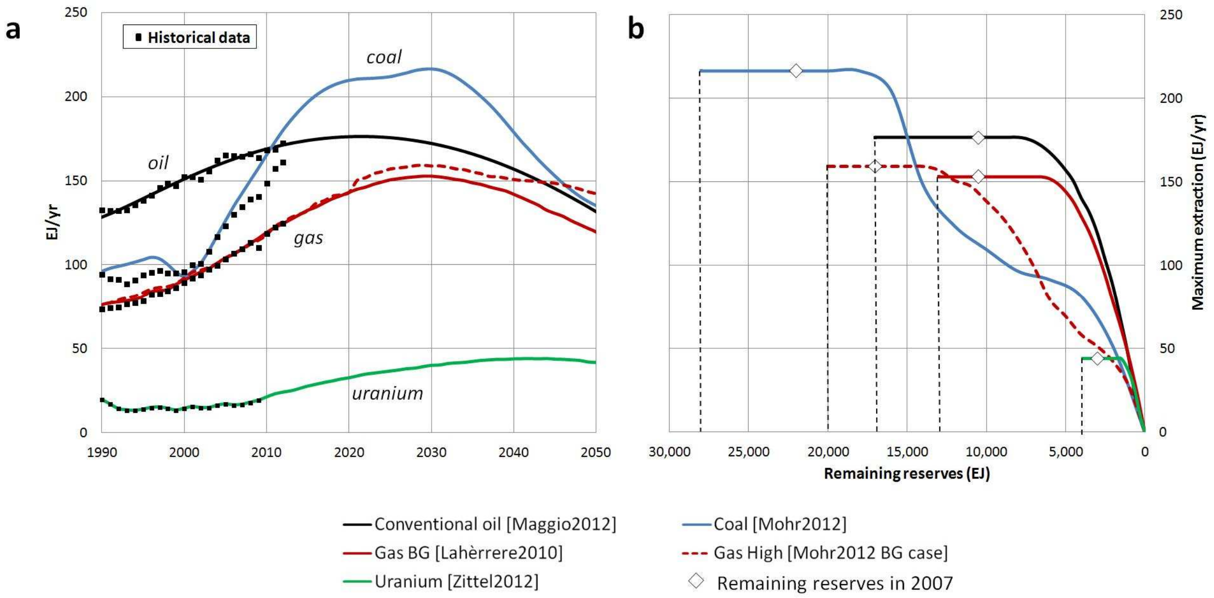

Figure 7: (a) Energy resource extraction curves as a function of time from the original references; (b) Curves of maximum extraction in function of the remaining reserves for all the non-renewable resources (Primary Energy). The y axis represents the maximum achievable extraction rate (EJ per year) associated to the remaining reserves (EJ). For each resource, the extreme left point (that coincides with the maximum value of reserves) represents its URR. Thus, as extraction increases and the remaining reserves fall below the point where the maximum extraction can be achieved, the extraction is forced to decline following the estimations of the studies selected. They also show by a rhombus the 2007 level of remaining reserves for each resource. See Appendix B for wider explanations.

3.2 Renewable resources

Renewable energy is usually considered as a huge abundant source of energy; therefore, the technological limits are assumed to be unreachable for decades, and the concern is on the economic, political or ecological constraints imposed (IPCC, 2011). However, several important constraints limit their practical availability. In this section, we discuss the techno-ecological potential of the main renewable energies.[8]

Bioenergy

Bioenergy provides approximately 10% of global primary energy supply and is produced from a set of sources (dedicated crops, residues and Municipal Solid Waste (MSW), etc.) that can serve different uses (biofuels, heat, electricity, etc.). Its techno-ecological potential estimation critically depends on the future land availability since its land requirements are huge and the foreseeable needs of land for food and infrastructures for the growing population poses a limit on its expansion (de Castro et al., 2013a). The potential of bioenergy has been established in the model based on the land surface that could be dedicated to it. It varies between occupations similar to present value (maximum 100 MHa) and a maximum of 200 MHa (a complete description in Appendix F).

Electrical generation from renewable resources

The most promising electric renewable energies are solar and wind (Smil, 2010). However, recent assessments (done by the authors of this paper) using a top-down methodology, which takes into account real present and foreseeable efficiencies and surface occupation, suggest that their potential is greatly limited by technical and sustainable limits[9] (de Castro et al., 2013b, 2011). Thus, the evaluation of the global technological wind power potential, acknowledging energy conservation, leads to a potential of 30 EJ/yr (de Castro et al., 2011); while the estimation of the real and future density power of solar infrastructures (4-10 times lower than most published studies) leads to a potential of approximately 60-120 EJ/yr (de Castro et al., 2013b). Following these considerations, the global techno-ecological potential of electric renewable is estimated at 150 EJ (5 TWe) (see Table 3).

[8] For a detailed analysis of the modelling see (Capellán-Pérez et al., 2014).
[9] The technical potential takes into account the energy that the windmills or panels can extract, considering current or future plausible technological efficiencies. Economic potential and sustainable potential are the fractions of the technical potential considering, respectively, the restrictions derived from the costs of the technologies and the constraints derived from sustainability and ecosystem damage criteria (see for instance (de Vries et al., 2007) for similar definitions).

In terms of investment and costs, we compute the investment for building new plants and to replace or re-power the already existing ones following (Teske et al., 2011), grid reinforcement costs following (Mills et al., 2012), and balancing costs as modeled by (Holttinen et al., 2011)[10] (Table G1). For a detailed description of the modeling of electrical generation from renewable resources see (Capellán-Pérez et al., 2014).

Thermal renewable

The Industry and Buildings sectors are much more complex sectors to analyze since they use all kinds of fuels and energy vectors in a great diversity of technologies. Consequently, we decided to focus in this study on the Transport and Electricity generation sectors, while maintaining a high level of aggregation in IB (industrial and buildings) sectors. Thus, thermal uses of renewable energies (e.g. solar, geothermal) are not explicit in the model, nor are they assigned to a concrete technology (except for the 3rd generation biomass residues). Energy transition policies include a switch to renewable, more efficient systems, as well as improvements in construction (e.g. in order to enhance isolation and access to natural light) or even changes at a higher level (e.g. district heating), in the same way as done in WORLD3 (Meadows et al., 2004). These policies are modeled as target-policies of market penetration level for a given year (see Appendix D for a description of the modeling).

4 Energy demand estimation

A diversity of techniques can be used for estimating the energy demand for an economy or sector. Since the model is highly aggregated, the Energy Intensity method, that has already been used in similar studies (Furtado and Suslick, 1993; Saddler et al., 2007) has been applied. This method is simplistic because it does not explicitly include the price and the economic structure; however, at medium term, energy demand and its main drivers (GDP and technological improvement) dominate over the variations of fuel prices (de Castro, 2009; Furtado and Suslick, 1993; Saddler et al., 2007). In fact, prices and costs can falsely signal decreasing scarcity. (Reynolds, 1999) demonstrate that, when considering the size of the resource base as unknown (or ignored), it is possible to have several years of increasing production simultaneous with lower prices and

[10] We do not consider here the so called "energy trap" (Murphy, 2011; Zenzey, 2013). If it were taken into account, the results would be worse (in energy terms), because the energy needed to build the infrastructure necessary for a sustainable and renewable energy system must come from current consumption of fossil fuel. Following (Zenzey, 2013, p. 80): "Unlike monetary investments, which can be made on credit and then amortized out of the income stream they produce, the energy investment in energy infrastructure must be made upfront out of a portion of the energy used today (…) The arithmetic is daunting. To avoid, for example, a 2-percent annual decline in net energy use, replacing that loss with solar photovoltaic (with an EROEI pegged at 10:1) will require giving up 8 percent of the net energy available for the economy".

costs until a sudden, intense price rise occurs with a huge cut in production, similar to the oil shock in 2007-08 (Hamilton, 2009).

Considering the sectoral Energy Intensity as energy used by a sector divided by the total GDP of the economy (equation 1), this method can be summarized as follows:

1- Estimation of the future evolution of GDP (set exogenously depending on the scenario),
2- Estimation of the evolution of the Energy intensity for each sector (econometrically calculated in this study),
3- Finally, multiplying the GDP by the Energy intensity of each sector (I_i), the Energy Demand for that sector (E_i) is obtained dynamically, see equation 1 below:

$$E_i = GDP \cdot I_i \qquad \text{equation (1)}$$

Index i refers to the 3 economic sectors considered: Transport, Electric and IB (Industrial and Buildings) sectors.

The results of the sectoral historic World energy intensity regressions are shown in Table 2 and Figure 8. They indicate that, in the last 40 years, the world TP energy intensity has improved at a yearly average rate of 1.15 % , but that, since 2000, its value has remained constant at around 8 EJ / 2011 US$. Transport and Buildings primary energy intensities have also improved in the last decades, although at smaller rates (0.7% and 0.5% respectively). Finally, the electricity generation intensity has remained stable at 275 TWh/2011 US$.

Energy sector	**Sectoral Energy Intensities**		**Period**
Total PE demand	$I_{tot} = 0.988582 \cdot I_{tot-1}$ (R^2=0.999840)	EJ / US$	1971-2010 (regression)

Transport PE demand	$I_{transp} = 0.993298 \cdot I_{transp-1}$ (R^2=0.999841)	EJ / US$	1971-2007 (regression)
Electricity generation	$I_{elec} = 1.00127 \cdot I_{elec-1}$ (R^2=0.999916)	TWh/ US$	1980-2010 (regression)
IB PE demand	$I_{IB} = 0.995 \cdot I_{IB-1}$	EJ / US$	1990-2010 (calibration)

Table 2: Results of the sectoral energy intensity regressions for Total, Transport, and Electricity generation; and of the calibration for the IB sector. All dollars in the paper are in 2011 US$. PE: Primary Energy. The (World Bank database, 2014) is used for the historical series of world GDP at constant prices in US2011 T$ and Total Primary Energy (PE) demand, (IEA ETP, 2010) for Transportation PE use and (US EIA db, 2014) for the electrical generation. IB PE intensity was calculated internally in the model for the calibration period (1990-2010) as the subtraction of Total energy minus Transport and Electrical sector (generation and losses).

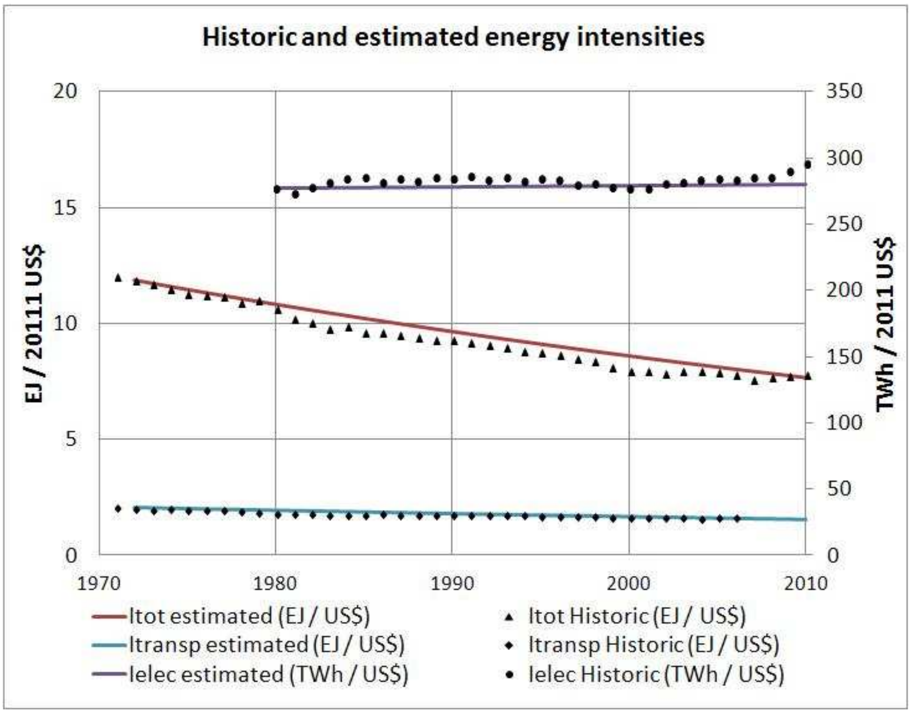

Figure 8: Historic and estimated energy intensities by sectors. Itot refers to Total Energy Primary intensity (EJ/US$), Itransp to Transportation intensity (EJ/US$), and Ielec to Electrical generation intensity (TWh/US$). All dollars in the paper are in 2011 US$.

In order to account for the biophysical and thermo-dynamical limits in the substitution of inputs in production in the medium and long-term (as stated by Ecological Economics, e.g. (Ayres, 2007; Ehrlich, 1989;

Stern, 1997)), the following expression of the energy intensity (equation 2) as proposed by (Schenk and Moll, 2007) is used:

$$I_{tot} = I_{min} + (I_{t=0} - I_{min}) \cdot a^t \qquad \text{equation (2)}$$

AEI represents the Annual Efficiency Improvements, thus, the parameter "a", or (1-AEI), accounts for technological change, and I_{min} is a horizontal asymptote that represents the minimum value of the energy intensity. Both values will vary depending on the scenario storyline and quantification (see Section 6). The studies of (Baksi and Green, 2007; Lightfoot and Green, 2002) are used as a reference.[11] Sectoral primary energy demand is dynamically corrected to take into account the fact that renewable technologies are more efficient that fossil-fuel based ones.

5 CO2 emissions and concentrations

The model computes the CO_2 emissions associated with the use of fossil fuels: coefficients from (BP, 2013) for conventional and from (Brandt and Farrell, 2007; Howarth et al., 2011) for unconventional. Biofuels are far from being neutral carbon emitters due to Indirect land use changes (ILUC); in accordance with (European Commission, 2010; Fargione et al., 2008; Haberl et al., 2012; Searchinger et al., 2008) we assign a similar emission power to natural gas (see Table 3).

Resource		**Reference**	**Value [tCO2 / toe]**
Coal		(BP, 2013)	3.96
CTL		(Brandt and Farrell, 2007)	6.94
Natural gas	Conventional	(BP, 2013)	2.35
	Unconventional	(Howarth et al., 2011)	3.53
GTL		(Brandt and Farrell, 2007)	4.34
Oil	Conventional	(BP, 2013)	3.07
	Unconventional	(Brandt and Farrell, 2007)	3.84 (6.14 for shale oil)

Table 3: CO2 emissions for non-renewable resources used in the model.

[11] A practical application for illustrating its behavior is done in (Capellán-Pérez et al., 2014).

In order to assess climate change, the net[12] CO_2 emissions are converted to concentration levels which assume that, in the period studied, the ocean and ground will continue to absorb 45% of total emissions as in the past (Canadell et al., 2007). Due to the high inertia and long-term scope of climate change, the emission projections are extended until 2100, as the IPCC usually does, with the aim of comparing concentration levels in at least the order of magnitude.

6. Scenarios and policies of the model

As described in Section 2, the WoLiM model needs assumptions about the world socio-economic evolution (such as economic and population growth or technological progress) as external inputs. In order to establish those policies in a coherent and sensible way, we have applied the scenario methodology (e.g. IPCC's Assessment reports (IPCC, 2007a, 2001; IPCC SRES, 2000), UNEP's Global Environmental Outlook (UNEP, 2012, 2007, 2004) or (MEA, 2005)).

Testing system dynamics models and obtaining results from them can be a cumbersome task when the models have several policies that can be varied at the same time. Scenario methodology offers an approach to deal with the limited knowledge, uncertainty and complexity of natural and social sciences and, applied to System Dynamics models, can be used to group the variations of policies into coherent and meaningful scenarios. Each scenario (or storyline) represents an archetypal and coherent vision of the future -which may be viewed positively by some people and negatively by others- (IPCC SRES, 2000; MEA, 2005).

By using this methodology we replicate the usual visions of future explored by these international agencies (van Vuuren et al., 2012), *allowing them to confront with the case of the energy development constraints. In fact, to date, these international scientific bodies have largely ignored these constraints* (Aleklett et al., 2010; Höök and Tang, 2013).

In this section, a summary of the most important characteristics of the different scenario families identified in GEA studies by (van Vuuren et al., 2012) is provided, describing first the qualitative features of

[12] In this model version we implement the afforestation as the only CO_2 sequestration policy following (Nilsson and Schopfhauser, 1995), which analyzed the changes in the carbon cycle that could be achieved with a large global afforestation program covering 345 Mha. Other technologies such as CCS are not considered in this study due to their uncertain development and benefits (Fischedick et al., 2008; Scott et al., 2013).

each scenario[13], and then their quantification. A Business-as-Usual scenario is added as reference that assumes that historical dynamics will also guide the future).[14]

Scenario 1- Economic optimism with some market reforming: Strong focus on the mechanism of competitive, efficient market, free trade and associated rapid economic growth, but including some additional policy assumptions aimed at correcting some market failures with respect to social development, poverty alleviation or the environment. The scenario typically assumes rapid technology development and diffusion and convergence of income levels across the world. Economic growth is assumed to coincide with low population growth (given a rapid drop in fertility levels). Energy and material scarce resources are upgraded to reserves or substituted efficiently through market signals (price rising). Eventually, everyone will benefit from globalization and technological advances will remedy ecological problems (e.g. 'Environmental Kuznets Curve').

Scenario 2- Global Sustainable Development: Strong orientation towards environmental protection and reducing inequality, based on solutions found through global cooperation, lifestyle change and technology (more efficient technologies, dematerialization of the economy, service and information economy, etc.). Central elements are a high level of environmental and social consciousness combined with a coherent global approach to sustainable development. Within this scenario family, it is assumed that a high level of international governmental coordination is necessary and possible in order to deal with international problems like poverty alleviation, climate protection and nature conservation. It entails regulation of markets but on a global scale and based on the conviction that the Earth's limits are in sight and that therefore pro-active policies are necessary.

Scenario 3- Regional competition/regional markets*:* Scenarios in this family assume that regions will focus more on their self-reliance, national sovereignty and regional identity, leading to diversity but also to tensions between regions and/or cultures. Countries are concerned with security and protection, emphasizing primarily regional markets (protectionism, deglobalization) and paying little attention to common goods. Due to the significant reduction in technological diffusion, technological improvements progress more slowly.

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[13] We have completed the descriptions from (van Vuuren et al., 2012) with the IPCC Reports on Scenario Emissions (IPCC SRES, 2000) and the (MEA, 2005).

[14] In reality (van Vuuren et al., 2012) recognize 6 scenario families. As they argue in their paper, family scenario 1 "Economic optimism/conventional markets scenarios" and 2 "Reformed market scenarios" are very similar. Thus, we decided to join them for the sake of simplicity and minimize the number of representative scenarios.

Scenario 4- Regional Sustainable Development*:* this scenario is the "friendly" version of the previous one, where globalization tends to be deconstructed and an important change in traditional values and social norms happens against senseless consumerism and disrespect for life. Citizens and countries must each take on the responsibilities they can bear, providing aid or setting a green example to the rest of the world, from a sense of duty, out of conviction or for ethical reasons or to solve primarily their own problems. In fact, although barriers for products are re-built, barriers for information tend to be eliminated. The focus is on finding regional solutions for current environmental and social problems, usually combining drastic lifestyle changes with decentralization of governance.

Quantification of the Scenarios

In order to use these storylines in our model, we must set specific numbers to every assumption and policy. Global[15] scenario quantification is a delicate and inherently subjective task. We have followed other GEA assessments as a guideline; however, divergences in the interpretation and hypothesis considered sometimes emerge and are justified.

Socioeconomic inputs: GDP per capita and population evolution estimations were taken from (MEA, 2005); numbers are in fact very similar to (IPCC SRES, 2000).

Energy available resources: due to the Scenario 1 storyline (enhanced technological advances in extraction together with an economic short-term benefit priority), we consider that unconventional oil and gas can be extracted at higher rates than for the rest of the scenarios ("High cases" considered in Section 3). In scenarios that prioritize the environment over the economy, we consider that unconventional fuels are not extracted at larger levels than the "Best Guess" case (e.g. (Olmstead et al., 2013; Osborn et al., 2011)).

CTL and GTL: While there is no shortage of liquids in the economy, there is a growth of these technologies following recent past trends: strong growth for GTL and slow for CTL. When liquid shortage begins, a crash program following a logistic curve is launched with a strong yearly growth, as indicated in Table 4. For the sake of simplicity, CTL deployment is not constrained, and the yearly growth is set to match current GTL growth.[16] When gas and/or coal resources are not able to balance the global demand, the crash program is stopped.

[15] Ethical issues regarding equitable distribution of natural capital and burden sharing rules in a resource-constrained world are beyond the scope of this paper.

[16] This can be considered as an optimistic assumption since CTL, differently to GTL, is still an immature technology (excepting South Africa) and faces significant deployment constraints (Höök et al., 2013).

Sectoral efficiency improvements: Each sectoral efficiency (Transportation, IB and Electrical generation) is governed by its energy intensity (Equation 2) with the values in Table 4 for each scenario. The energy intensity of each sector (and the total energy intensity) can thus be computed when accounting for all the policies (see Figure 10 and Table 4). Electricity generation intensity is maintained constant along the period, assuming that the current electrification trends will continue in all scenarios (the New Policies Scenario from (WEO, 2011) still projected 1.0 billion people without electricity by 2030). In Scenarios 3 and 4, where deglobalization occurs, a 1.5% yearly decrease in the transport energy efficiency is assumed (i.e., doubling current trends), accounting for an absolute reduction in transport needs but also due to the promotion of public transport in Scenario 4.[17]

Notice that the evolution of all the energy intensities in our model can be considered optimistic, since in recent years, the sectoral energy intensities yearly averages have diminished at smaller rates than historical values, the total energy intensity has been constant since 2000, and electricity generation intensity has even increased (Figure 8).

Nuclear: Considering the study by (Schneider et al., 2012) of the nuclear status in the world, the conservation of the already existing power in the coming years would already be an optimistic assumption; we assign this case to BAU and Scenario 3. For Scenarios 1 and 2, where nuclear may be promoted, we take as reference the World Nuclear Association (WNA) forecast of 1-2%/year growth for the coming decades (Dittmar, 2013). Finally, for scenario 4, where the environment is actively protected, we program a progressive phase-out as nuclear power stations reach the end of their lifetime.

Electric/Hybrid (HEV&hybrid) car: the evolution of hybrid and electric vehicles in our model follow the estimations of (EVI IEA, 2013). EVI is "a multi-government policy forum dedicated to accelerating the introduction and adoption of electric vehicles worldwide" that seeks to "facilitate the global deployment of at least 20 million passenger car EVs by 2020" (EVI IEA, 2013). We will consider this forecast as an optimistic development and we assign it to scenarios 2 and 3, while for BAU and Scenario 3 we will keep half of the projection. For Scenario 4, we will interpret the "lifestyle change" as a higher shift. After 2020, the growth

[17] Potential reductions of energy consumption in the Transportation sector in the deglobalization scenarios are in fact very limited due to the small contribution of world aviation and marine bunkers in relation to the primary energy used by the whole sector (below 13%, while road transport accounts for more than 65% (IEA ETP, 2010)). In fact, a wide range of deglobalization scenarios can be conceived, from (world) regionalization of the exchanges to more local reconfigurations that would unfold in very different energy use patterns (e.g. (Bueno, 2012)).

rate is assumed to increase two-fold for all scenarios, assuming that a shift to alternative mobility systems will, in any case, be promoted, due to the scarcity of conventional liquid fuels in all scenarios.

Natural Gas Vehicles: Despite the strong growth in the past decade (+20% per year), the total number of 16.7 million NGVs (http://www.iangv.org/current-ngv-stats/) still pales in comparison to a total worldwide number of around 1,150 million motor vehicles in 2009 (World Bank database, 2014) – i.e.1.45% of the total. Thus, due to the insensitivity of the model to different NGV growth rates (because of reaching the gas peak), for the sake of simplicity, an annual growth rate is assumed for all scenarios that follows the past trends.

Bioenergy: As stated in section 3.2, a very large surface dedicated to bioenergy at a global level is not compatible with future scenarios such as the ones explored in this paper. As a reference, since the year 2000, the area from southern countries that has been bought or long-term rented by transnationals and investment funds has been estimated at more than 80 MHa (Anseeuw et al., 2012). Two possibilities of bioenergy expansion are considered. For scenarios 3 and 4 (regionalization), land grabbing is not going to increase significantly from present levels in the future (maximum 100 MHa), since currently, there is a worldwide rush for land (around 1.7% of agricultural area has been reported to have been bought or rented for long periods of time since the year 2000, (Anseeuw et al., 2012)). For scenarios 1 and 2, a "south occupation" that would be deployed in a maximum of 200 MHa is assumed (more details in Appendix F and (Capellán-Pérez et al., 2014)).

Renewable and efficiency improvements in the Industrial and Building sectors: different levels of penetration by renewable technologies to 2050 are considered. More potential is assigned to Buildings than to Industry (e.g. (European Comission, 2007)).

Carbon-climate policies: Storylines from scenarios BAU and 3 exclude the adoption of carbon valuation. The scenario 1 storyline suggests that measures could be taken, but probably *too late*. Thus, effective carbon valuation only seems probable in scenarios 2 and 4 with proactive environmental protection. Although carbon valuation would intensify the transition to a low carbon economy, we consider that many of the changes it would induce are in fact already implicit in the interpretation of both storylines. Additionally, we consider that a world afforestation program is set from 2020 as proposed by (Nilsson and Schopfhauser, 1995). They analyzed the changes in the carbon cycle that could be achieved with a large-scale global program covering 350 MHa. Thus, a maximum carbon capture of 1.5 GtC/year, 50 years after the start of the program, would be attained. Other technologies such as CCS are not considered in this study due to their uncertain development and benefits (Fischedick et al., 2008; Scott et al., 2013).

Table 4 provides a detailed summary of the policies implemented for each scenario.[18]

[18] In fact, although (IPCC SRES, 2000) scenarios do not consider explicitly the use of policies, it has been argued that they are implicitly assumed (Arvesen et al., 2011; Girod et al., 2009; Pielke et al., 2008).

	SCENARIO - INPUT	**0 – BAU**	**Scenario 1 Economic optimism with some market reforming**	**Scenario 2 Global Sustainable Development**	**Scenario 3 Regional competition**	**Scenario 4 Regional sustainable development**
Socioeconomic (% 2010-2050)	GDPcap	Hist + 1.9% (1960-12)	+ 3%	+ 2.4%	+ 1.1%	+ 1.9%
	Population	UN Medium-Variant +0.75%	+0.5%	+0.65%	+0.81%	+ 0.8%
Sectoral efficiency improvements	a_{Transp}	Past trends (-0.67%)	Rapid (-0.9 %)	Rapid (-0.9 %)	Deglobalization (-1.5%)	Deglobalization (-1.5%)
	a_{elec}	Past trends (0%)				
	a_{BI}	Past trends (-0.5%)	Past trends (-0.5%)	Past trends (-0.5%)	Past trends (-0.5%)	Past trends (-0.5%)
	I_{min}[a]	25 %	25 %	15 %	25 %	15 %
Resource availability	Non-renewables	Best Guess	Best guess (coal, conv. oil) High case (gas, unconv. oil)	Best Guess	Best Guess	Best Guess
	CTL, GTL	Crash program (+15 %)	Crash program (+20 %)	Crash program (+20 %)	Crash program (+15 %)	Crash program (+15 %)
Electric renewables	Solar FV&CSP	Medium (+15%)	Past trends (+19%)	Very rapid (+25%)	Medium (+15 %)	Very rapid (+25%)
	Wind	Medium (+20%)	Past trends (+26%)	Very rapid (+30%)	Medium (+15%)	Very rapid (+30%)
	Hydroelectric, Geothermal, Bioenergy&Waste	Past trends (slow)	Past trends (slow)	Very rapid (x3 past trends)	Past trends (slow)	Very rapid (x3 past trends)

	Oceanic	Rapid (+20% from 2020)	Rapid (+20% from 2020)	Very rapid (+30% from 2020)	Rapid (+20% from 2020)	Very rapid (+30% from 2020)
Nuclear		Constant	+ 3 % from 2015	+ 1.5% from 2015	Constant	Progressive shutdown
BioEnergy	2nd generation	Slow (+8%, 100 MHa available)	Rapid (+ 20%, 200 MHa available)	Rapid (+ 20%, 200 MHa available)	Slow (+8%, 100 MHa available)	Medium (+15%, 100 MHa)
	3rd generation	Slow (+8% from 2025)	Rapid (+ 20% from 2025)	Rapid (+ 20% from 2025)	Slow (+8% from 2035)	Medium (+15% from 2035)
	Residues	Slow (+8% from 2025)	Rapid (+20% from 2025)	Rapid (+20% from 2025)	Slow (+8% from 2035)	Medium (+15% from 2035)
Thermal renewables & efficiencies	Industrial sector (market share 2050)	Low (12.1%)	Medium (23.1%)	Rapid (37.6%)	Low (12.1%)	Rapid (37.6%)
	Buildings sector (market share 2050)	Low (4.7 %)	Medium (22.6%)	Rapid (48%)	Low (4.5%)	Rapid (48%)
Alternative transport[b]	HEV & Hybrid (market share 2050)	Medium (9%)	Rapid (18%)	Very rapid (36%)	Medium (9%)	Very rapid (50%)
	NGVs	Past trends (+20 % annual)				
Afforestation program		-	-	350 MHa	-	350 MHa

Table 4: Hypothesis and policies of each scenario. Percentages refer to yearly growth rates, otherwise it is specified differently. [a]The minimum intensity level (I_{min}) is set at 25% of current intensity for scenarios BAU, 1 and 3, and at 15% for 2 and 4 following (Baksi and Green, 2007). [b] The "Alternative transport" policies are maintained while the "scarcity point" in the fuel inputs (i.e. electricity for HEV&EV) and gas for NGVs).

7. Results and Discussion

In this section the results of our model to 2050 under the scenarios described in section 6 are presented. It should be recall that some important issues have not been integrated in the modeling (see Appendix E), most of these issues have the potential to worsen the results obtained.

A fundamental consideration must be made: as the model does not integrate a feedback between energy scarcity and GDP, if the demand cannot be fulfilled, a divergence appears between demand and energy supply (though in the real world there would be an interaction that would reduce this gap). We will qualitatively interpret that small divergences are compatible with the storyline; however, large divergences will be interpreted as potential energy-scarcity challenges that make the scenario unfeasible.

7.1 Socioeconomic inputs and sectoral efficiencies

Socioeconomic inputs considered for each scenario are presented in Figure 9. Population increase is similar in all scenarios due to its high inertia and estimates vary between 8.3 (Scenario 1) and 9.5 billion people in 2050 (Scenarios 3 and 4). Scenarios are more diverse in terms of GDP: in 2050, Scenario 1 almost doubles the GDP estimated in Scenario 3 (which doubles the 2010 value). Also, the variety of policies and different sectoral efficiency considered unfold in very different (always decreasing) sectoral energy intensity paths (Figure 10).

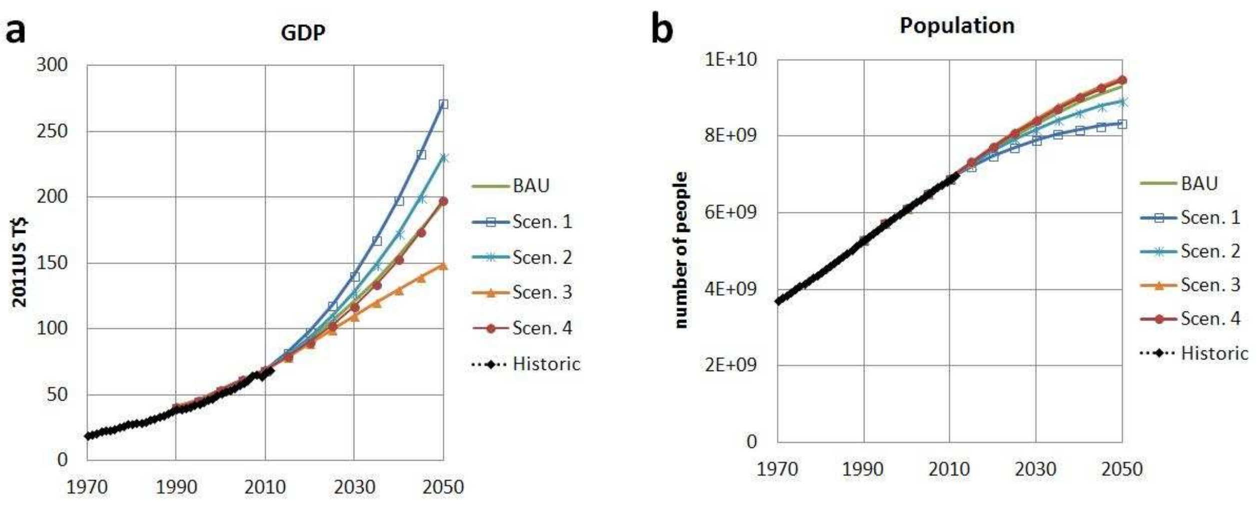

Figure 9: Socioeconomic exogenous inputs for each scenario: (a) GDP (2011 US$) and (b) Population. Historic data from (World Bank database, 2014). Since in this model version no feedbacks are applied, impacts of energy supply scarcity and climate change are not computed in the projections and these variables are thus not modified.

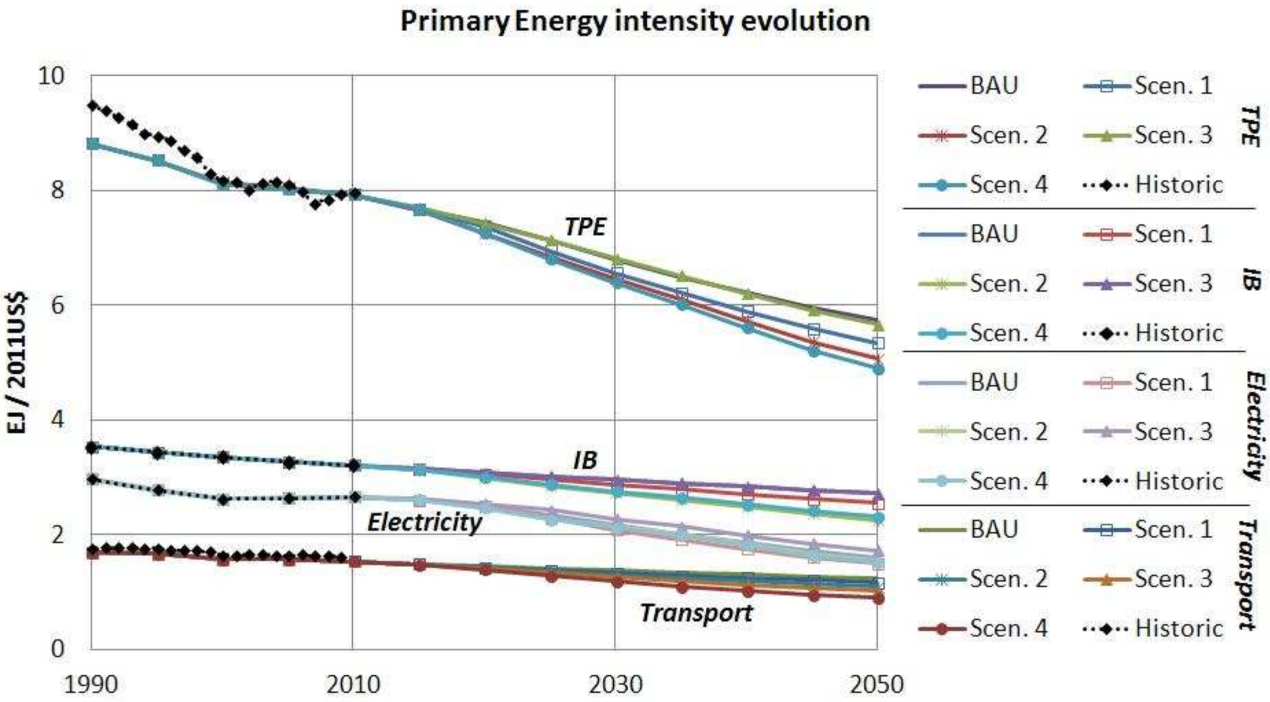

Figure 10: Total and by sector Primary Energy (PE) intensity evolution for each scenario in EJ / 2011 US$. TPE: Total Primary Energy, IB: Industrial and Buildings sectors. Historic data from (IEA ETP, 2010; World Bank database, 2014) and our own adjustments for the IB and Electricity PE intensity past evolution as explained in Section 4.

In Table 5, the total energy intensity yearly average decrease obtained for each scenario is represented and compared with the declines assumed by (IPCC SRES, 2000). Our results are in the range 0.8% - 1.25% and coincide with (Baksi and Green, 2007; Lightfoot and Green, 2002; Pielke et al., 2008) that find greater efficiency improvements implausible due to the biophysical limits in process substitution, as proposed by A1 and B1 (IPCC SRES, 2000) scenarios.

Total Energy Intensity evolution	**BAU**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
This study	-0.82 %	-1.04%	-1.24%	-0.84%	-1.21%
(IPCC SRES, 2000)	-	-1.5% (A1)	> -2% (B1)	-0.65% (A2)	-1% (B2)

Table 5: Total energy intensity evolution (average yearly reduction rates for the period 2010-2050) as a result of the interpretation and quantification of scenarios and the comparison with (IPCC SRES, 2000) results.

7.2 Results by sector and fuel

Electricity generation: The comparison of the energy generation and demand from different sources can be seen in Figure 11. In the scenarios where the renewable technologies are promoted at a very rapid pace (2 and 4), electricity supply is roughly able to fulfill the demand, but in scenarios BAU and 1, renewable electricity cannot sustain the increasing demand by 2030. In Scenario 3, even the smallest growth of the demand cannot be compensated because of the modest growth of renewable technologies.

Wind maximum potential is reached in the 2030s, and solar growth slows down significantly by 2050 due to the proximity of its maximum potential. Uranium restrictions make nuclear technology largely irrelevant.

However, the massive expansion of renewable technologies has repercussions.

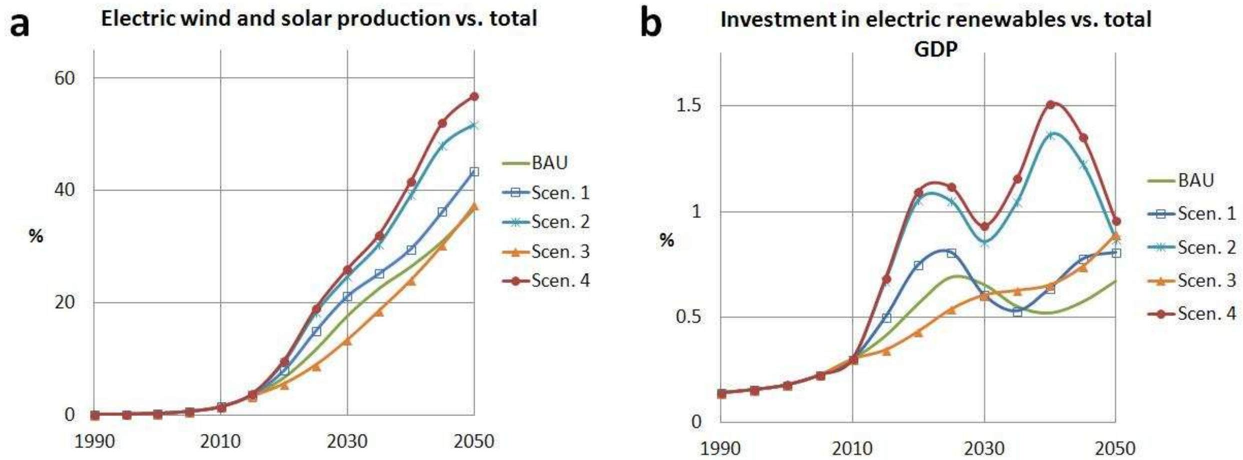

Figure 12:a shows the proportion of variable electric generation technologies (wind and solar) in function of the total production. In Scenarios 2 and 4, this proportion exceeds 50% of the total generation by 2050, which would imply an important challenge for the integration of intermittent production (Trainer, 2012). In terms of investment (Figure
12

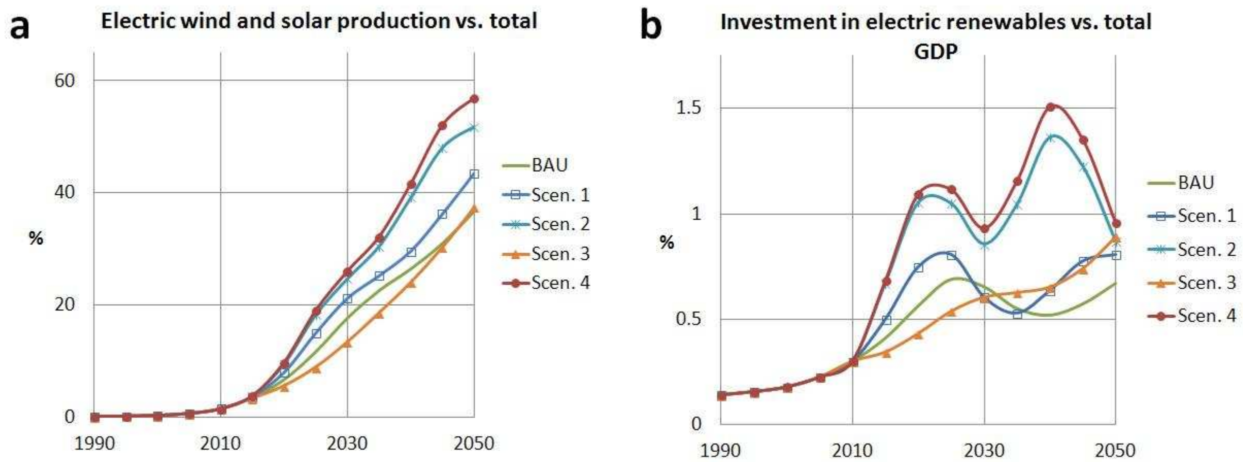
a
Electric wind and solar production vs. total
%
60
40
20
0
1990
2010
2030
2050
BAU
Scen. 1
Scen. 2
Scen. 3
Scen. 4
b
Investment in electric renewables vs. total GDP
%
1.5
1
0.5
0
1990
2010
2030
2050
BAU
Scen. 1
Scen. 2
Scen. 3
Scen. 4

Figure 12-b), electric renewable deployment investment would remain below 1.5% of the total world GDP of all scenarios and is in the same magnitude order as other studies (e.g. *Bloomberg New Energy Finance*[19] and (Teske et al., 2011)).

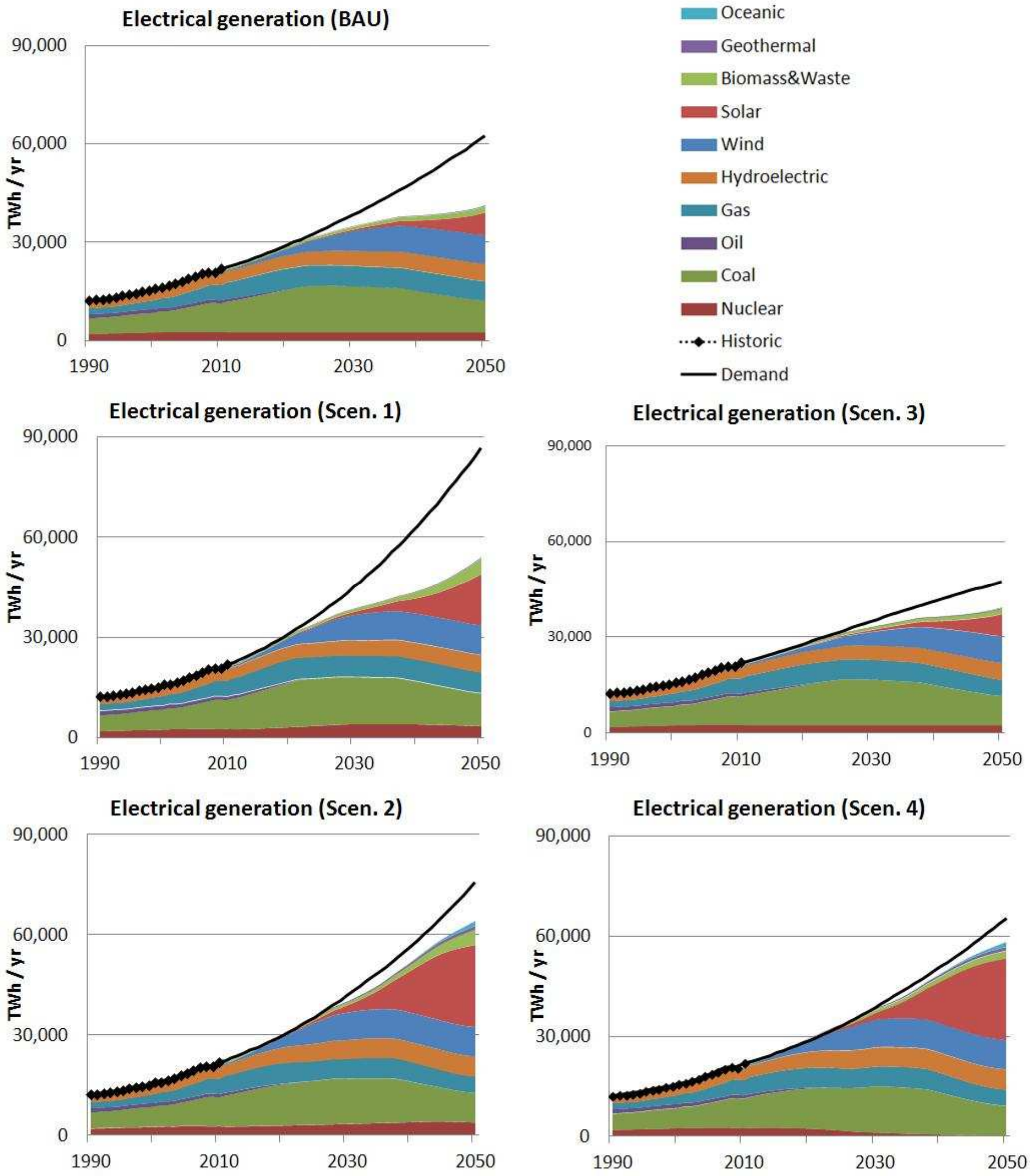

Figure 11: Electricity generation and demand (TWh/yr) by fuel source for each scenario. Historic consumption data increased by transportation losses (9% average) are taken from (US EIA db, 2014) **.**

[19] < http://about.bnef.com/press-releases/strong-growth-for-renewables-expected-through-to-2030/ >

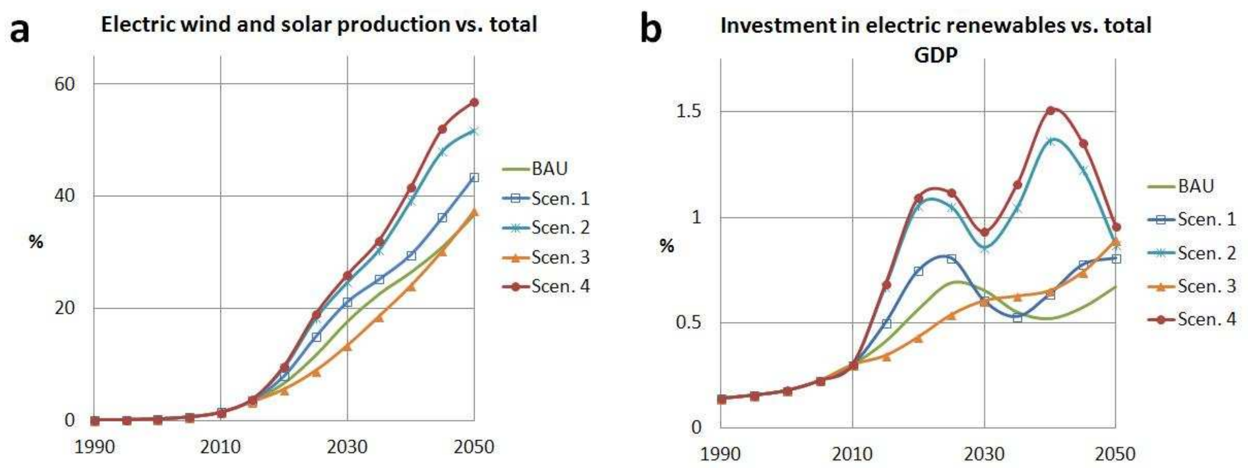

Figure 12: For each scenario, (a) Proportion of variable electric generation (wind and solar) vs. total and (b) Proportion of the investment in electric renewable related to total GDP.

Transportation The comparison of the demand and the supply of energy for transportation can be seen in Figure 13. In spite of the diversity of policies applied in the different scenarios, the peak of conventional oil in the early 2010s determines a decline or stabilization of energy available for transportation. Biofuels, alternative electric and hybrid transport, CTL&GTL (that does not develop significantly in any scenario due to the ending of the crash programs when gas and coal reach their peaks), efficiency improvements, and even the higher development of unconventional oil in Scenario 1, cannot reach a substitution rate able to compensate the conventional oil decline. Thus, as also found in (Mediavilla et al., 2013), ***energy shortages appear in the Transportation sector for all scenarios before 2020*** (Figure 15).

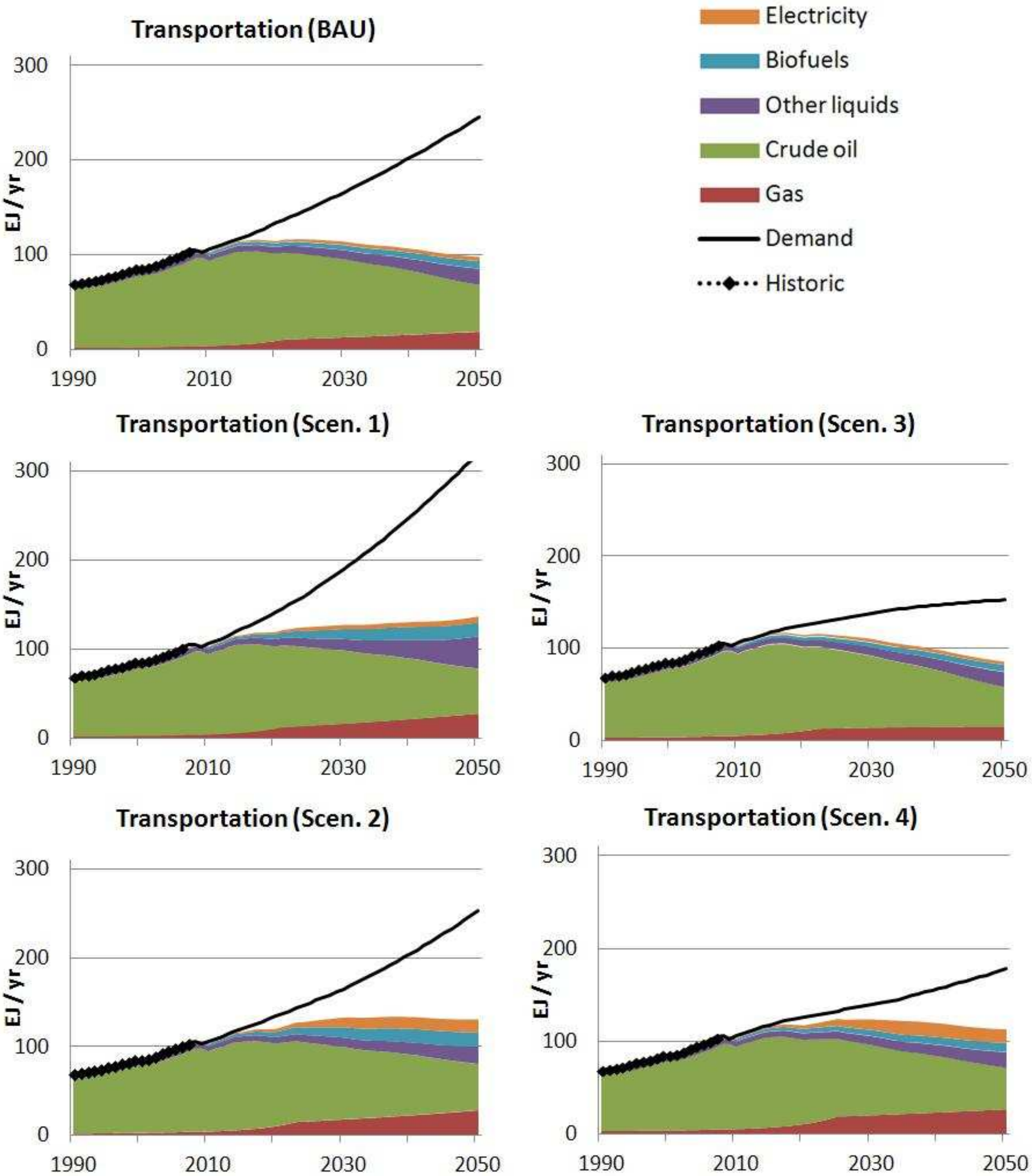

Figure 13: Transportation Primary Energy demand and supply by source fuel (EJ/yr) for each scenario. Historic consumption data is taken from (IEA ETP, 2010). Other liquids include unconventional oil, CTL, GTL and refinery gains. Note: Primary Energy demand is dynamically corrected to take into account the fact that renewable technologies are more efficient than fossil-fuel based ones.

Total Primary Energy (TPE) extraction The comparison of the Total Primary Energy (TPE) demand and extraction can be seen in Figure 14. Broadly speaking, TPE extraction remains below 800 EJ/yr in 2050 (around +50% in relation to the 2010 level). Moreover, the past growth trend (+ 2.6%/yr 1965-2012 (BP, 2013)) cannot be maintained and the yearly energy available by 2050 is either decreasing (-0.7 %/yr in scenarios BAU and 3), roughly stabilized (slower growth than 0.5%/yr in Scenarios 1 and 4) or growing slightly at around 1%/yr in Scenario 2). This occurs because the decrease in fossil fuel extraction can only be partially compensated by renewable energies, alternative policies and efficiency improvements. In fact, between 2020 and 2030, differences between supply and demand appear to be significant in all scenarios (Figure 15).

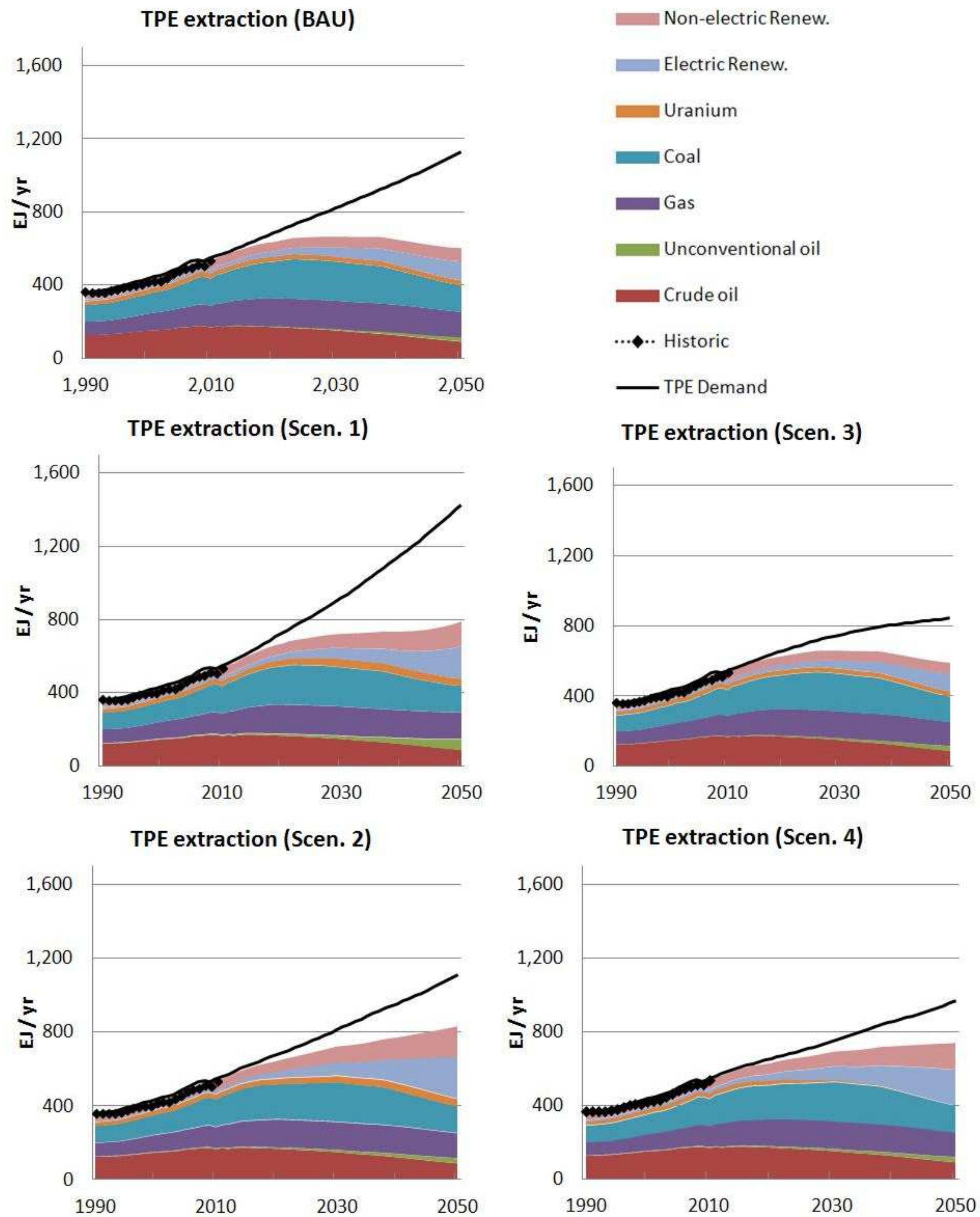

Figure 14: Total Primary Energy extraction and demand by source fuel (EJ/yr) for each scenario. Note: Primary Energy demand is dynamically corrected to take into account the fact that renewable technologies are more efficient that fossil-fuel based ones.

Comprehensive analysis of scenarios: Energy Scarcity Matrix

In order to analyze the supply constraints on the demand of each sector and energy resources for all scenarios, we represent the "Energy Scarcity Matrix" in Figure 15. For each economic sector and non-renewable resource, each point represents the date when the relative difference between the demand and supply is greater than 5%. We select 5% as a qualitative threshold as it is when the price-mechanism adaptation could force important socio-economic structural changes that would modify the underlying hypothesis of the scenarios and the model. For renewable resources, each point represents the date when 95% of the potential is reached. A similar sequence of facts appears for all scenarios:

1- Liquid scarcity in 2015-20 precipitates energy scarcity in the Transportation sector immediately afterwards, and in the IB sector a few years later.

2- Total Primary Energy and Gas scarcity roughly coincide in 2020-25.

3- By 2035, Coal supply is not able to cover its demand in any scenario. Restrictions in the coal supply could appear sooner than usually expected.

4- Electricity generation for all scenarios is not able to fulfill the demand in 2025-2035 (in spite of the strong promotion of renewable energies in some of them).

5- Uranium resources are able to provide the mineral needed to maintain the current production to 2050; however, when even a modest increase in capacity is considered, uranium extraction limits appear.

6- A large expansion of electric renewable energies move us close to their potential limit (e.g. solar), which may even be reached before 2050 (wind and hydroelectric).

As revealed by the scenario approach, these dynamics are not independent: when increasing the number and intensity of links between the non-renewable energies (transition policies), the different peaks tend to converge in time.

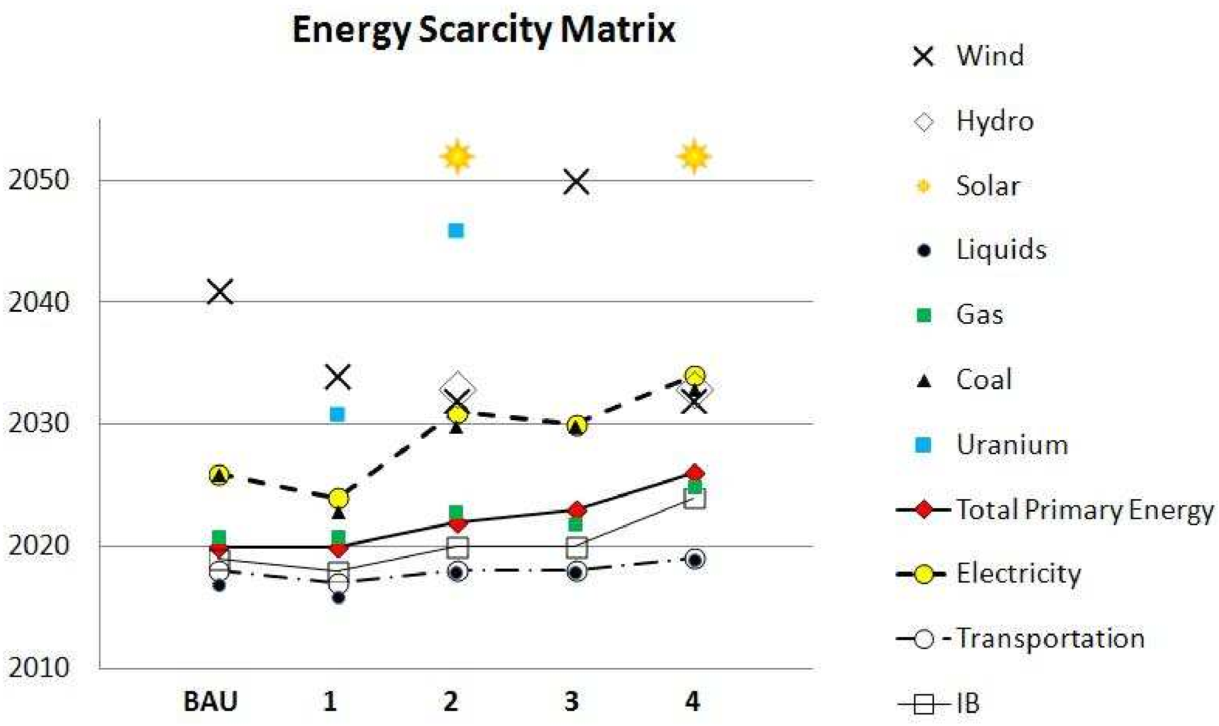

Figure 15: Energy Scarcity Matrix of the scenarios. For each non-renewable resource/sector, we mark the "scarcity point" when the relative difference between supply and demand is greater than 5%. For renewable energies, each point represents the date when 95% of the potential is reached. Strong similarities in the relative scarcity outcomes between scenario 1 and BAU are evident. Note: It may happen that a given resource does not reach its "scarcity point" for a specific scenario (e.g. solar in scenarios BAU, 1 and 3).

Fuel / Sector	**Supply-demand divergence (5%)**
Liquids	2015-2018
Gas	2022-2032
Coal	2024-2034
Uranium	2031-…
TPE	2020-2027
Electricity	2025-2036
Transportation	2015-2018
IB	2017-2025
	Potential reached (95%)

Wind	2032-2050
Solar	2052-…
Hydroelectric	2033-…

Table 6: Supply-demand divergence (7%) and potential reached (95%) range in the 5 modeled scenarios for all fuels and sectors. Data from the Energy Scarcity Matrix from Figure 15.

Finally, in

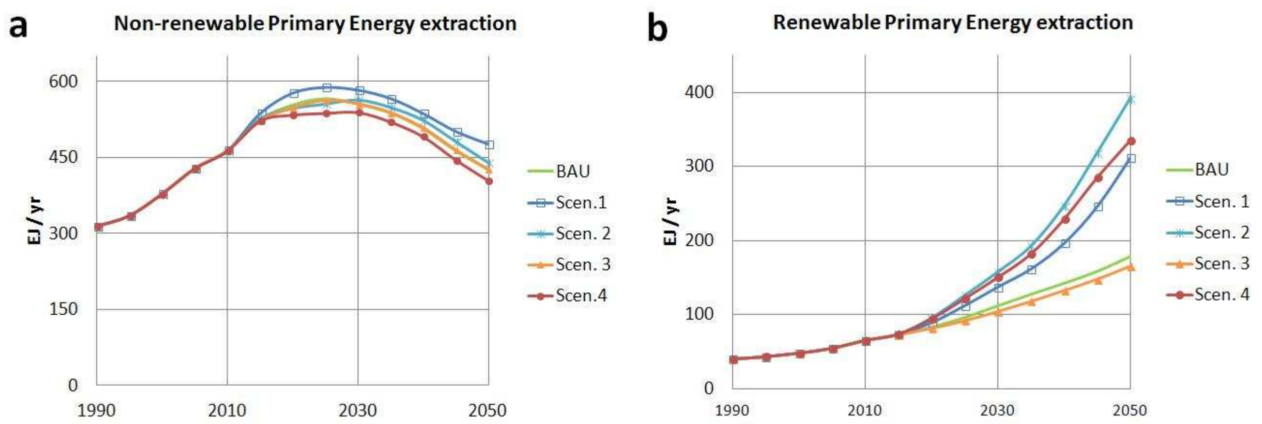

Figure 16-a, the evolution of the extraction of fossil fuels for all scenarios is represented. In spite of the diversity of policies and assumptions applied (notably renewable development, see

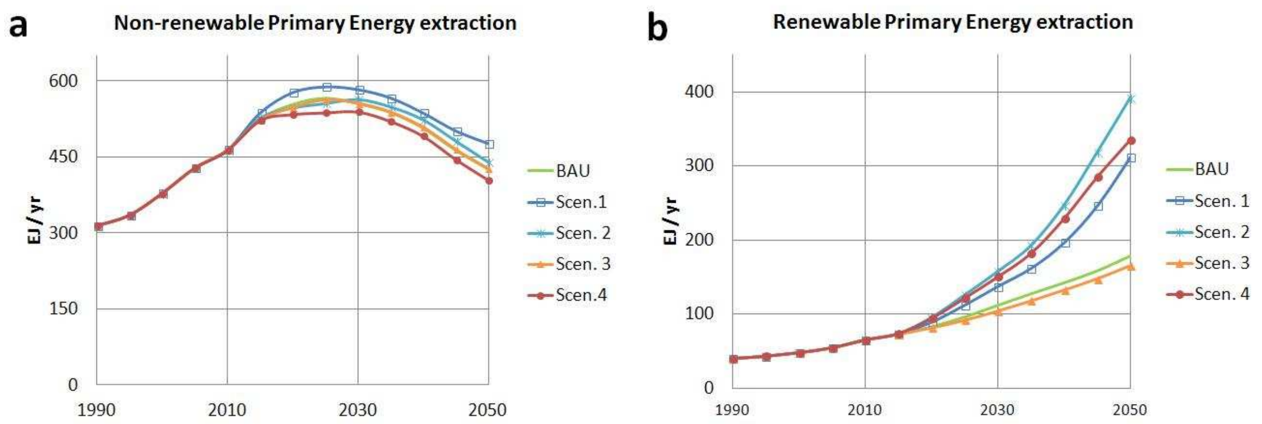

Figure 16-b), a "decline path" for the future extraction of fossil resources emerges, reaching a "plateau" at around 500-525 EJ of maximum extraction between 2020 and 2035, depending on the scenario. This plateau is followed by a sharp reduction between 1 and 1.5 % per year.

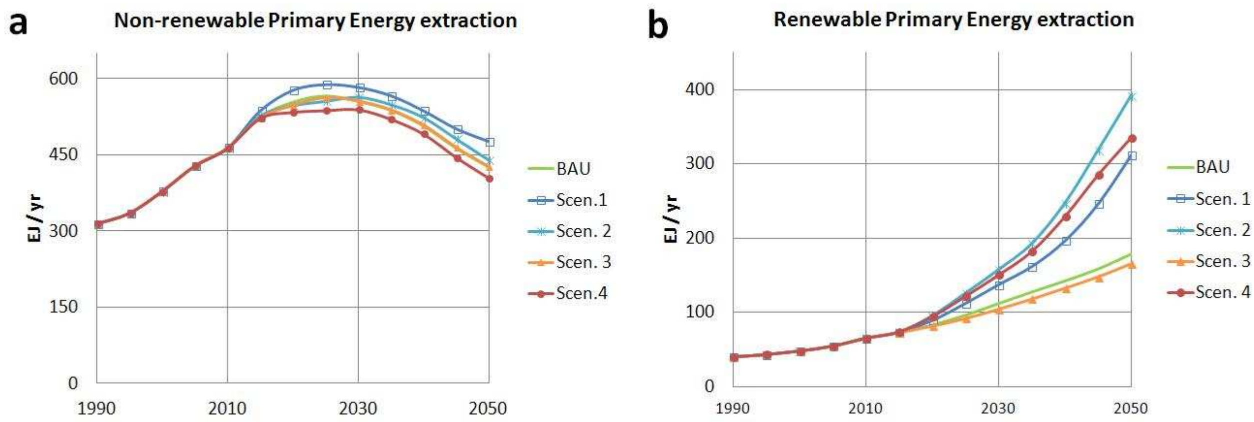

Figure 16: Primary energy resources extracted by scenario: (a) Fossil fuel and (b) Renewable energies.

7.3 Global Warming

The results of CO2 for all scenarios show a peak of emissions in 2020-2030 at 40-45 GtCO2, which is a value 35-50% higher than 2005 emissions (Figure 17-a). Scenarios BAU, 2, 3 and 4 project a decline along the century in a path very similar to B1 from (IPCC SRES, 2000). Scenario 1, however, maintains higher emission levels, similar to the A2 SRES scenario due to the higher extraction of unconventional fuels.

Likewise, all scenarios project similar concentration values in the first half of the century (Figure 17-b), reaching around 475 ppm in 2050. In 2100, all scenarios reach the 550 ppm level, and Scenario 1 almost reaches 600 ppm. Paleoclimate evidence and ongoing climate change suggest that CO2 would need to be reduced to at most 350 ppm if humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted (Hansen et al., 2011, 2008; Rockström et al., 2009).[20] In fact, if high concentration levels are maintained during a certain time, anthropogenic climate change could be boosted by (irreversible) slow feedback dynamics (e.g. ice-free poles). Thus, in all of our scenarios, despite the fact that CO2 emissions fall because of the peak of fossil fuels, these concentrations during the 21st Century are highly alarming and dangerous. Moreover, we consider our results to be optimistic, since the absorption capacity of natural sinks is likely to decrease as the planet warms (Canadell et al., 2007; Le Page et al., 2013).

[20] Institutional talks and agencies consider that the critical threshold for stabilizing climate change *"at a level that would prevent dangerous anthropogenic interference with the climate system"* is 450 ppm: e.g.: UNFCCC (Cancun Agreements), UE, IEA (450 ppm Scenario). However, even this higher value would be exceeded by 2050 in all scenarios.

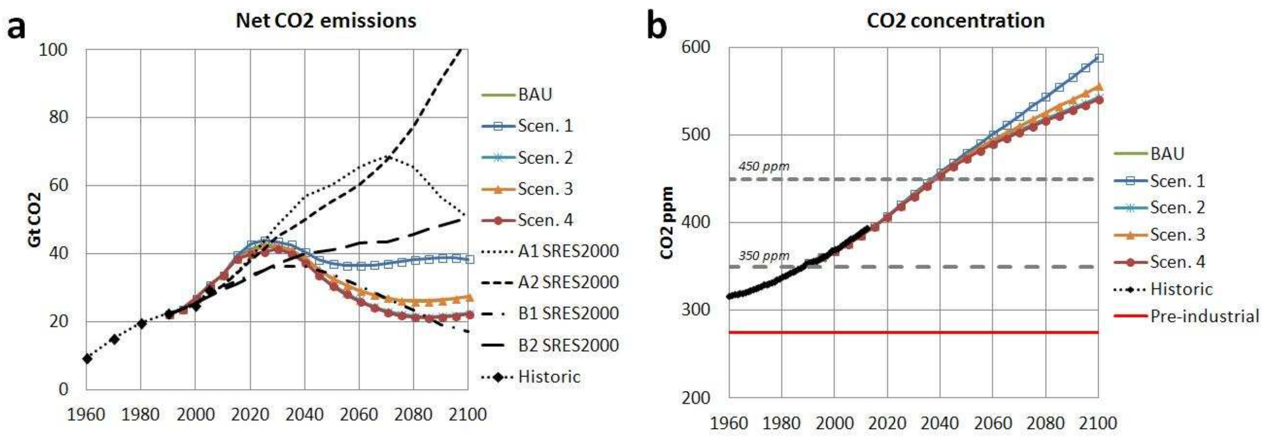

Figure 17: a) Evolution of net CO2 emissions (Gt CO2) for each scenario and comparison with the SRES scenarios A1, A2, B1 and B2; b) Evolution of net CO2 concentration (ppm) for each scenario during 21st Century compared to past historical observations at Mauna Loa and pre-industrial value. Horizontal lines represent the pre-industrial CO2 concentration value (in red) and two different representative thresholds in the literature: 350 ppm and 450 ppm (in grey).

Some other research teams that have studied the links between the structural limits to fossil fuel supply and Climate Change and have found that the emissions levels tend to align with low and medium scenarios from (IPCC, 2007a, 2001; IPCC SRES, 2000) (Brecha, 2008; Nel and Cooper, 2009; Ward et al., 2012), thus corresponding to a moderate climate change (Höök and Tang, 2013). Our results coincide with them; however, even these relatively "low" emission profiles imply that climate change could reach dangerous dimensions.

7.4 Summary and discussion on the results

Our results confirm the short-term lock-in of energy developments and suggest that, *the world socioeconomic system will not be able to follow any of the scenarios proposed to 2050*. Specifically:

- **Electricity generation** seems to be the least worrisome sector, especially in scenarios where electrical renewable generation is strongly promoted. In such cases, saturation in their expansion potential by 2050 is appreciable for some technologies (e.g. hydro and wind).

- **Transportation:** all of the scenarios presented are unfeasible before 2020. Biofuels, alternative electric and hybrid transport, CTL&GTL, efficiency improvements and even the higher development of unconventional oil cannot reach a substitution rate able to compensate the conventional oil decline (even taking the highest estimations for oil resources). In scenarios where deglobalization is simulated, the supply-demand gap is strongly reduced due to a decrease in energy requirements. We identify this feature as a "clue" to developing sustainable scenarios.

- **Total Primary Energy (TPE) extraction**: the supply of TPE can be stabilized or even grow in some scenarios to 2050, but the past growth trend (+ 2.6%/yr 1965-2012) cannot be maintained, since the decrease in fossil fuels extraction can only be partially compensated by alternative technologies and efficiency improvements.

- **Emissions:** All scenarios show a peak in CO_2 emissions in 2020-2030 at 40-45 $GtCO_2$. These emissions profiles are lower than high-medium emissions scenarios from the IPCC; however, they already have the potential to lead to a climate change of dangerous dimensions.

Our results do not intend to describe a plan concerning how the global system will evolve, since, once the first disequilibrium is reached in a sector, the system would evolve in a different way from the scenario proposal. However, compelling conclusions can be extracted: the results indicate that from the current decade, the world socioeconomic system *will progressively be forced to become independent of cheap and abundant energy resources* that were available in the past. In fact, the data of the last few years suggests that past trends are changing (the energy consumption of OECD countries is falling, the oil consumption of Southern Europe is dropping while suffering severe economic crisis, etc.).

We recall again that the exclusion of important issues in the model (see Appendix A) could only exacerbate these trends. Thus, the obtained results suggest that the current socioeconomic paradigm may not be sustainable and continuous economic growth may be rather more the problem than the solution. However, GDP was not designed to measure social welfare (e.g. (van den Bergh, 2009)); and research with welfare indicators show not only that, above a certain level, there is no link between higher GDP per capita and subjective wellbeing, but reductions in GDP per capita may be welfare enhancing (Kubiszewski et al., 2013). Thus, different socio-economic paradigm scenarios can be modeled in order to propose real sustainable future paths such as those proposed by Degrowth (Kallis et al., 2012), Steady-State (Daly, 1996; Kerschner, 2010) or the New Economics of Prosperity (Jackson, 2009) and are the subject of current research.

We add two considerations in relation to the modeling assumptions:

- Of the fossil fuels, coal is the most abundant. However, it is also the least studied from a depletion point of view. Thus, in order to reduce the uncertainty in future global studies, we make a call to motivate further research on this topic.

- All GEA scenarios consider GDP growth. However, our results suggest that the objective of *continued exponential GDP growth* in a system incapable of effective energy-material decoupling should be promptly replaced, instead, by the objective of improving *economic welfare*.

8. Conclusions

In this paper we introduce and apply a System Dynamics model, WoLiM, which aims to fill a gap found among Energy-Economy-Environment models, since few of them integrate the estimations of fossil fuel depletion and alternative energy expectations with the energy demand generated by the socio-economic system. The model is applied to a set of scenarios that replicate the habitual scenarios in Global Environmental Assessment studies (van Vuuren et al., 2012), IPCC's Assessment reports (IPCC, 2007a, 2001; IPCC SRES, 2000), UNEP's Global Environmental Outlook (UNEP, 2012, 2007, 2004) or (MEA, 2005)).

The results show that a significant systemic-energy scarcity risk exists: future global energy demand-driven transitions as performed in the past might be unfeasible. These critical energy constraints have the potential to provoke unexpected abrupt changes in societies and the world configuration, making all 5 implemented families of scenarios from the GEA studies impossible to achieve by 2050. Transportation is the most critical sector due to the stagnation of liquids fuel production and the inefficacy of all compensation policies before 2020. The Electricity sector seems the least worrisome, especially in scenarios where electrical renewable generation is strongly promoted. However, CO_2 levels still have the potential to lead to a climate change of dangerous dimensions by the mid-century. Moreover, the use of unconventional fuels in a context of rising demand-supply divergence will tend to induce energy prices to grow in the future with very likely adverse economic impacts (Murphy and Hall, 2011; Tverberg, 2012).

In order to find global scenarios compatible with fossil fuel restrictions and sensible limits to technological development, we are obliged to set hypotheses which are hardly used in Global Assessment scenarios, such as zero or negative economic growth. Therefore, an *authentic economic paradigm shift* might be needed in order to avoid dangerous energy lock-in pathways in a context of climate deterioration in the coming decades.

Most of the current Economy-Energy-Environment models tend to use (very) large resource estimates that are subject to high uncertainties and are strongly biased towards overestimation. The analysis performed here shows that depletion should be incorporated into such policy-influential analyses as the IEA and IPCC reports.

In spite of our narrower scope, our conclusions meet with the *Limits to Growth* reports (reinforced after 40 years of favorable comparison (Turner, 2012, 2008)), which stated that *"current policies will produce global overshoot and collapse through ineffective efforts to anticipate and cope with ecological limits"* in the first half of the 21st Century, pledging *"profound, proactive, societal innovation through technological, cultural and institutional change*" (Meadows et al., 2004, 1993, 1972).

Acknowledgments

The authors gratefully acknowledge Steve Mohr and Gaetano Maggio for their valuable comments and share of data.

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Appendix A. Basic structure of the model

Figures A1 and A2 show an overview of the Forrester diagram of WoLiM, where the main relationships and subsystems can be seen. Demands are shown in green, non renewable resources in light blue, renewable electricity in dark blue, policies in red and emissions in orange[21].

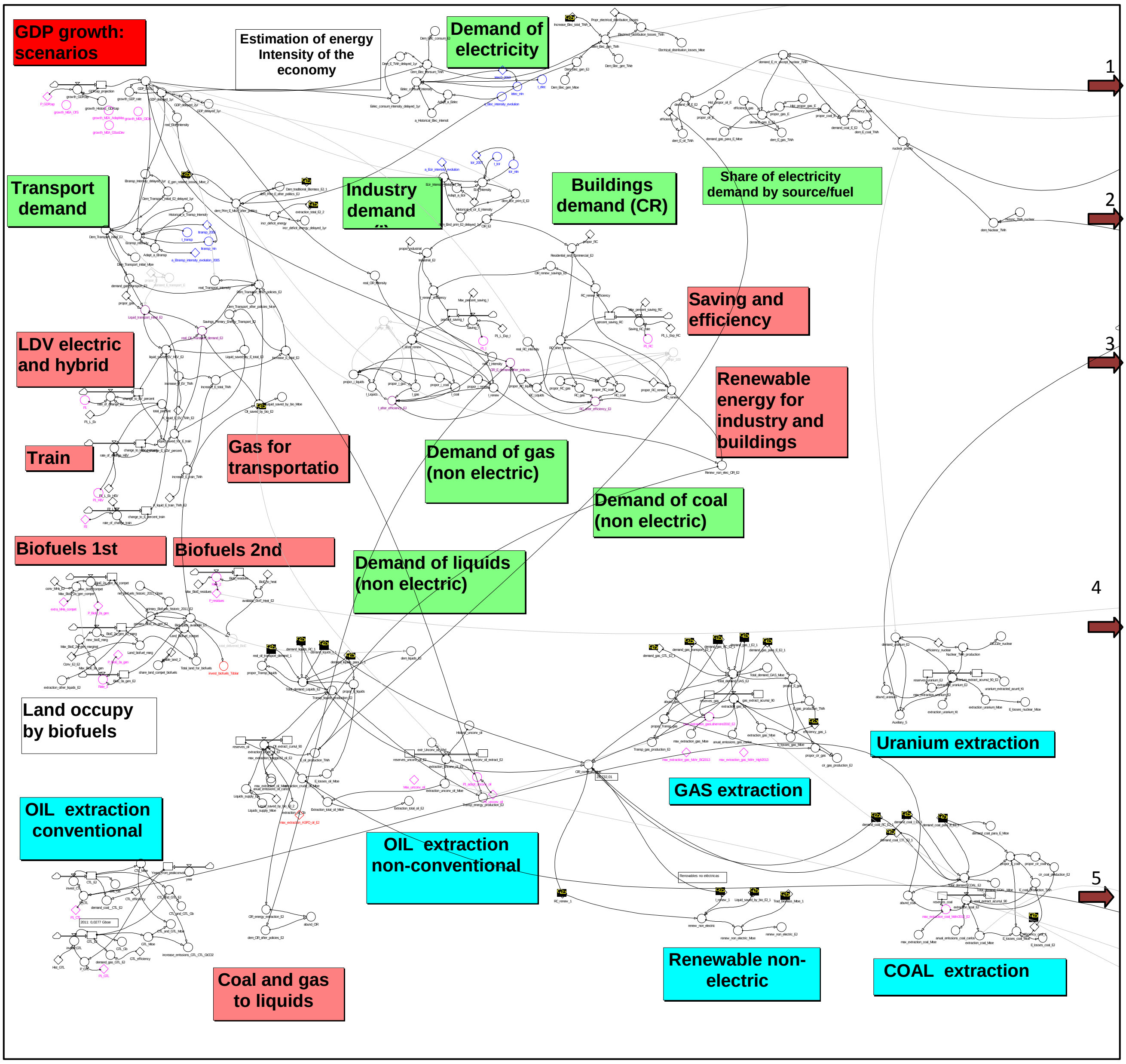

Figure A1: Forrester diagram of WoLiM model (left side). Stocks are represented as squares, flows by the arrows related to stocks, variables are represented by circles and constants by rhombus. Most of the relationships between variables are represented by lines but some are hidden for simplicity

[21] For a complete description of the model, please see (Capellán-Pérez et al., 2014).

*Capellán-Pérez, I, et al., "**Fossil Fuel Depletion and Socio-Economic Scenarios: An Integrated Approach**." Energy. Accessed October 25, 2014. doi:10.1016/j.energy.2014.09.063.*

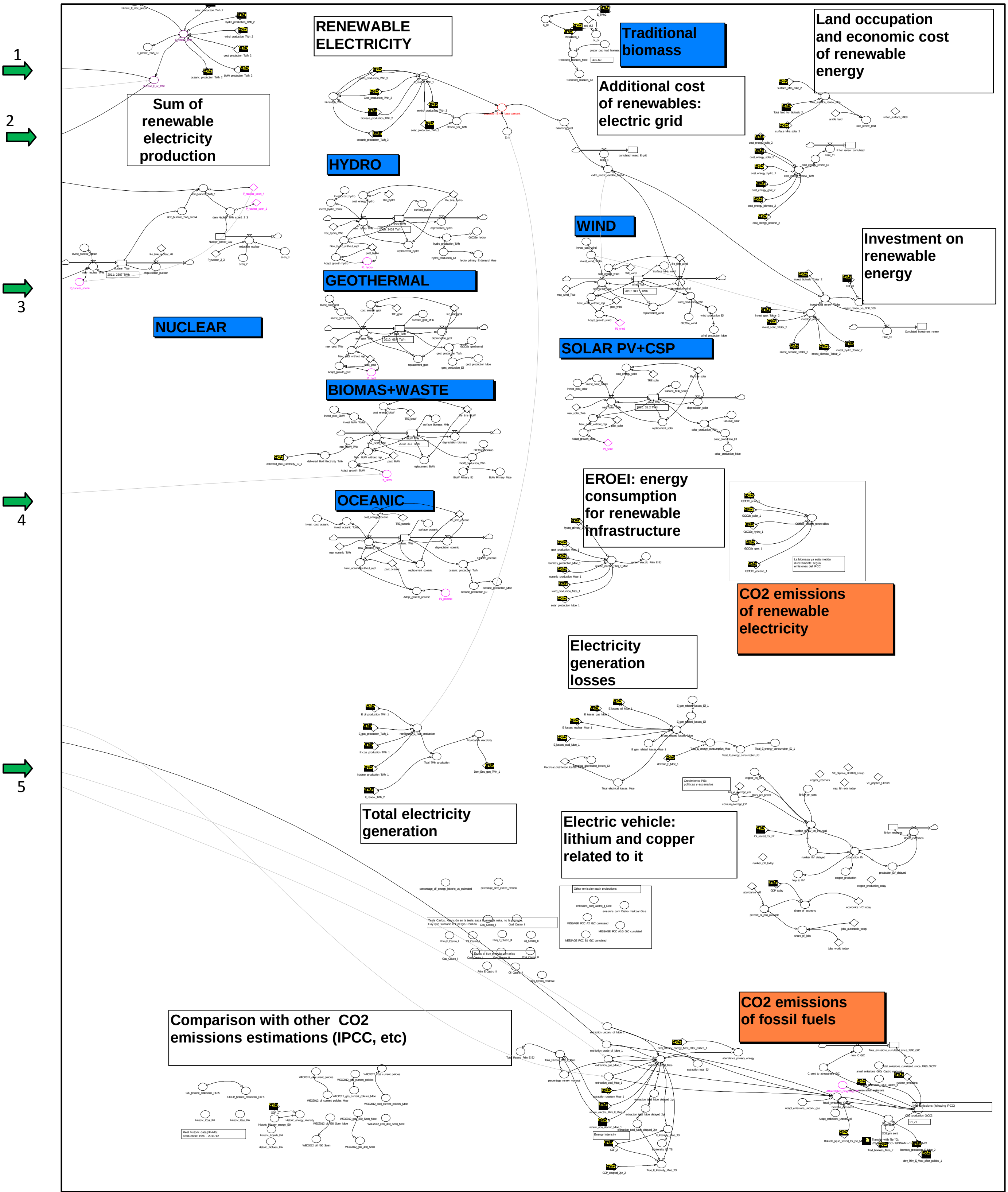

Figure A2: Forrester diagram of WoLiM model (right side). Stocks are represented as squares, flows by the arrows related to stocks, variables are represented by circles and constant by rhombus . Most of the relationships between variables are represented by lines but some are hidden in order to simplify the graph.

Appendix B. Integration of resource curves

The maximum energy resource extraction curves, described in section 3, are curves of maximum energy extraction as a function of time. In order to use them in the model they 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 and studies how this stock is emptied depending on production, which is in turn determined by demand and maximum extraction.

Figure B1 gives a hypothetical example of the dynamic model used (left) and an example of a maximum production curve (right). The x-axis of Figure B1(right) represents the stock of non-renewable energy available. The y-axis represents the maximum production of this energy that could be obtained depending on the stock of the resource still unexploited. As can be seen, when the resources diminish, the maximum production decreases until it reaches zero (when the resource is exhausted). The Forrester diagram of Figure B1(left) shows the **stock of resources.** A variable called **maximum production** is calculated as a function of the **stock of resources** and a curve similar to the one of Figure B1(right). **Stock of resources** is emptied by the flow called **Extraction**, whose value is the minimum between **demand** and **maximum production**.

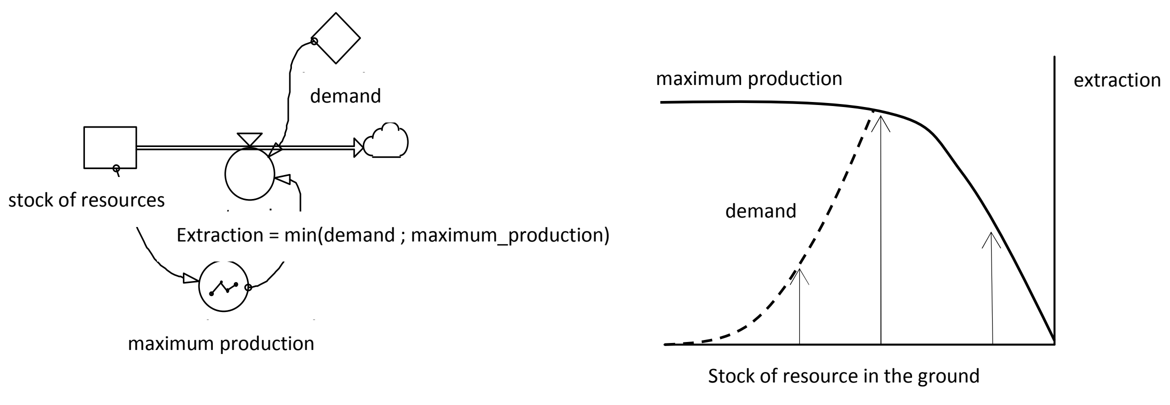

Figure B1: Maximum production curves as a function of resources. Left: the Forrester diagram used to model extraction. Right: a curve of maximum production (solid) compared with the demand (dashed). Both curves meet when the peak of the resource is reached.

Appendix C: Renewable energies modeling

The growth of the renewable electricity production from all sources is modeled by a similar structure to the one presented in Figure C1 for solar. The Forrester diagram shows the stock of renewable electricity infrastructure (**solar_TWe**) with its two flows: the inflow of new infrastructure determined by investments (**new_solar_TWe**), and the outflow determined by the depreciation (**depreciation_solar**) driven by the lifetime (**life_time_solar**).

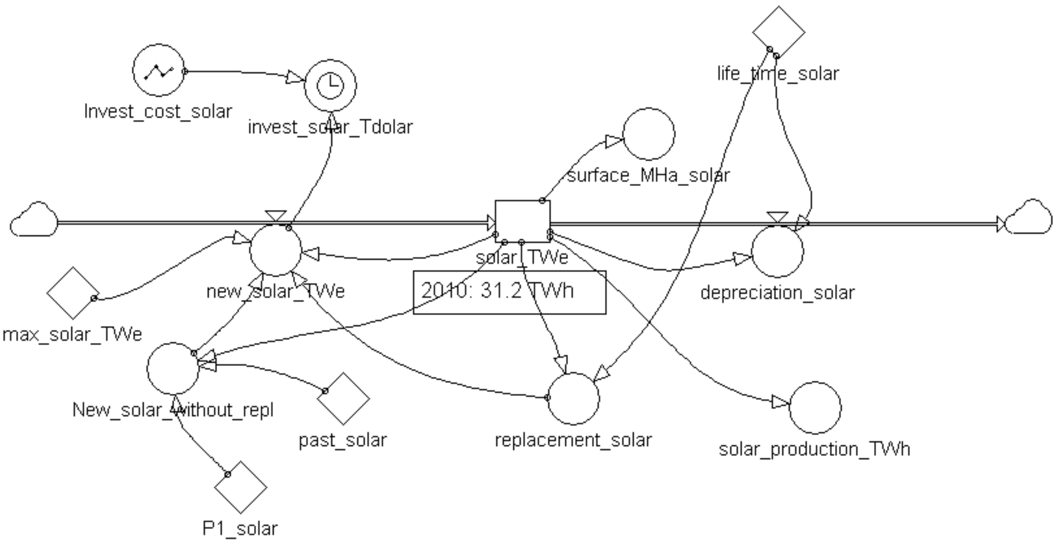

Figure C1: Structure of the renewable electric technologies (here, solar).

Therefore, the equation that determines **Solar_TWe** is:

$$\frac{d(solar_{TWe})}{dt} = \text{new\_solar\_TWe} - \text{depreciation\_solar} \qquad \text{Equation D2}$$

Replacement_solar just compensates for the depreciation rate, and **P1_solar** represents the annual growth considered in each scenario. However, this growth is adjusted to a function that introduces diminishing returns on the new solar power (**new_solar_TWe**) depending on the proximity to the potential (**max_solar_TWe**); creating a feedback loop that reduces the exogenous growth initially set (logistic growth):

$$New\_solar(t) = replacement\_solar + P1\_solar(t) * solar\_Twe(t-1) * (max\_solar\_TWe - solar\_Twe(t-1))/(max\_solar\_TWe)$$

Equation D1

The model also accounts for the electrical production (**solar_production_TWh**), the land occupied (**surface_MHa_solar**) and the investment required (**invest_solar_Tdolar**):

Appendix D: Modeling of alternative technologies and saving policies

The policies that represent alternatives to oil, non-electrical renewable energies and saving (biofuels, electric and hybrid vehicle, train, savings and renewable thermal energy for buildings and industry) are described in the model with a similar structure to the one represented in Figure D1 (savings in the industry sector in this case). The thermal uses of renewable energies are not explicit or assigned to a concrete technology (except for the 3rd generation biomass residues), but modeled as a general policy, in the same way as done in WORLD3 (Meadows et al., 2004).

In the example of Figure D1, the total Industrial energy demand (**Industry_EJ**) is calculated in a different part of the model (as a function of GDP and sectoral intensities). The stock variable **percent_saving_I** represents the share to the total Industrial energy demand that is concerned with the transition policies. This variable is a stock because it is assumed that these savings accumulate as the change to better equipment is done. The variable **percent_saving_I** causes a drop in energy demand, and the variables **dem_industrial_after_savings** and **I_after_renew** account for the new demand, which is divided into the demands of individual fuels (**I_gas, I_coal, I_oil, I_renew**) according to a share consistent with the past evolution.

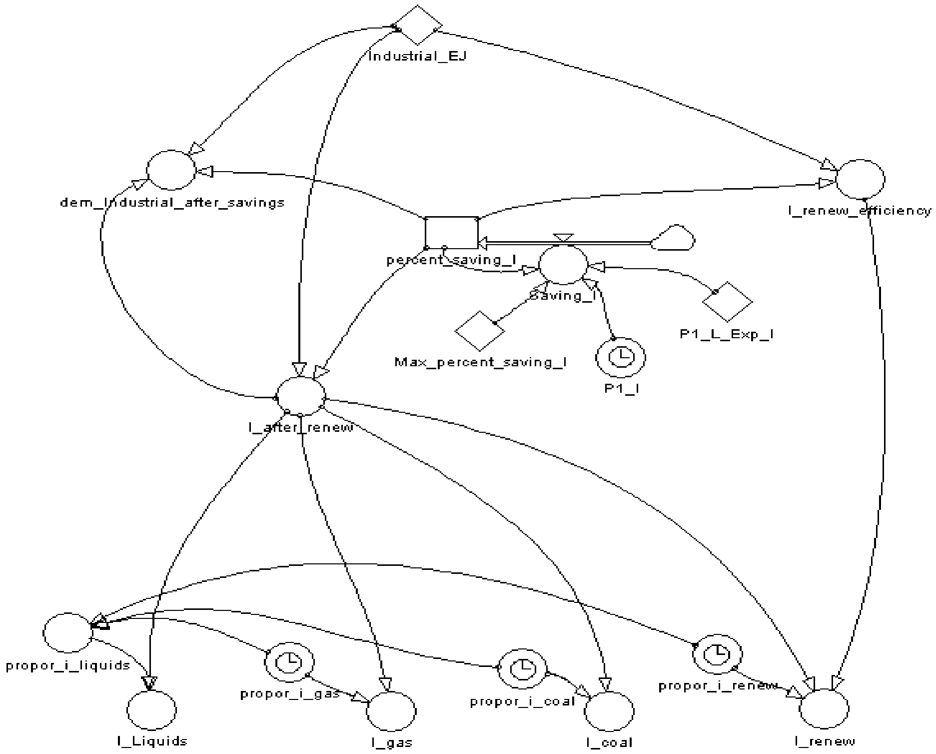

Figure D1: Forrester diagram of the representation of the Industrial sector and the policies applied.

Appendix E: Limitations of the modeling

As mentioned in the paper, the modeling of complex systems always implies a trade-off between simplicity and the loss of detail. Thus, uncertainties and limitations arise: some are solvable (and are targeted as "future research directions"), while others are related to unavoidable judgment calls in the extrapolation of the future. Among the first are:

- **Non-inclusion of Energy Return of Energy Investment (EROEI)**: The model operates in terms of primary energy, but in reality the useful energy used by society (Net Energy) in the future may decrease at the same time as the EROEI of the non-renewable resources diminishes, due to the smaller EROEI of unconventional resources (Murphy and Hall, 2010). Some modern renewable energies also perform low EROEI ratios (e.g. solar (Prieto and Hall, 2013)).

- **Non-inclusion of material limits and other non energetic renewable sources** (e.g. water availability (Postel, 2000), minerals (e.g. phosphorus (Cordell et al., 2009), copper (Harmsen et al., 2013)).

- **Absence of dynamic feedback between the main subsystems**. In this model version, climate impacts and energy scarcity are not fed back to the economic system. Similar studies have shown that models are biased optimistically when feedback is omitted (e.g. (Barney, 1980; Randers, 2000)). The (MEA, 2005) report concluded that approximately 60% (15 out of 24) of the ecosystem services examined are currently being degraded or used unsustainably. Also, (Rockström et al., 2009) identifies 3 out of 10 planetary boundaries that have already been overstepped. However, high uncertainties are involved in the feedback quantification and remain beyond the scope of this paper.

- **Others:** intermittency of renewable energies, non-consideration of phenomenons such as the "energy trap", the rebound effect, conflicts (within and between countries, e.g. corruption, wars), unexpected events (e.g. natural disasters), etc.

The omission of restrictions when solving a system can only lead to optimistic results. However, interesting conclusions have already been extracted and ongoing research on these issues will explore the influence of these constraints.

On the other hand, other assumptions such as the non-modeling of technology-fuel competition (through cost and efficiency as typically done in demand-driven models), might seem as in significant weakness of the model. However, since in all scenarios the peak of all fossil fuels occurs in the range of 15-20 years, the introduction of the competition would only tend to slightly delay the first "scarcity points" while hastening the last ones. In brief, for each scenario, the points in Figure 15 would tend to converge in time, thus, not affecting the main conclusions of the work. However, from a societal point of view, the transition might be less challenging if the "scarcity points" are more spread in time.

Appendix F: Potential of bioenergy

The techno-ecological potential estimation of bioenergy depends critically on the future land availability. The foreseeable growth of land for food over the next few decades (due to population and affluence growth) is projected to be 200–750 MHa (Balmford et al., 2005; Bruinsma, 2003; Rockström et al., 2007; Schade and Pimentel, 2010), while the projected growth of new infrastructures because of population and affluence growth is more than 100 MHa. Moreover, it is estimated that current and future crop yields will be affected negatively by climate change (IPCC, 2014), offsetting potential productivity gains from technological innovation. According to (FAOSTAT, 2014), there were 1,526 MHa of arable land and permanent crops in 2011. In view of the current situation, in which almost 15% of the world population is undernourished (FAO, 2012), a very large surface for bioenergy at global level is not compatible with future scenarios, such as the ones explored in this paper.

For the sake of simplicity, we decided to divide it into 3 categories for differentiated uses: traditional biomass, dedicated crops for biofuels and residues for thermal uses (Municipal Solid Waste and 3rd generation). The techno-ecological potential estimation of these categories is a sensitive and complex task: different lands (e.g. current arable vs. marginal) have different productivities, land competition issues, etc. The energy density and potentials assumed for each resource are presented in Table F1. These values are based on estimations from (de Castro et al., 2013a; Field et al., 2008; UNEP, 2009, p. 2009; WBGU, 2008) and our assumptions are detailed in (Capellán-Pérez et al., 2014).

		Reference	Surface	Gross power density	Potential
			MHa	W/m2	EJ/yr
2nd generation	Marginal lands	(Field et al., 2008)	386	0.033[a]	4.1 (gross power)
	World average	(de Castro et al., 2013a)	100 (standard scenario)	0.155[b]	4.9 (gross power)
3rd generation (from 2025)	Dedicated crops	(WBGU, 2008)	0	0.18	+2.3 (gross power)
	Agriculture & Forestry residues	Own estimation	-	-	25 (NPP)

Table F1: Bioenergy power density and potentials assumed for each resource. Other potential resources, such as 4th generation biomass (algae), are not considered due to the high uncertainties of the technology and the long-term nature of its eventual commercial appearance (Janda et al., 2012).

NPP: Net Primary Production.

[a] (Field et al., 2008) find that 27 EJ of NPP can be extracted from 386 Mha of marginal lands. A transformation efficiency to biofuels of 15% is assumed.

[b] The gross power density for the best quality lands was estimated at 0.3-0.36 W/m2 in Brazil (de Castro et al., 2013a).

Appendix G: Potential of renewable electricity

Techno-ecological potential of renewable energies as estimated by (Capellán-Pérez et al., 2014; de Castro et al., 2013b, 2011) are shown in table G1. These limits are lower than some other estimations found in the literature mainly because they consider aspects frequently ignored such as the prorated degradation of the cells over the entire life cycle, maintenance, self-consumption or the real land occupation of the solar parks (not only he panels).

	Techno-ecological potential	Investment cost		
References	(Capellán-Pérez et al., 2014; de Castro et al., 2013b, 2011)	(Teske et al., 2011)		
Technology/Unit	TWe	2011$/We		
		2010	2030	2050
Hydroelectricity	0.5	4.8	6.3	6.9
Wind[a]	1	8.3	6.6	6
Solar	3	26.9	7.4	7.4[b]
Waste & MSW	0.3	3.9	3.3	3.2
Geothermal	0.2	15.9	9.3	6.6
Oceanic	0.05	9.2	2.8	2.1
TOTAL	5.05			

Table G1: Data of electric renewable in the model. "TWe" represents power electric production: TWh/8760. [a]The learning curve for wind is adapted from (Teske et al., 2011) in order to aggregate both onshore and offshore wind. [b] The solar investment cost is maintained constant after 2030 since we judge it to be too optimistic that the solar technologies will manage to be less expensive than wind. In fact, in recent years, the price of solar modules has fallen significantly due to efficiency improvements but also to dumping and excess capacity effects in the crisis.

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