More Growth? An unfeasible option to overcome critical energy constraints and climate change

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Iñigo Capellán-Pérez[a,1,]*, Margarita Mediavilla[b], Carlos de Castro[c], Óscar Carpintero[d], Luis Javier Miguel[b]

[a]*Low Carbon Programme. Instituto de Economía Pública, University of the Basque Country (Spain).*
[b]*Systems Engineering and Automatic Control, Escuela de Ingenierías Industriales, Paseo del Cauce s/n, University of Valladolid, 47011 Valladolid, Spain.*
[c]*Applied Physics department, Escuela de Arquitectura, Av. Salamanca, 18 , University of Valladolid, 47014 Valladolid, Spain.*
[d]*Department of Applied Economics, University of Valladolid, Valladolid, Spain.*

*Corresponding author: inigo.capellan@ehu.es.
[1]The opinions expressed in this paper are the authors' own opinions and do not necessarily correspond with those of the Low Carbon Programme.

Abstract

Growing scientific evidence shows that world energy resources are entering a period shaped by the depletion of high quality fuels, whilst the decline of the easy-to-extract oil is a widely recognized ongoing phenomenon. The end of the era of cheap and abundant energy flows brings the issue of economic growth into question, stimulating research for alternatives as the de-growth proposal.

The present paper applies the system dynamic global model WoLiM that allows economic, energy and climate dynamics to be analyzed in an integrated way. The results show that, if the growth paradigm is maintained, the decrease in fossil fuel extraction can only be partially compensated by renewable energies, alternative policies and efficiency improvements, very likely causing systemic energy shortage in the next decades. If a massive transition to coal would be promoted in order to try to compensate the decline of oil and gas and maintain economic growth, the climate would be then very deeply disturbed. The results suggest that growth and globalization scenarios are, not only undesirable from the environmental point of view, but also not feasible. Furthermore, regionalization scenarios without abandoning the current growth GDP focus would set the grounds for a pessimistic panorama from the point of view of peace, democracy and equity.

In this sense, an organized material de-growth in the North followed by a steady-state shows up as a valid framework to achieve global future human welfare and sustainability. The exercise qualitatively illustrates the magnitude of the challenge: the most industrialized countries should reduce, on average, their per capita primary energy use rate at least 4 times and decrease their per capita GDP to roughly present global average levels. Differently from the current dominant perceptions, these consumption reductions might actually be welfare enhancing. However, the attainment of these targets would require deep structural changes in the socioeconomic systems in combination with a radical shift in geopolitical relationships.

Keywords: renewable limits, fossil fuel depletion, global warming, system dynamics, peak oil, scenarios.

1. Introduction

The current energy crisis, and notably peak oil, is at the heart of the de-growth proposals (Latouche 2006; Alier 2009; Martínez-Alier et al. 2010; Kallis 2011; Kerschner 2014), as it is for other proposed alternatives to the growth paradigm (Daly 1991; Jackson 2009; van den Bergh 2011; García-Olivares and Solé 2015). We interpret the energy crisis as a progressive and already ongoing reduction of high-quality-easy-to-extract, and therefore cheap, energy.

The average world energy consumption per capita has increased almost 4 times (10-15 times in developed countries) since the Industrial Revolution (Smil 2008). The intensive and growing consumption of high quality and economically affordable energy is an essential element of the functioning of current wealthy societies (Cleveland et al. 2000; Murphy and Hall 2011; Ayres et al. 2013; Bithas and Kalimeris 2013). Whether these energy consumption intensification trends are to be followed by Southern countries is challenged by a body of literature in expansion that disputes the conventional view of the vast abundance of non-renewable resources, especially in the field of fossil fuels (Campbell and Laherrère 1998; ASPO 2009; Höök et al. 2009; Sorrell et al. 2010; Heinberg and Fridley 2010; Rutledge 2011; Maggio and Cacciola 2012; EWG 2013; Mohr et al. 2015), but also for other fuels and materials (Bardi 2014; Valero and Valero 2014).[1] Moreover, it is argued that the interaction of these supply restrictions with the economic and financial system might have strong economic consequences (Reynolds 1999; Hirsch 2008; Hamilton 2009; Murphy and Hall 2011; Tverberg 2012; Murphy 2012; Kerschner et al. 2013).

On the other hand, energy consumption drives climatic change (IPCC 2014a). Yet few studies have focused on the effect of energy scarcity in climate (Kharecha and Hansen 2008; Ward et al. 2012; Höök and Tang 2013; Capellán-Pérez et al. 2014a; Mohr et al. 2015). In fact, the exhaustion of conventional fuels is already leading to the increasing use of unconventional resources that are characterized by considerably worse energy return on energy invested (EROEI) and higher CO_2 emission rates (Capellán-Pérez et al. 2014a). It is commonly assumed that the greenhouse problem can be solved by the combination of efficiency improvement, sequestration of CO_2, and by shifting from fossil fuels to extraordinary abundant renewable sources (IPCC 2011; Kerschner and O'Neill 2016). However, the large scale deployment of renewable alternatives faces serious challenges in relation to their integration in the electricity mix due to their intermittency, seasonality and uneven spatial distribution requiring storage (Trainer 2007; Smil 2008; Lenzen 2010), their lower energy density (Smil 2008; de Castro et al. 2011; de Castro et al. 2013; de

[1] The peak of conventional oil constitutes a paradigmatic example. (Campbell and Laherrère 1998) recovered (Hubbert 1956) theory, and carried out a study that "*conclude[d] that the [conventional oil production] decline will begin before 2010*". This study inaugurated a decade of fertile analysis of the projection of oil and gas maximum extraction studies that were, however, largely ignored by mainstream science and international scientific and governmental bodies (e.g. (Aleklett et al. 2010; Höök and Tang 2013)). However, in 2010, the *IEA* stated in their annual report that the maximum extraction of conventional oil was reached in 2006 (WEO 2010) and a debate also exists in the *IMF* (Benes et al. 2012).

Castro et al. 2014) and lower EROEI than fossil resources (Prieto and Hall 2013), their dependence on minerals and materials for the construction of power plants and related infrastructures that pose similar problems than non-renewable energy resources depletion (García-Olivares et al. 2012; de Castro et al. 2013), and their associated environmental impacts (Keith et al. 2004; Danielsen et al. 2009; Miller et al. 2011; Abbasi and Abbasi 2012), which all together significantly reduce their sustainable potential (Trainer 2007; Smil 2008; de Castro et al. 2011; de Castro et al. 2013; Capellán-Pérez et al. 2014a; de Castro et al. 2014).

Of the fossil fuels, coal is largely the most abundant but also the least studied from a depletion point of view. Research teams and approaches to forecast its future evolution are few in number (Patzek and Croft 2010; Laherrère 2010; Höök et al. 2010; Rutledge 2011; Maggio and Cacciola 2012; Mohr et al. 2015). However, most of these analyses fail to represent the recent coal trends (+70% growth since 1999 (BP 2014)). Since a controversy about the coal extraction limits also exists (e.g. (Thielemann 2012)) and the range found in the literature is broad (Dale 2012), in this paper, we pay special attention to coal as an energy source which could be envisaged to compensate the decline of oil and natural gas. In fact, the promotion of a coal-based economy in energy crisis contexts has already happened in the past (Stranges 2007; Höök and Aleklett 2010).

On the other hand, a strong debate has re-emerged recently around the critique of the growth economy, which is diagnosed as ecologically unsound, economically unsustainable and no longer improving social welfare and happiness (Daly 1996; Jackson 2009; Kerschner 2010; Martínez-Alier et al. 2010; Kallis et al. 2012). "*A starting premise* for [sustainable de-growth proposals] *is that resource and CO_2 limits render further growth of the economy unsustainable*" (Kallis et al. 2012), which directly connects with previous work with the World Limits Model (WoLiM) model. In fact, (Capellán-Pérez et al. 2014a) showed that GDP growth scenarios have the potential to lead the socio-economic system to structural energy scarcity in the next two decades in a context of climate deterioration, suggesting that an energy demand-driven transition as performed in the past might be unfeasible without an *authentic* paradigm shift. Thus, "no-GDP-growth" socioeconomic paradigm scenarios to face the energy crisis are modeled in this paper, with special attention being paid to reaching "acceptable" climate outputs by 2050. Moreover, special attention is devoted to equality as a central element of a stable and sustainable future (Motesharrei et al. 2014).

The modeling and scenario simulation of alternatives to the growth paradigm is a minority field in the literature in relation to other more common theoretical approaches (e.g. critique to growth, actors and strategies, links to democracy/autonomy, etc.). A first group of studies has focused on the modeling of degrowth scenarios for developed economies such as Canada (Victor 2008; Victor 2012) and UK (Jackson and Victor 2011), while (Stocker et al. 2014) studied a low-growth path for Austria. (Bilancini and D'Alessandro 2012) approached the topic from a theoretical economic point of view. A second group has explored the long-term economic implications of the depletion of high-quality energy resources at national (Ayres 2006; D'Alessandro et al. 2010; García-Olivares and

Ballabrera-Poy 2015) and global (Meadows et al. 1972; Meadows et al. 2004; Nel and Cooper 2009; de Castro et al. 2009; Yücel and Barlas 2010; Dale et al. 2012; Capellán-Pérez et al. 2014a) level, concluding that growth of developed countries could cease in the next few decades. In spite of the simulation effort of the 1970s (Meadows et al. 1972), few studies have explored alternatives to the growth paradigm from a global perspective (Raskin et al. 2010). Moreover, this focus has been recently proposed in order to effectively achieve climate stabilization (Anderson and Bows 2011; Anderson and Bows 2012). This paper contributes to this gap in the literature proposing an explorative "no-GDP-growth focus" modeling exercise from the global energy and climate perspectives.

The paper is organized as follows: Section 2 overviews the applied methodology, describing the WoLiM model and the scenarios implemented. Section 3 overviews the results and assess the feasibility of scenarios. Section 4 explores the implications of a feasible, sustainable and desirable global future. Finally, Section 5 sets out the conclusions.

2. Methodology

A dual analysis is proposed by combining the scenario approach with WoLiM System Dynamics (SD) modeling. On the one hand, scenario approach provides a set of consistent narratives (i.e. storylines) that is subsequently implemented into the model to assess the physical and dynamical feasibility of each scenario. Finally, among those feasible scenarios, their desirability is assessed in terms of the preferred narratives.

2.1. Overview of the WoLiM model

WoLiM is a simulation SD model that focus on energy resource constraints and its implications for human socioeconomic systems at world aggregated level, which is a continuation of previous models (de Castro 2009; de Castro et al. 2009; Mediavilla et al. 2013). It aims to describe the relation between Economy-Energy-Environment focusing on biophysical limits, deployment potential of renewable and non-renewable energies, efficiency, alternative technologies as well as on anthropogenic Climate Change (Capellán-Pérez et al. 2014a; Capellán-Pérez et al. 2014b). The model includes the following trends in a dynamic framework:

- The exhaustion patterns of non-renewable resources,
- 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.

The standard version of WoLiM 1.0 is based on a lineal structure 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 and that allow potential energy scarcity risks to be detected while tracking climate evolution (Figure 1).

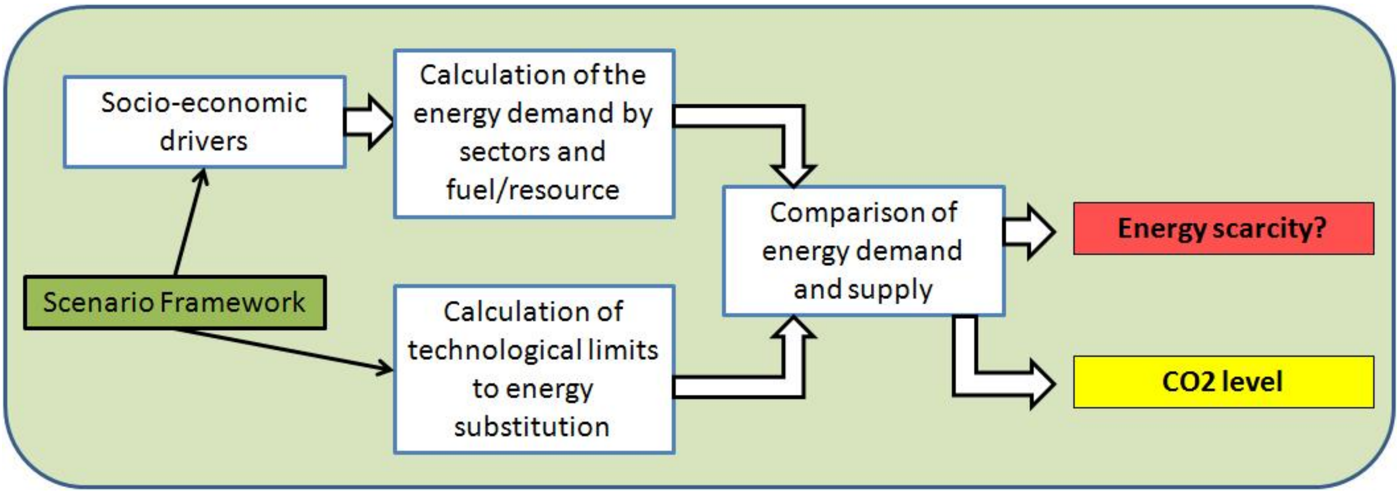

Figure 1: Functioning of the standard version of WoLiM model.

GDP[2] and population projections in combination with technological assumptions establish the world energy demand by 3 aggregated sectors (Transportation, Electricity and Industrial and Buildings (IB)). Each sectoral end-use energy demand (electricity, liquid fuels, etc) is ultimately disaggregated into the primary energy demand by resources (oil, gas, etc.). These demands are compared with the extraction of each particular resource, which is limited by the geology-based peaks and the rates of technological substitution. Each sectoral energy demand is estimated by a modified expression from (Schenk and Moll 2007) of the sectoral energy intensity accounting for biophysical substitution limits:

$$I_t = I_{min} + (I_{t=0} - I_{min}) \cdot a^t \qquad \text{equation (1)}$$

The Energy Intensity method to estimate energy demand might seem, *a priori,* simplistic from the economic point of view because it does not explicitly include either the price or the economical structure. However, when medium and long-term projections are made, it is possible to consider that energy demand and its main drivers (GDP growth and technological improvements) dominate over the variations of fuel prices and its substitutes (de Castro 2009; Capellán-Pérez et al. 2014a). In fact, prices and costs can falsely signal decreasing scarcity (Reynolds 1999; Murray and King 2012). Since energy transitions have been shown to be slow (Fouquet 2010), we consider this analysis valid in the medium term (2050).

Finally, CO_2 emission and concentration levels are computed. Different scenarios and a wide range of alternative hypothesis and policies can be applied when running the model (see circled variables in Figure A1) by varying:

[2] We interpret GDP not as a welfare indicator, but as a driver of economic activity that demands energy and materials. We recall that GDP was not designed to measure social or economic welfare (Kubiszewski et al. 2013). In fact, up to now, the world socioeconomic system has been unable even to approach absolute decoupling between GDP and resource use (e.g. (UNEP 2011; Bithas and Kalimeris 2013)).

sectoral energy-efficiency improvement, promotion of electric transportation, renewable production (electric, thermal, biofuels), non-renewable maximum extraction curves, nuclear expansion, Gas-to-Liquids (GTL) and Coal-to-Liquids (CTL) (Appendix A depicts the causal loop diagram of the model with its basic elements).

(Capellán-Pérez et al. 2014a; Capellán-Pérez et al. 2014b) discuss the omission of other important restrictions in this model version, such as the absence of dynamic feedback between subsystems (e.g. energy scarcity[3] or climate impacts), the non-inclusion of the EROI, material constraints, the intermittency of renewable energies or phenomenon's such as the "energy trap" (Zenzey 2013). 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 and dynamic restrictions*. This approach is fully consistent with the laws of thermodynamics (Entropy Law (Georgescu and Roegen 1971)), which are one of the cornerstones of ecological economics.

2.2. Applied scenarios

Scenario methodology offers a comprehensive approach to deal with complexity and uncertainty. Each scenario is characterized by a storyline that entails representing a plausible and relevant story about how the future might unfold, thus allowing an exploration of a range of potential futures. In previous work, the standard scenarios applied in Global Environmental Assessment (GEA) studies (van Vuuren et al. 2012) were confronted with the physical limits of fossil fuel extraction and alternative energy developments, concluding that these scenarios are unfeasible to 2050, thus proposing the exploration of "no-GDP-growth" scenarios (Capellán-Pérez et al. 2014a).

Since a controversy about the coal extraction limits exists and the uncertainties surrounding its potential available resource base are the greatest among all fossil fuels (Rutledge 2011; Thielemann 2012; IPCC 2014a; Mohr et al. 2015), in this paper we furthermore focus on the possible role that coal might play in the compensation of the decline in gas and oil, exploring whether its massive use would make some of these standard GEA storylines feasible, and how the CO_2 emissions projections would be affected.[4] Coal extraction, which continued to grow throughout the XXth Century and is currently the second fuel in the world mix (30% of the Total Primary Energy Supply (TPES) (BP 2014)), has already been used intensively in the past in concrete periods of energy scarcity by some countries. For example, Axis powers during World War II synthesized petroleum from the coal resources, Coal-to-Liquids (CTL)[5]

[3] The development of a more sophisticated model with a greater degree of energy-economy feedback 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 economic processes.

[4] In this paper we focus on coal since it is the fossil fuel resource (1) with the highest carbon-content, and (2) where the uncertainties in its future availability are the most important: there is one order of magnitude of discrepancy between URR figures and official resource estimates for coal (see for example (IPCC 2014a; Mohr et al. 2015)).

[5] CTL refer to the transformation of coal into liquid hydrocarbons. Different technologies exist, however, all are characterized by low efficiencies between 27-50% (Greene 1999; IPCC 2007; Höök and Aleklett 2010). Their current production is exiguous: 0.2 Mb/d in 2011 (WEO 2012). Growth projections from international agencies are usually relatively modest (e.g. +8.5%/yr in the *New Policies Scenario* of (WEO 2012), i.e. less than 1.5 Mb/d in 2035), mainly because they assume that no liquids restrictions

providing 92% of Germany's air fuel and over 50% of their petroleum supply in the 1940s (Stranges 2007; Höök et al. 2014). Another classical example is the development of CTL production in South-Africa from the 1950s to defend against international blockade because of the Apartheid regime, providing nowadays a significant share of the liquid fuel demand (Höök and Aleklett 2010). Several countries with large coal deposits, but limited domestic oil reserves, show high interest in CTL technologies (Hirsch et al. 2005); however, to date, South-Africa and China are the only current producers at commercial level (WEO 2012).

We have developed five scenarios: three of them are *"growth and coal"* (BAU, A and B), focused on economic growth with different degrees of technological development and environmental concern (implementing GEA storylines, but assuming that the *coal supply is not constrained* and strongly promoted). Since *"growth and coal"* scenarios show up to be unfeasible (see Section 3), we develop two other scenarios to explore instead the maximum GDP per capita (GDPpc) level that would allow for an energy-demand-driven transition without any shortage in any sector. We name these two scenarios under the tag "no-GDP-growth focus", assuming that the current growth paradigm will be either impossible or abandoned. Thus, the scenario C studies the case where economic growth would be *forced to adapt* to the energy development constraints. On the other hand, the scenario D assumes a context where the growth perspective is collectively and consciously abandoned in order to achieve: (i) a demand-energy-transition (ii) not surpassing "dangerous" climate outcomes (~450 ppm CO_2) and (iii) assuming full convergence of per capita primary energy use and income between countries by 2050.[6]
These scenarios follow closely the narrative of the identified scenarios in GEA (van Vuuren et al. 2012) and can be summarized as follows:

- **Scenario BAU: "Business as usual + coal".** It follows the historic trends of economic development, population growth and globalization, with low (reactive) environmental protection and medium technological development. Coal extraction is unrestricted and a strong crash program of oil substitution by CTL, as well as a gas and oil substitution strategy in the Industry and Buildings sectors, is assumed.
- **Scenario A: "Economic optimism + coal"**. A combination of GEA's storylines "*Economic optimism"* and "*Reforming Markets*" with a strong focus on the mechanism of competitive, efficient market, free trade and associated rapid economic growth and technological development and diffusion (assuming "Environmental Kuznets Curve" for environmental impacts and higher extraction rates for non-renewable sources), but including some additional policies aimed at correcting some market failures.

will exist in the scope of their projections. Thus, when interpreting the scenarios, we will assume higher deployment rates due to the Liquids scarcity in our model.

[6] In a context of a nearly constant world average GDPpc along the century (see Section 3), this last point implies that, in scenario D, the current industrialized countries would reduce their income accordingly to allow the Southern ones to increase their consumption (see Section 4).

Coal extraction is unrestricted and a strong crash program of oil substitution by CTL, as well as a gas and oil substitution strategy in the Industry and Building sectors, is assumed.

- **Scenario B: "Regional competition + coal".** Similar to GEA's scenario "*Regional competition"*, it focuses more on self-reliance, national sovereignty and regional identity. Countries are concerned with security and protection, emphasizing primarily regional markets (protectionism, deglobalization). Due to the significant reduction of technological diffusion, technology improvements progress more slowly. Coal extraction is unrestricted and a strong crash program of oil substitution by CTL, as well as a gas and oil substitution strategy in the Industry and Building sectors, is assumed.

- **Scenario C: "Regional competition + no-GDP-growth focus**" similar to scenario "*Regional Competition*" from GEA storylines in most aspects (smaller technological development, trade barriers, reactive environmental policies), but its GDPpc growth is set to the maximum level that avoids any energy shortage in any sector for the period studied.

- **Scenario D: "Sustainable development + no-GDP-growth focus":** similar to scenario "*Regional Sustainable Development*" of the GEA storylines -where globalization tends to be deconstructed, drastic lifestyle changes against senseless consumerism occur and renewable and alternative technologies are strongly promoted. The prompt application of strong proactive energy transition policies would allow for a slightly increase of the world average GDPpc from current levels, avoiding both energy shortages in any sector, as well as CO_2 concentrations higher than 450 ppm for the analyzed period (see Section 3).

Table 1 provides a qualitative summary of each scenario's features, while Supplementary Table 3 shows the specific numbers assigned in WoLiM for each variable and scenario (see Section 6.1 from (Capellán-Pérez et al. 2014a) for the applied quantification procedure).

	BAU	**A**	**B**	**C**	**D**
World GDP	Growth	Growth	Growth	Forced no-GDP-growth	Adopted no-GDP-growth
Convergence	Not defined	Slow	No	No	Full by 2050
Population growth	Medium	Very low	Medium	Medium	Medium
Energy resources	Best guess + unlimited coal	High guess + unlimited coal	Best guess + unlimited coal	Best guess	Best guess
Technology development	Medium	Rapid	Slow	Slow	Rapid
Main objectives	Not defined	Various goals	Security	Security	Local sustainability
Environmental protection	Both reactive and proactive	Mainly reactive	Reactive	Reactive	Proactive. Target: < 450 $ppmCO_2$

Trade	Weak globalization	Globalization	Trade barriers	Trade barriers	Trade barriers

Table 1: Qualitative summary of the main assumptions and drivers of each scenario following (van Vuuren et al., 2012). (Capellán-Pérez et al., 2014a) applied the same scenario methodology; thus, equivalences between both sets of scenarios can be set: among growth scenarios, BAU scenarios are equivalent, Scenario A corresponds to 1 and Scenario B to 3 (excepting for coal constraints). Scenario C and D correspond to Scenario 3 and 4 respectively, except for the no-GDP-growth focus.

3. Results and feasibility of scenarios

The assessment of the feasibility of those scenarios where the storyline does not imply an adjustment to the energy supply constraints is based on the capability of WoLiM to detect unfeasible futures due to its incompatibility with physical and dynamic restrictions. Hence, a divergence may appear between the supply and the demand when a fuel/sectoral demand cannot be fulfilled. These divergences are interpreted qualitatively: small divergences as compatible with the storyline while large divergences as potential energy-scarcity challenges in the studied fuel/sectors (Capellán-Pérez et al. 2014a).

Our approach to deal with complexity and uncertainties to assess the feasibility of the scenarios is to explicitly assume optimistic hypotheses in the modeling.[7] In this way, scenarios that happen to be unachievable under such optimistic hypotheses can be discarded. Correspondingly, the feasibility of those scenarios that might seem achievable cannot be fully guaranteed.

Figure 2 depicts the resultant GDPpc level per scenario. In 2050, Scenario A doubles the GDPpc estimated in Scenario B (15,000 2011US$), reaching an income greater than 30,000 per capita. The BAU scenario lies between those two, projecting a GDPpc slightly over 20,000 $ for the same year. On the other hand, in Scenario C, where the economy adjusts to the energy development constraints, the GDPpc is reduced 0.4% per year, dropping below 9,000$ by 2050. In Scenario D, despite the strong proactive policies applied, the GDPpc can only slightly increase (+0.4% per year) in order to avoid the energy shortages, reaching around 12,000 $ per capita by 2050 (Figure 2).

[7] Optimistic hypotheses are considered: (i) to overcome the energy constraints (non-geologically constrained coal, transition to coal in Industry and Buildings sectors, a very optimistic deployment level of CTL, the non inclusion of EROI and net energy, etc) and (ii) to assess climate impacts by considering only energy use emissions and assuming that the natural CO2 sinks maintain their absorption capacity along the studied period. For more details see (Capellán-Pérez et al. 2014b).

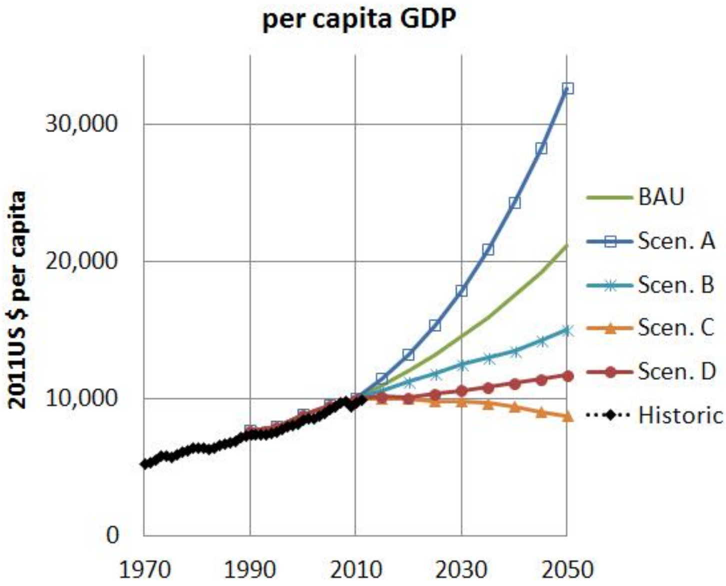

Figure 2: per capita GDP (2011US$). Historic data from World Bank.

As previously found (Mediavilla et al. 2013; Capellán-Pérez et al. 2014a), the most critical sector in all scenarios is the Transportation (see Figure 3 and for the rest of sectors see the Supplementary Figures 3 to 6). In the “*growth + coal*” scenarios, the strongly promoted coal-transition in the Industry and Buildings sectors, together with the rapid CTL crash program, release a significant amount of liquids that are then available for transport. However, for scenarios BAU and A, even the diversity of policies applied still cannot reach a substitution rate able to compensate the conventional oil decline. Interestingly, even the huge CTL crash program (reaching more than 25 Mb/d by 2050) shows itself to be ineffective due to its small current production capacity and the proximity of the liquids peak. Since Transportation is a key sector in those storylines based on an intensification of globalization, and due to the critical energy shortages that appear in that sector before 2020, both scenarios BAU and A are tagged as unfeasible. In scenario B, although the supply maintains a plateau during the entire period studied, the demand also stabilizes due to the deglobalization scenario hypothesis.

On the other hand, the ”no-GDP-growth focus” scenarios manage to deal with the energy development constraints by reducing between 20% (C) and 10% (D) the TPES demand for Transportation in relation to the 2010 level. The oil dependence is hard to overcome: even in scenario D, with strong transition policies and declining demand, by 2050 crude oil still represents more than 45% of the TPES of the sector.

It is important to highlight that, despite the estimations of techno-ecological potential for renewable sources considered in WoLiM are in the lower range of the literature (see Supplementary Material for a discussion), by 2050 at least 40% of the solar potential is still available, and wind potential is not reached before 2040 in any of the explored scenarios in this paper.

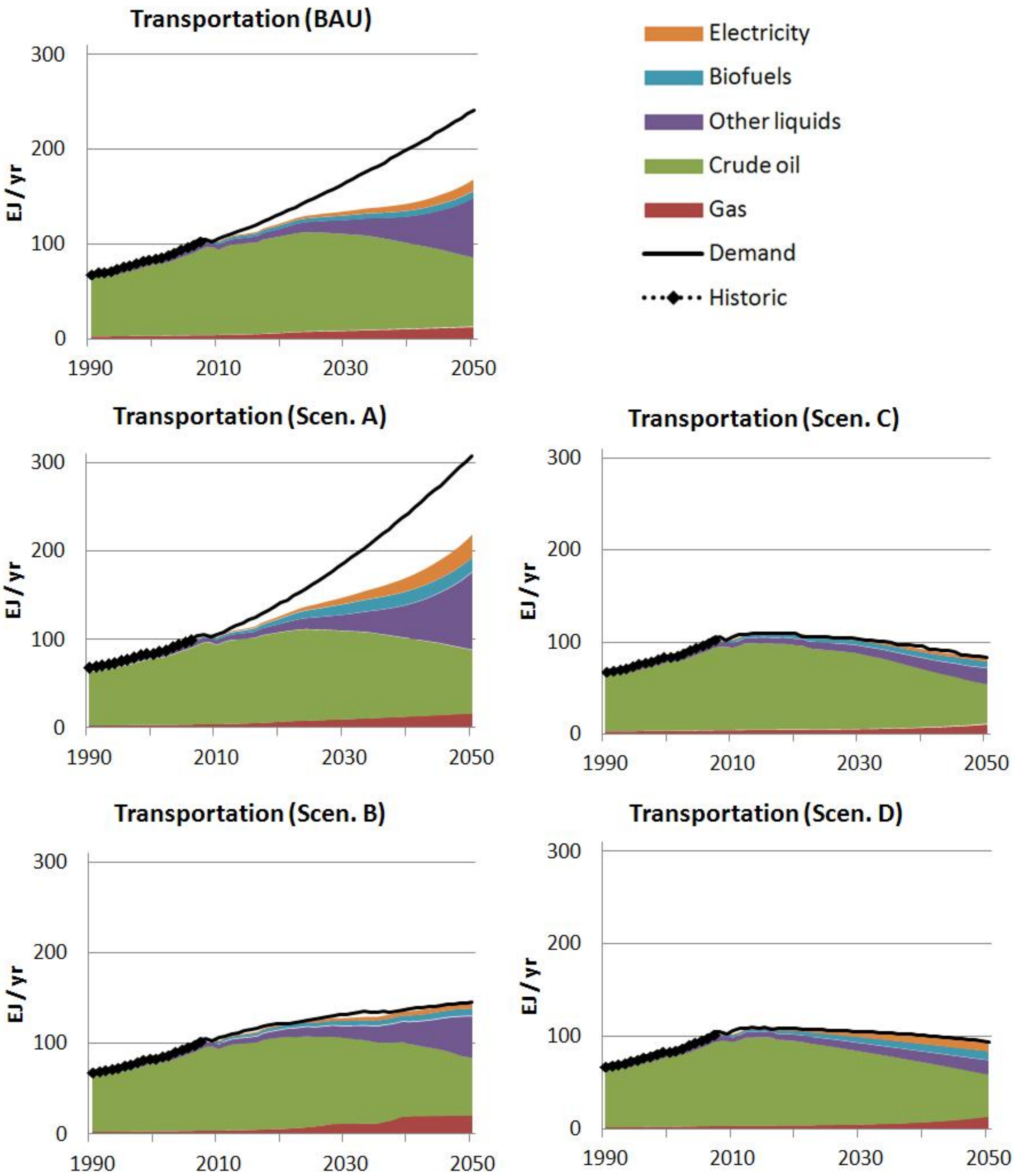

Figure 3: Transportation Primary Energy demand and supply by source fuel (EJ/yr) for each scenario. Historic consumption from (IEA ETP 2010). Other liquids include: unconventional oil, CTL, GTL and refinery gains.

Coal is the conventional fossil fuel with the highest emission factor, emitting around 70% more than natural gas and around 30% more than crude oil per unit of energy (BP 2014). Its massive use in the scenarios where no coal extraction constraints are considered (BAU, A and B), including the high CO_2 emitter coal-to-liquids process (Höök et al. 2014), would lead to a stunning emissions level along the first half of the century. All 3 scenarios reach higher levels than the most pessimistic scenario A1 from (IPCC SRES 2000). These emissions levels would translate into CO_2

concentration levels over 500 ppm by 2050 (Figure 4b).[8] Focusing on scenario B, its temperature increase by that year would be certainly greater than 2 ºC, which would be related to significant adverse impacts by the mid-century (IPCC 2014b). Thus, this scenario seem clearly unfeasible from the climate perspective in the medium and long-term: it is very probable that, before reaching these emissions levels, the associated impacts of Climate Change would provoke unexpected abrupt changes in the socioeconomic system and the world configuration that would invalid the scenario underlying hypothesis.

On the other hand, for the scenarios C and D, where economic growth is constrained, we observe a prompt reduction in the CO_2 emission path (Figure 4a) that would lead by 2050 to an emission level similar to the one in the 1990s for scenario C and the 1970s for D (-20% and -45% in relation to 2010, respectively); thus, at significantly lower levels than the most optimist scenario B1 from (IPCC SRES 2000). However, the concentration levels continue to increase, although at a lower rate, since the process of CO_2 accumulation continues: by 2050, scenario C and D reach 450-460 ppm. Although a controversy exists around the safe level threshold (IPCC 2014b), here we will take into account the 450 ppm threshold, as generally considered in the policy realm. Thus, both scenarios would be in the limit zone, although scenario D is more likely to be on the safe side.

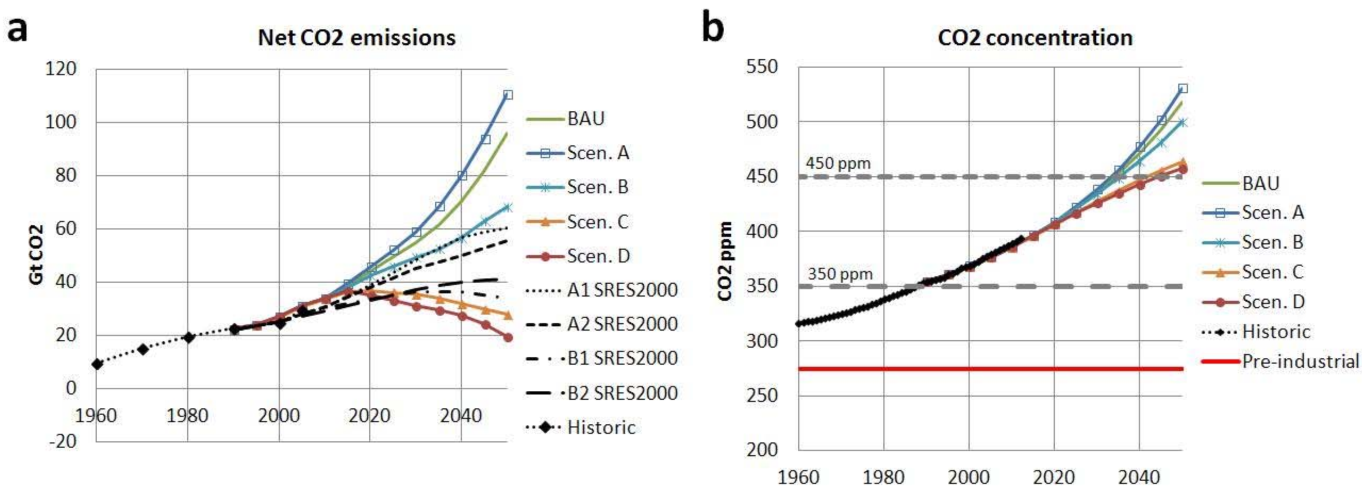

Figure 4: a) Evolution of net CO2 emissions (GtCO2) for each scenario and comparison with the IPCC SRES scenarios; b) Evolution of CO2 concentrations (ppm) for each scenario compared to past observations at Mauna Loa.

Summarizing the scenario assessment (see Table 2):

- Scenario BAU and A are clearly unfeasible from both energy-scarcity and climate disturbance perspectives.

[8] Without accounting for the "warming in the pipeline" that would follow in the second half of the century due to the energy imbalance of the Earth. Even if the anthropogenic emissions were stopped in 2051, the Earth would continue to warm in the following decades due to the physical inertia of the warming process that includes delayed effects though feedback processes.

- Neglecting coal extraction constraints,[9] scenario B is the only growth-focus scenario that might be feasible in the short-term due to its low GDPpc growth (+1.1% per year). Although its high emissions level would make it certainly unfeasible in the medium/long-term, the consideration of other constraints to CTL development not included in this analysis (e.g. water use or economic) might also invalidate its short-term feasibility (WEO 2012; Höök et al. 2014).
- Thus, the only scenarios that seem able to escape from both critical energy constraints and dangerous climate change are the "no-GDP-growth focus" scenarios C and D.

Scenario is…	Undesirable	Desirable & Sustainable
Feasible	C	D
Unfeasible	BAU, A, B	-

Table 2: Assessment of feasibility, sustainability and desirability of the scenarios. This classification provides us with a straightforward definition of a "wishful thinking scenario" as the combination of any desirable but unfeasible scenario.

4. Exploring the implications of a feasible, sustainable and desirable global future

We recall that Scenario C assumes a context of "Regional Competition" where "*countries are concerned with security and protection, emphasizing primarily regional markets and paying little attention to common goods […] A key issue in these scenarios is how much self-reliance is possible without becoming harmfully ineffective with respect to supranational issues of resource depletion and environmental degradation"* (van Vuuren et al. 2012). Moreover, this scenario was implemented assuming that the GDPpc would *be obliged to adapt to the energy development constraints*. In this context of strong energy resources scarcity, where the economic activity is *forced* to decrease (global average GDPpc dropping below 9,000 US$ by 2050) and with CO_2 concentrations surpassing 450 ppm, this scenario would very likely be neither a peaceful, nor an equitable scenario, and a drift towards technocratic, totalitarian and/or military regimes would be plausible (Leder and Shapiro 2008; Friedrichs 2010; Exner et al. 2013).[10]

On the other hand, scenario D assumes a context of "Regional Sustainable Development" with environmental proactive policies where "*globalization and international markets loss of traditional values and social norms" rejecting "senseless consumerism"* focusing on "*finding regional solutions for current environmental and social problems, usually combining drastic lifestyle changes with decentralization of governance*" (van Vuuren et al. 2012). Differently to the previous scenario C, here, anticipated democratic collective decisions are assumed to drive a shift to a prosperous and equitable socio-economic system not dependant on economic growth, as proposed by the de-

[9] For example, the coal extraction rate of scenario B in 2050 is 2 times the maximum geological extraction rate found in the literature (Mohr et al. 2015). For the scenarios BAU and A, the rate would be between 3.5 and 4 times higher respectively.

[10] Collapse could be another unwanted possible outcome (Tainter 1990; Greer 2005; Motesharrei et al. 2014).

growth approach (Martínez-Alier et al. 2010). Moreover, equitable resource allocation has been found as a central element of stable and sustainable scenarios (Motesharrei et al. 2014).

A stabilization of the average world GDPpc in an equitable context would imply that the current industrialized countries would have to decrease their income to allow the South to increase their material needs (Ayres 2008; Kerschner 2010; Schneider et al. 2010; Kallis 2011). GDP was never designed to measure social or economic welfare (e.g. (van den Bergh 2009)); and research with welfare indicators shows that in fact, above a certain level, reductions in GDP may be welfare enhancing (Kubiszewski et al. 2013).

Thus we consider scenario C as "undesirable" and D as the only scenario "feasible" and "desirable".

4.1. Scenario D: global and regional implications

This section focuses on the implications of scenario D: "*The de-growth movement calls for a decrease in material and energy consumption in countries that exceed their 'allowable ecological footprint' and acknowledges the allowance for Southern countries or societies, where ecological impacts are low relative to their biocapacity, to increase their material consumption and thus their ecological footprint*" (Martínez-Alier et al. 2010). That is, material degrowth aims for an equitable sharing of the common (limited) resources among the world's population. Thus, this exercise, despite representing a regionalization trend by a world aggregated model, allows some guidelines to the future energy development by 2050 to be identified in this context:

- Promptly application of strong sustainable and transition policies. Renewable energies could cover around 50% of the TPES mix and almost 100% of the Electricity mix (Figure 5),[11]
- Decrease in the global TPES demand of around 10% compared to current levels (see Supplementary Figure 6),[12]
- Radical transformation of the transportation sector (Figure 3), including the end of hypermobility,
- Sharing of the TPES per capita (TPESpc) from the current very unequal levels (Figure 6).

[11] This transition would certainly require a great effort, necessitating a global reassessment of objectives to carry out large economic (D'Alessandro et al. 2010) and physical resource (García-Olivares et al. 2012) investments.

[12] However, the net available energy resulting from this scenario would be ambiguous: on the one hand enhanced due to the significant renewable penetration and efficiency improvement , on the other hand reduced by the inclusion of EROI and the so-called "energy trap".

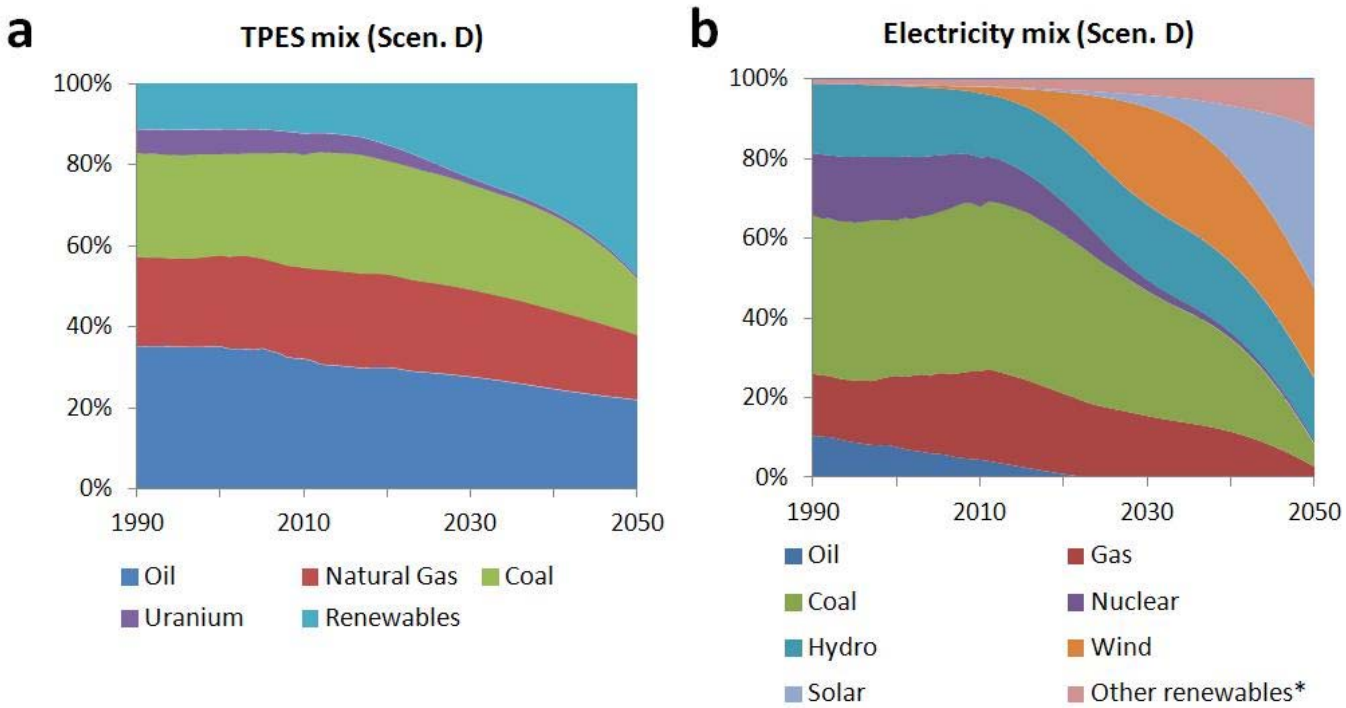

Figure 5: Results for Scenario D: (a) Total Primary Energy Supply mix share evolution by fuel; (b) Electricity mix share evolution by fuel.

This last point is illustrated in Figure 6, following a "sustainable development path" as proposed by (Ayres 2008), representing the TPESpc at world average level and by two groups of regions: "group-I", which includes the most intensive energy users and "group-II" with the least intensive ones. Solid lines represent the past evolution, while the future projection is built by imposing the global average TPESpc from scenario D and a lineal convergence for the countries from "group-II" achieved in 2050.[13] We observe that people living in countries from "group-I" should reduce their current energy consumption at a pace of 3% per year (-70% between 2010 and 2050). This would allow the people living in the "group II", i.e. 70-75% of the global population in this period, to increase its TPESpc +30% from current levels.[14] The convergence level (50-60 GJ per capita) is below the threshold to reach a high development level under the current socioeconomic paradigm (Martínez and Ebenhack 2008; Arto et al. 2015), but above the energy consumption needed to cover basic needs (WBGU 2003; Rao et al. 2014), strengthening the storyline of Scenario D.

[13] This egalitarian policy-path could be implemented, for example, following a "cap-and-share" scheme. As proposed by (Douthwaite 2012), a supranational institution would be in charge of allocating the use of fossil fuels around the world, thus preventing excessive competition for them that might damage the global economy. At the same time, it would allow a declining annual global cap to be placed on the tonnage of CO_2 emitted by fossil fuels and allocate a large part of each year's tonnage to everyone in the world on an equal per-capita basis.

[14] Figure 6 is a simplification because the official statistics only account for the TPES consumed within sovereign territories, ignoring the significant embodied energy transfer through international trade (Chen and Chen 2011). Accounting for this fact, an even higher gap between both aggregate regions exists.

A large-scale transition from fossil fuel to renewable energy sources would involve a shift to resources with a lower energy density, which would inevitably translate into a reduced productivity of the whole economy (Smil 2008; Murphy and Hall 2011), which may allow employment to increase (Jackson and Victor 2011).

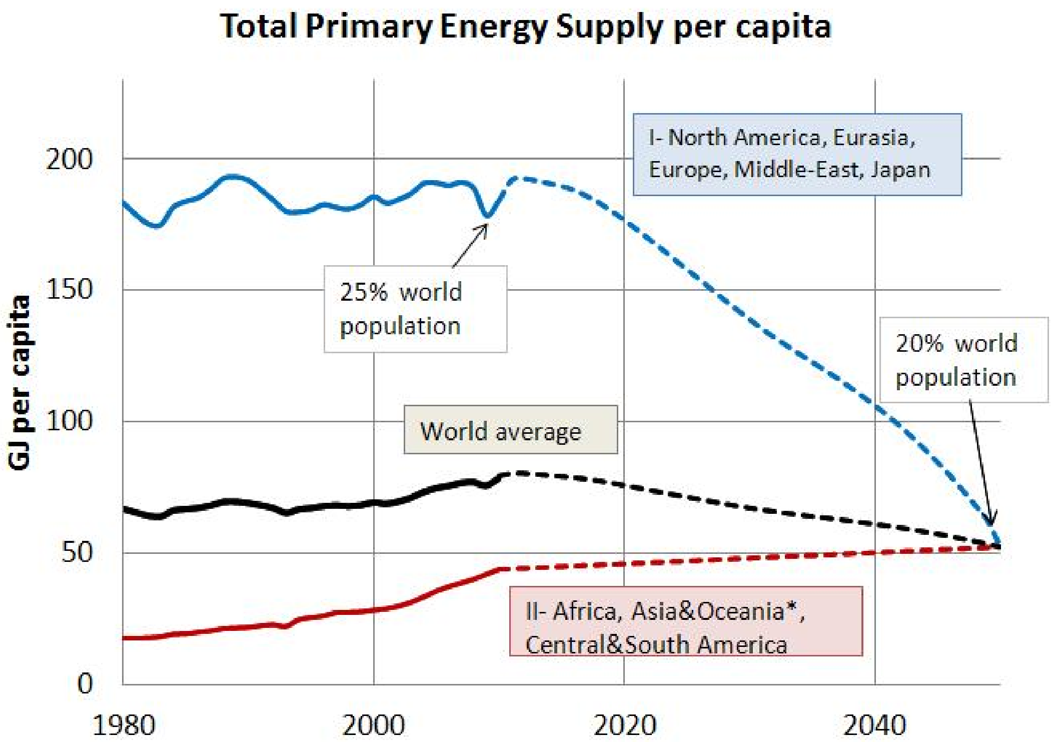

Figure 6: Evolution of the Total Primary Energy Supply per capita (TPESpc, GJ/pers) from 2010 of two world aggregated group of regions (I and II) assuming that the regions with TPESpc below the world average would reach the world average value in 2050. The composition of each region is from the US EIA database. *Asia&Oceania does not include Japan.

The results from our explorative modeling exercise suggest that the global GDPpc to assure an equitable access to energy, avoiding critical constraints and threatening climate change outcomes, would be similar to the current world average level, reaching around 12,000 2011US$ per capita by 2050 (Figure 7);[15] i.e., in the range of the current *average* GDPpc (PPP) in countries such as Brazil, Costa Rica, Montenegro or Thailand. That would mean that industrialized countries (group-I') would have to reduce their *average* per capita income 4 times at a yearly pace of -3% until 2050. On the other hand, this would allow people living in Southern countries (group-II') to increase their GDPpc 3-fold in the same period. Since this convergence level is in the neighborhood of the decoupling-threshold between income and well-being (Frey and Stutzer 2002; Kubiszewski et al. 2013), reductions from higher GDP levels through lifestyle changes oriented towards "sufficiency" might be welfare enhancing, differently from the dominant perceptions (e.g. (Alexander 2012)). In fact, some of the cases of countries currently being in the convergence range of 50-60 GJ / 12,000 US$ per capita display levels of Human Development Index (HDI) close to the UN "high

[15] WoLiM operates in GDP in Market Exchange Rates (MER). Thus, a conversion to GDPpc Purchasing Power Parity (PPP) has been done in order to perform the comparison: 11,200 2011 US$ MER ≈ 14,200 2010 US$ PPP (World Bank).

development" threshold (HDI≥0.8), i.e. Montenegro (HDI=0.791), Uruguay (0.789) or Costa Rica (0.77). Also, in an egalitarian perspective, social inequality would be significantly reduced between states but also within them, the Gini index progressing to significantly smaller values.

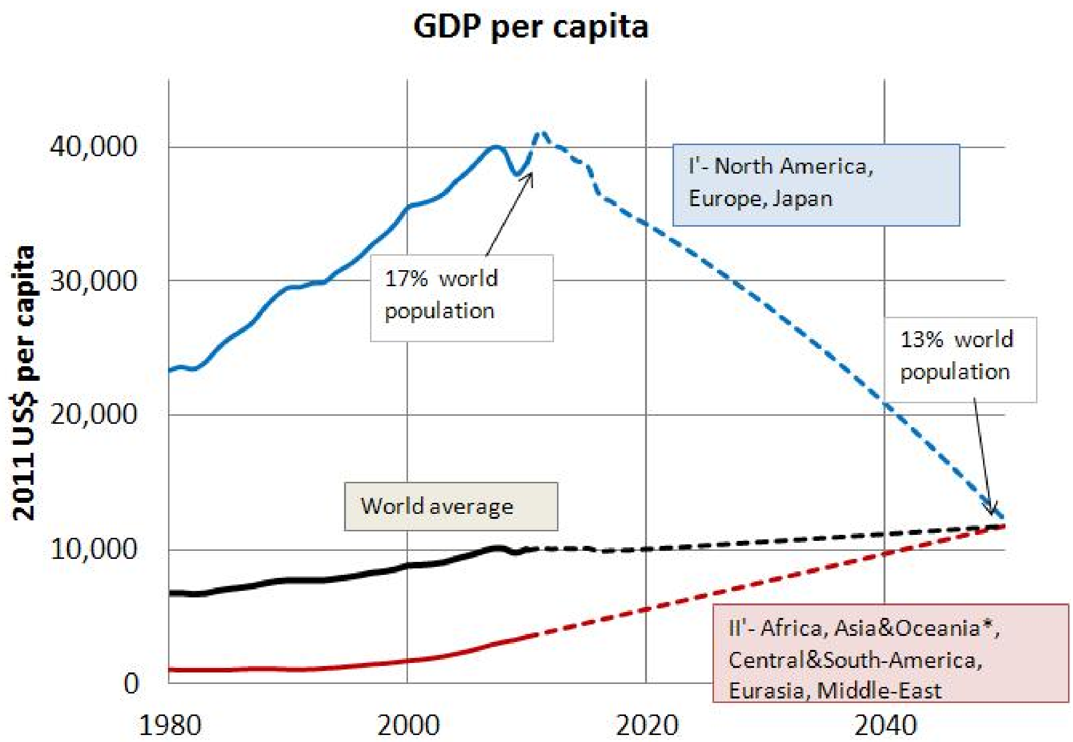

Figure 7: Evolution of the GDP per capita (2011 US$) from 2010 of two world aggregated groups of regions (I' and II'), assuming that the regions with GDPpc below the world average would converge to the world average value in 2050. *Asia&Oceania does not include Japan.

However, these conclusions must be drawn carefully: we recall that the model ability to depict a feasible future is restricted by the omission of significant constraints. Also, the present exercise has analyzed the socioeconomic system as if the only critical factors were potential energy scarcity and climate alteration. Since, in fact, an array of interconnected issues are not considered[16] (e.g. nitrogen and phosphorus cycle disturbance, biodiversity loss, etc.) that may have the potential to provoke a drastic environmental change (Steffen et al. 2015), the assessed feasibility of scenario D could then be *too* optimistic. The Scenario D presented in this paper is, in fact, very close to the scenarios 8 and 9 from (Meadows et al. 2004), where more than 30 years of prosperity were obtained by implementing similar intensive transition policies and aiming for a modest increase in the global average Industrial output level per capita. However, in these scenarios, the ecological footprint does not reverse its trend and the system is then forced into a decline after 2040.

[16] Another limit that the model highlights is land availability. In scenario D, deforestation is assumed to be reversed and 500 Mha are afforested. By 2050, solar would occupy around 50 Mha, and biofuels would use 100 Mha of high productivity land and almost 400 Mha of marginal lands. In a context of rising population, and if current erosion and water cycle degradation processes are not reversed, land scarcity might also become a critical problem.

5. Conclusion

The present paper uses the SD model WoLiM, which is a world aggregated model that allows the economy, the energy and the climate dynamics to be analyzed in an integrate way. We perform an exploratory scenario exercise that sheds light on the potential dangers of not addressing these dynamics properly in the context of the current energy crisis and climate change. Since the main objective of SD and scenario development is to understand the system analyzed, the results presented in the paper must be interpreted qualitatively. With the optimistic assumption that no limits exist for coal extraction, if a massive transition to coal were promoted in order to (try to) compensate for the decline of oil and gas to maintain economic growth, the climate would then be deeply disturbed before 2050. On the other hand, if the growth paradigm is not abandoned promptly, the economy might be forced to adjust to the energy supply constraints, setting the grounds for a pessimistic panorama from the point of view of peace, democracy and equity (Kerschner 2010).

Scenarios can also be assessed from the point of view of the globalization process: those scenarios that include GDPpc growth in a globalization context show up to be unfeasible because of the proximity of the peak of conventional oil production and the strong dependence of the transportation sector on liquid fuels as previously found (Mediavilla et al. 2013; Capellán-Pérez et al. 2014a). Even the implementation of huge CTL crash programs appear not to be sufficient. On the other hand, deglobalization scenarios that do not include an anticipated and conscious abandoning of the growth paradigm would very likely face significant threats from the interplay of critical energy constraints with a troubling context of increasing regionalization, countries' self-reliance and climate deterioration. Thus, a global race to coal extraction in order to sustain low GDP growth cannot be discarded in the coming years. In this sense, the sustainable de-growth proposal, *"an equitable and democratic transition to a smaller economy with less production and consumption, […] allow[ing] a prosperous way down or at least a soft landing rather than a crash due to environmental collapse*" (Martínez-Alier et al. 2010), provides a valid and equitable framework escape route for these issues.

This explorative exercise also illustrates the magnitude of the challenge. In an ideal sustainable de-growth scenario, assuming that global and equitable convergence is reached by 2050, the most energy-intensive consuming countries (i.e. the most industrialized) should reduce, on average, their per capita energy use rate by at least 4 times and decrease their GDPpc roughly to the current world average. On the other hand, this would allow people living in Southern countries to increase their per capita energy use by +30% that would translate in a 3-fold increase of GDPpc in the same period. Thus, if an equitable and fair development is to be achieved at world level, consumption levels would need to considerably shrink in these industrialized countries in order to allow for an expansion in Southern countries. Differently from the current dominant perceptions, these reductions through lifestyle and cultural changes oriented towards "sufficiency" might actually be welfare enhancing. The attainment of these targets would require deep structural changes in the socioeconomic systems, such as lower productivities or the consideration of cap-and-share schemes, in combination with a radical shift in geopolitical relationships.

It is commonly assumed that technological innovation will be the main driver to overcome all limits (resources & sinks) and problems if the markets work appropriately and the right investments are made. However, the overshoot trends pointed out by (Meadows et al. 1972; Meadows et al. 2004) and the conclusions extracted in this analysis, together with previous works (Capellán-Pérez et al. 2014a), disagree with these statements due to the very likely collision of the economy-energy dynamics with the resource and sink limits of the Earth before 2050. Moreover, the reduction of global greenhouse gas emissions is a classic commons problem. Hence, social innovation and cooperation will then be required, *besides* technical improvements, to drive a change not only in individual lifestyles, but in the whole socioeconomic system (Ostrom 1990; Brouseau et al. 2012). Thus, two main conclusions are that: (i) *only* technical solutions are not enough, (ii) prosperity for all the world cannot be based on the current GDP growth paradigm.

The “Sustainable Development” discourse (30 years after the Brundtland Report (WCED 1987)) has been unable to produce the overarching policies and radical change of behavior needed at individual and collective scales. The literature on environmental Kuznets curves shows that decoupling between growth and environmental pressures does not hold in general and only applies to some specific issues (Arrow et al. 1995; Stern 2004). However, we no longer have the luxury of decades within which to operate a theoretically-grounded, gradual transition toward a post-fossil fuel world, as was the case in the 1970s (Meadows et al. 2004; Meadows 2012). In a context of increased, accelerating and interrelated global environmental problems, truly effective solutions must be proposed and promptly implemented.

Acknowledgments

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Appendix A:

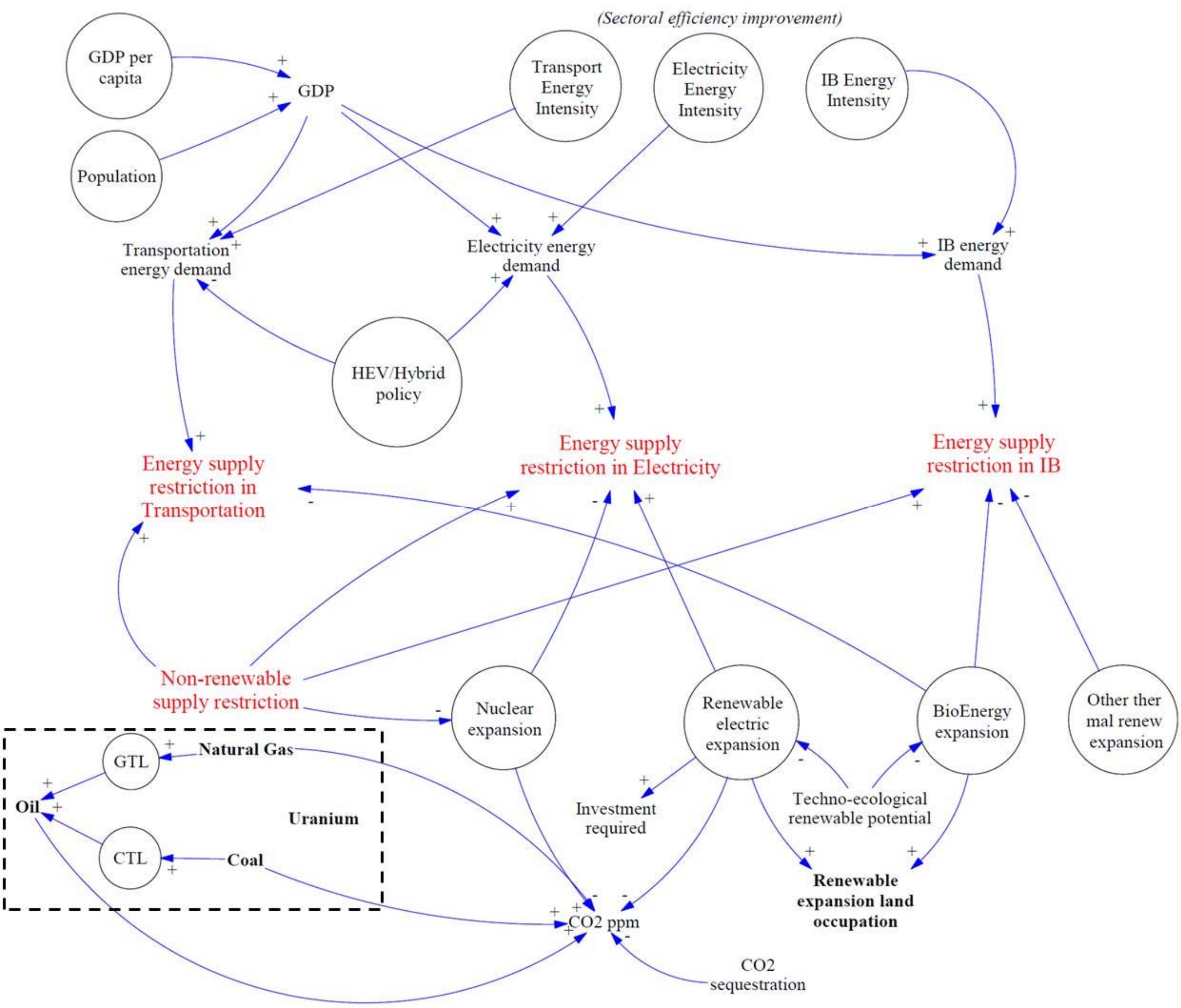

Figure A1: Causal loop diagram of the model with its basic elements. Scenario elements and policies are circled.

Supplementary Material to

"More growth? An unfeasible option to overcome critical energy constraints and climate change"

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1. WoLiM modeling

1.1 Energy resources data

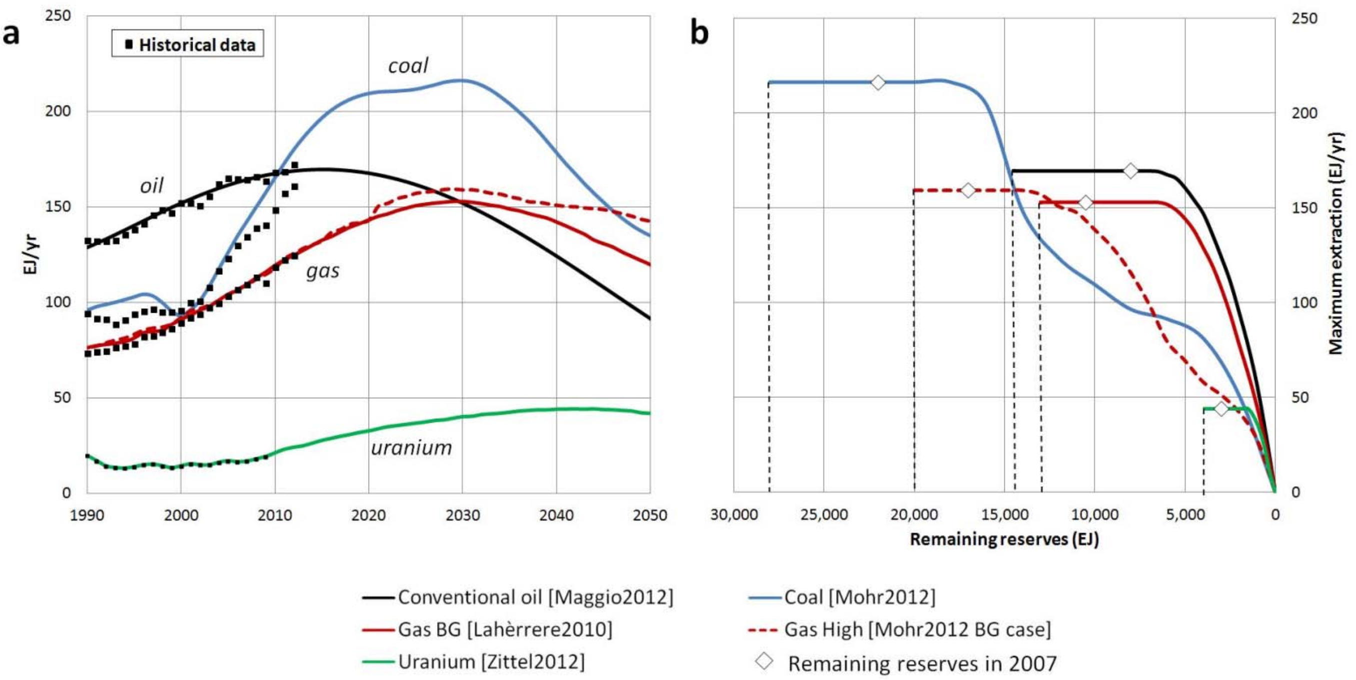
(Mediavilla et al. 2013; Capellán-Pérez et al. 2014a) extensively discuss the different individual fuel extraction profiles proposed in the literature and select some representative profiles to be implemented in the model. For some resources, we use a "Best Guess" and a "High Case" estimation: depending, in fact, on the socioeconomic assumptions of each scenario, the estimated available resources may be different. The non renewable resource inputs are assumed to be constrained mainly by geological factors as estimated by (de Castro et al. 2009; Laherrère 2010; Maggio and Cacciola 2012; Zittel 2012; Mohr 2012) and are summarized in Supplementary Table 1. These profiles, as a function of time, must be transformed, since WoLiM is a dynamic model that considers demand, to maximum energy resource extraction curves, as a function of resources (see Supplementary Figure 1 and 2). Production will therefore be the minimum between the actual demand and the achievable maximum production.

In general the same references as in (Capellán-Pérez et al. 2014a) are applied here, excepting for conventional oil where the middle scenario from (Maggio and Cacciola 2012) was chosen. In the previous paper the most optimistic scenario (i.e. less abrupt depletion) was applied in order to improve the robustness of the conclusions.

Resource		Reference	Description	URR	
	Conv.	(Maggio and Cacciola 2012) middle scenario.	Hubbert method.	2,600 Gb	14.5 ZJ

Oil	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) BG	Hubbert method: "creaming curve".	13,000 tcf	13.6 ZJ
		High Case: BG from (Mohr 2012)	12,900 tcf of conv. + 7,200 tcf of unc.	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
				Total	88.2 ZJ

Supplementary Table 1: Non-renewable resources used in the model. Other technologies for producing liquids such as CTL (coal-to-liquids) and GTL (gas-to-liquids) are also considered in the model. Different technologies exist, but all are characterized by low efficiencies (IPCC 2007). Their current production is exiguous: less than 0.3 Mb/d in 2011 (WEO 2012). Growth projections from international agencies are usually relatively modest (e.g. +11%/yr for GTL in the *New Policies Scenario* of (WEO 2012)).
[a]RAR: reasonably assured resources; IR: Inferred resources; NEA: Nuclear Energy Association.



Supplementary Figure 1: (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/year) associated to the remaining reserves (EJ).

A main feature of the model is the consideration of the available sustainable potential of renewable energies as estimated by a novel top-down methodology (de Castro et al. 2011; de Castro et al. 2013; de Castro et al. 2014). Thus, the estimation of the global technological wind power potential acknowledging energy conservation leads to 30 EJ/yr (de Castro et al. 2011). The estimation of the real and future net density power of solar infrastructures is 4-10 times lower than most published studies, and assessing its technological and sustainable limits leads to a potential of 60-120 EJ/yr, (de Castro et al. 2013). Globally, the techno-ecological potential of electric renewable is estimated in 5 TWe (150 EJ). Depending on the scenario assessed, wind potential can be reached between 2030-50 (i.e. growth between 15-30% per year); similarly, solar potential is only reached before 2050 in those scenarios where is this technology is strongly promoted (i.e. growth > 25% per year), see scenarios in (Capellán-Pérez et al. 2014a).

	Techno-ecological potential	Investment cost			Lifetime
References	(de Castro et al. 2011; de Castro 2012; de Castro et al. 2013)	(Teske et al. 2011)			Conventional values
Technology/Unit	TWe	2011$/We			years
		2010	2030	2050	
Hydroelectrical	0.5	4.8	6.3	6.9	100
Wind[a]	1	8.3	6.6	6	25
Solar	3	26.9	7.4	7.4[b]	25
Waste & MSW	0.3	3.9	3.3	3.2	40
Geothermal	0.2	15.9	9.3	6.6	40
Oceanic	0.05	9.2	2.8	2.1	25
TOTAL	5.05				

Supplementary Table 2 : Data of electric renewable in the model. "TWe" represents power electric production: TWh/8760. Source: (Capellán-Pérez et al. 2014a; Capellán-Pérez et al. 2014b).

***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.

Since the techno-ecological potential of renewable energies is so far a controversial subject in the literature, and the estimations considered in WoLiM are in the lower range of the literature (see for example (IPCC 2011; Jacobson and Delucchi 2011; García-Olivares et al. 2012)), we proceed to discuss the validity of its application in this paragraph.

(García-Olivares et al. 2012) studied the feasibility of a global alternative mix to fossil fuels based on proven renewable energy technologies not dependent on scarce materials. The proposed technical solution identifies an array of critical materials: steel, concrete, nitrates, neodymium, copper, aluminum, lithium, nickel, zinc and platinum. The high requirement material rates for the electrificated-renewable-based society would imply the depletion of copper and other mineral reserves, thus depriving other sectors of the economy from their use (and with the optimistic assumption that ores will not decrease with cumulated extraction (Bardi 2014; Valero and Valero 2014)). The achievement of such energy transition would require the set up of a global management organization similar to a "war economy", thus strongly altering the current geopolitical status quo.

On the other hand, in the case of wind, (García-Olivares et al. 2012) do not take into account the wind density power as argued in (de Castro et al. 2011), which reveals more restricted constraints than the material ones.[17]

For the specific case of solar power, (de Castro et al. 2013) considered additional material restrictions (e.g. silver) that were not considered by (García-Olivares et al. 2012), the trade-offs between material scarcity and efficiency (the more efficient a solar cell the more material restrictions), its EROEI (the complete cycle of solar power industry has a very low EROEI according to (Prieto and Hall 2013)), the density of land occupation, the real power density (it was demonstrated that real parks are much less efficient (≈3.3 We/m2) than it is generally assumed in the literature (12-25 We/m2)), and the additional land and infrastructures required to face the intermittency of renewable sources. Finally, the integration of all this constraints delivers a net real power density that allows comparing the real global infrastructure and land required by the other studies in the literature concluding that it would be several times and, in some cases, even some orders of magnitude higher, than all present global infrastructures (cities, roads, etc.).

However, (García-Olivares et al. 2012) remains as a very valuable contribution since they demonstrate that even with very generous assumptions the societal and economical challenges to implement the required changes are very large. Thus, the combined findings of (de Castro et al. 2011; García-Olivares et al. 2012; Trainer 2012) allow to justify that (Jacobson and Delucchi 2011) proposal is grossly exaggerated.

Additionally, the dynamic integration of renewable deployment in WoLiM allows considering that the energy transition requires time (i.e. dynamic constraints) since they start from a very low share of the global mix. (Jacobson and Delucchi 2011; García-Olivares et al. 2012) studies focus on the proposition of a "static" technically feasible generation mix. For example, (Jacobson and Delucchi 2011) proposal implicitly includes steady huge deployment rates for wind (+27% yearly) and solar (+40% yearly), thus extrapolating current

[17] Including continental shelves.

growth trends to 2030. However, although the deployment of new technologies can follow an exponential trend in the first years, decreasing returns tend to decrease the growth rates as total capacity increases.

In terms of investment and costs, we compute the investment for building new plants, and to replace or re-power the already existing ones, using the learning curves of (Teske et al. 2011), grid reinforcement costs following (Mills et al. 2012), and balancing costs as modeled by (Holttinen et al. 2011). We do not consider here the so called "energy trap" (Murphy 2011; Zenzey 2013). If we had taken it 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): "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 EROI pegged at 10:1) will require giving up 8 percent of the net energy available for the economy".

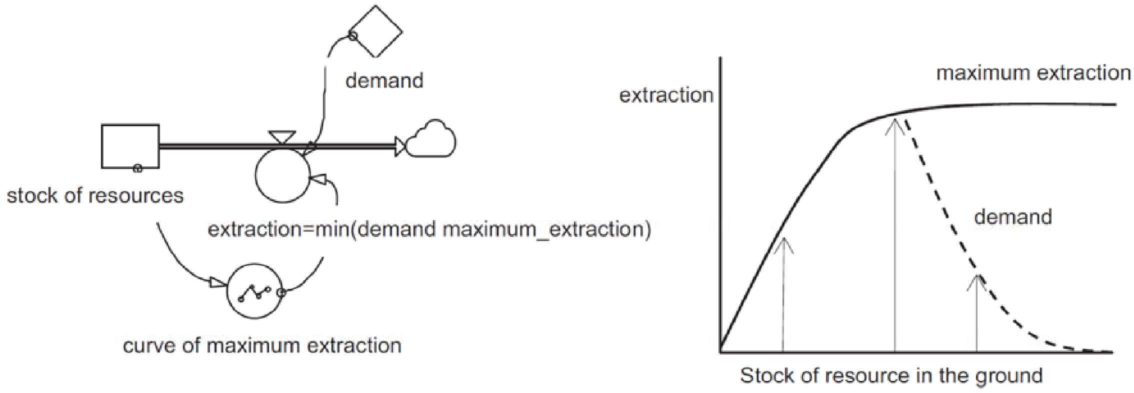
For a detailed description of the electrical generation as well as for bioenergy and thermal uses in the model see (Capellán-Pérez et al. 2014a).

1.2 Integration of resource curves

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

In these curves, as long as the resources are large, extraction will not be limited physically and we make it equal to the total maximum production. When the resources diminish, physical limits start to appear and production is reduced. In this way, the model uses a stock of resources (based on the URR taken by each author) and studies how this stock is emptied depending on production, which is in turn determined by demand and maximum extraction. Supplementary Figure 2 gives a hypothetical example of the dynamic model used and a production curve.

Supplementary Figure 1b shows the maximum extraction curve used in the model for all the non-renewable fuels in EJ. The x-axis represents the stock of non-renewable energy available, according to the estimated resources of fossil and nuclear fuels. The y-axis represents the maximum extraction 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 extraction decreases until it reaches zero, when the resource is exhausted.



Supplementary Figure 2: Maximum extraction curves as a function of resources. Left: the systems dynamics model used to model extraction. Right: a curve of maximum extraction (solid) compared with the demand (dashed). Both curves meet when the peak of the resource is reached. Source: (Mediavilla et al. 2013).

1.3. Socio-economy adaptation to supply constraints in scenarios C and D

The modeling of the socio-economy adaptation to the supply constraints in this paper does not intend to be a general representation of the role of energy in the economy, and it is closely related to the specific storylines of Scenarios C and D. The modest pursued objective is the estimation of the maximum economic activity (i.e. GDP growth, population is kept exogenous) compatible with the dynamic constraints on the available primary energy supply. The link is implemented by inverting the expression of the sectoral energy intensity from the most critical economic sector (i.e. the one with higher relative difference between supply and demand) for each time t. For the typical case where transportation sector is the critical one, we would apply the following expression:

$$I^{t}{}_{transp} = a_{transp} \cdot I^{t-1}{}_{transp} \qquad \text{equation (2)}$$

That, including a dumping factor (K), could be rewritten as:

$$\Delta GDP^{t}{}_{pc} = \frac{GDP^{t}{}_{pc}}{GDP^{t-1}{}_{pc}} = \frac{1}{a_{transp}} \cdot \frac{Pop^{t-1}}{Pop^{t}} \cdot \frac{E_{transp}{}^{t}}{E_{transp}{}^{t-1}} \cdot \frac{1}{K} \qquad \text{equation (3)}$$

Where:

GDP^{t}_{pc}: Gross Domestic Product per capita in time t,

Popt: Population in time t,

a_{transp}: represents the yearly efficiency improvements of the energy intensity of the transportation sector. In the model it is a constant, as derived from econometric analysis performed for past data during the construction of the model. See (Capellán-Pérez et al. 2014a; Capellán-Pérez et al. 2014b).

E_{transp}: Primary energy of transportation sector,

K: a dumping factor to distribute the effect of the feedback over time and obtain a soft dynamic behavior.

Note that the modeling structure is the same for both scenarios C and D. However, the interpretation of the link depends on each underlying storlyline.

1.4. Adaptation of WoLiM model to coal unlimited extraction scenarios

In the standard WoLiM 1.0 version, fuel substitution mechanisms between fossil fuels are not implemented in the IB (Industrial and Buildings) sectors for the sake of simplicity. In fact, when all fossil fuels are constrained, their peak production is reached at different dates. However, the modeling of these fuel substitution mechanisms in these sectors would only accelerate the depletion of the more lasting fuels (typically gas and coal). Thus, the essential conclusions would remain unchanged. However, when assuming unconstrained coal resources, these mechanisms are essential in order to allow for a transition to a coal-based economy.

We assume that in the moment when gas and coal scarcity approach a critical level, a scarcity signal would arise that would be strong and efficient enough to promote a shift in the fuel shares in the Industry and Buildings sector by increasing 1% per year the share of the coal in each sector. Also, for the sake of simplicity, we assume that 1 EJ of coal would substitute for 1 EJ of oil or gas (in primary energy). This is a very optimistic assumption since coal is usually used at lower efficiencies, and more (primary energy) than 1 unit of coal would be needed to substitute for 1 unit of gas/oil (Kerschner et al. 2009). For more information about the modeling see (Capellán-Pérez et al. 2014b).

2. Summary of the specific hypothesis and policies for each scenario: Supplementary Table 3

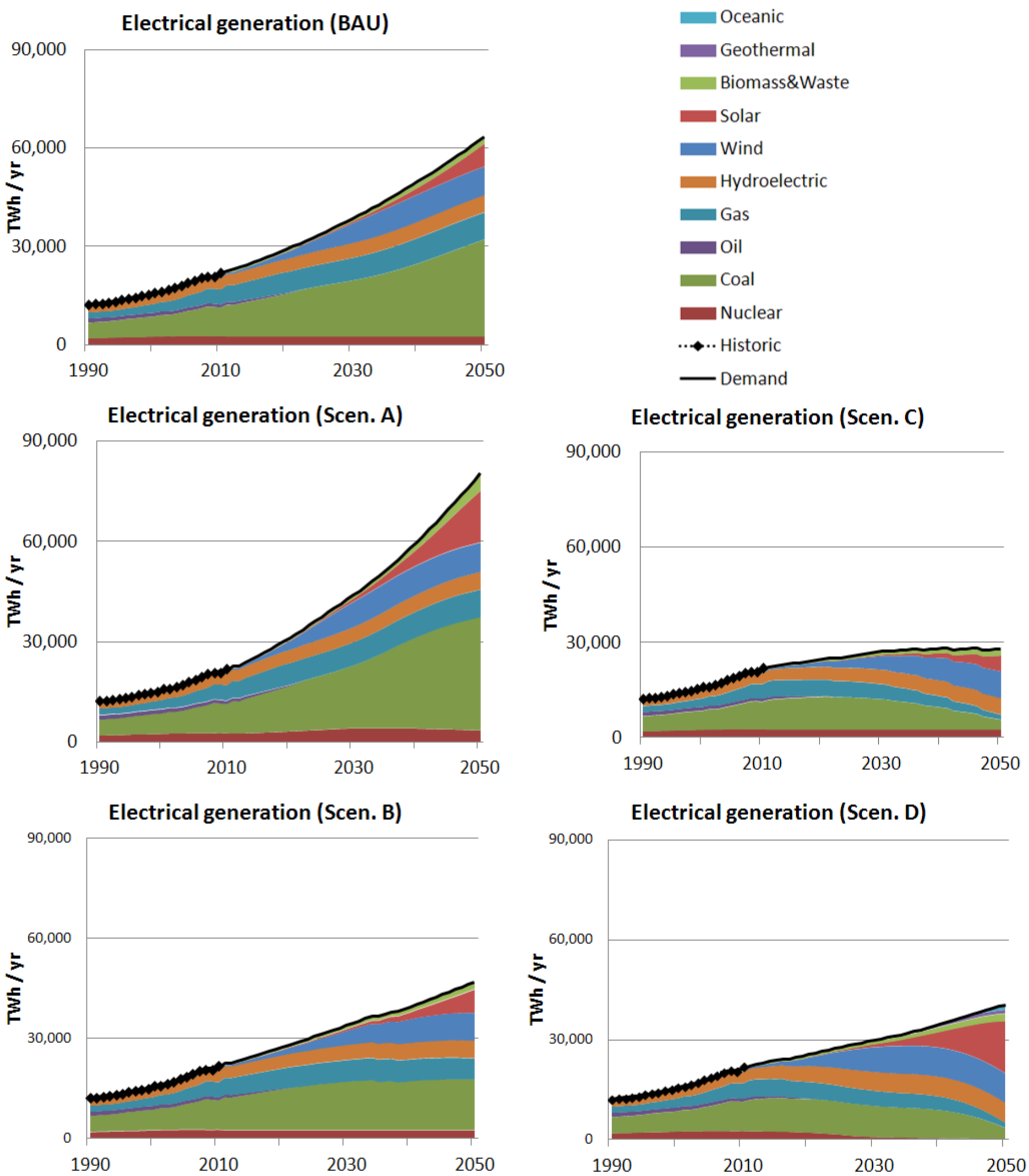
*Capellán-Pérez, I et al., « **More growth? An unfeasible option to overcome critical energy constraints and climate change",** Sustainability Science. April 25, 2015, 1–15. doi:10.1007/s11625-015-0299-3.*

	SCENARIO - INPUT	**BAU** *BAU + coal*	**Scenario A** *Economic optimism + coal*	**Scenario B** *Regional competition + coal*	**Scenario C** *Regional competition + no-growth focus*	**Scenario D** *Regional sustainable development + no-growth focus*
Socioeconomic (2010-50)	GDPcap	Hist + 1.9% (1960-12)	+ 3.1%	+ 1.1%	- 0.4%	+ 0.4%
	Population	(UN 2011)[a] +0.75%	+0.47%	+0.81%	+0.81%	+ 0.80%
Sectoral efficiency improvements	a_{Transp}	Past trends (-0.67%)	Rapid (-0.9 %)	Deglobalization (-1.5%)	Deglobalization (-1.5%)	Deglobalization (-1.5%)
	a_{elec}	Past trends (0%)	Moderate (-0.25% from 2030)	Past trends (0%)	Past trends (0%)	Past trends (0%)
	a_{IB}	Past trends (-0.5%)				
	I_{min} [b]	25 %	25 %	25 %	25 %	15 %
Resource availability	Oil, Gas, Uranium	Best Guess	Best guess + extra oil&gas unconventional	Best Guess	Best Guess	Best Guess
	Coal	Unrestricted	Unrestricted	Unrestricted	Best Guess	Best Guess
	CTL, GTL[c]	Rapid crash program	Rapid crash program	Rapid crash program	Medium crash program	Past trends (+0.05%)
Electric renewables	Solar FV&CSP	Medium (+15%)	Past trends (+19%)	Medium (+15 %)	Medium (+15 %)	Rapid (+20%)
	Wind	Medium (+20%)	Past trends (+26%)	Medium (+15%)	Medium (+15%)	Rapid (+25%)
	Hydroelectric, Geothermal, Bioenergy&Waste	Past trends (slow)	Past trends (slow)	Past trends (slow)	Past trends (slow)	Very rapid (x3 past trends)
	Oceanic	Rapid (+20% from 2020)	Rapid (+20% from 2020)	Rapid (+20% 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)	Slow (+8%, 100 MHa available)	Slow (+8%, 100 MHa available)	Medium (+15%, 100 MHa)
	3rd generation	Slow (+8% from 2025)	Rapid (+ 20% from 2025)	Slow (+8% from 2035)	Slow (+8% from 2035)	Medium (+15% from 2035)
	Residues	Slow (+8% from 2025)	Rapid (+20% from 2025)	Slow (+8% from 2035)	Slow (+8% from 2035)	Medium (+15% from 2035)
Thermal renewables & efficiencies	Industrial sector (market share 2050)	Low (12.2%)	Medium (23%)	Low (12.2%)	Low (12.2%)	Rapid (37.6%)
	Buildings sector (market share 2050)	Low (4.6%)	Medium (22.6%)	Low (4.6%)	Low (4.6%)	Rapid (52%)
Alternative transport	HEV & Hybrid (market share 2050)	Medium (9%)	Rapid (18%)	Medium (9%)	Medium (9%)	Very rapid (36%)
	NGVs	Past trends (+20%)	Past trends (+20%)	Past trends (+20%)	Medium (+10%)	Medium (+10%)
Afforestation program		-	-	-	-	500 MHa (from 2015)

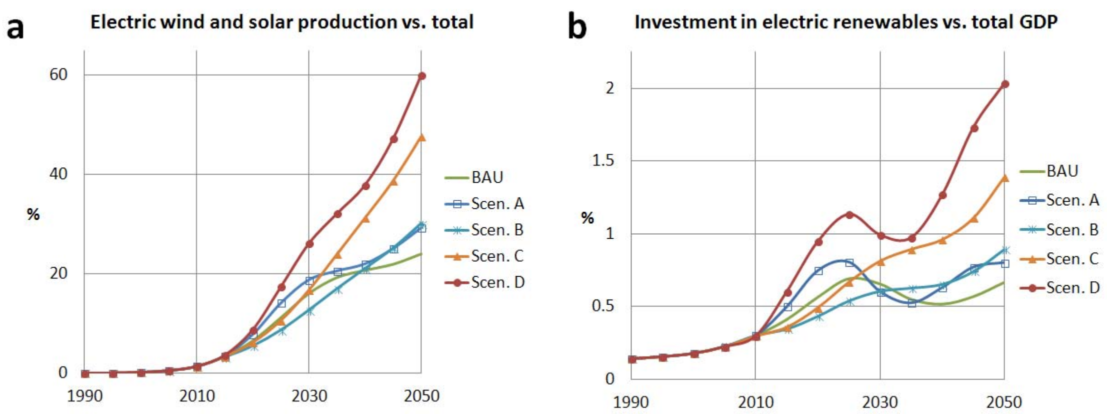
Supplementary Table 3: Hypothesis and policies of each scenario. Percentages refer to yearly growth rates, otherwise it is specified differently. [a]Medium-Variant estimation.[b]The minimum intensity level (I_{min}) is set at 25% of current intensity for scenarios BAU, A, B and C, and at 15% for D following (Baksi and Green 2007). [c]The CTL and GTL crash programs are only launched if and when liquid scarcity appears. When that occurs, a crash program following a logistic curve is launched.

3. Figures of results

Electricity generation (Supplementary Figure 3): No energy shortages appear in any scenario due to the introduction of non-constrained coal for the scenarios BAU, A and B and the strong reduction of the demand increase for the scenarios C and D. However, the large scale deployment of renewable energies in scenario D, with lower GDP total levels, means that the investment effort increases significantly compared to the other scenarios, reaching 2% of GDP by 2050. For both scenarios C and D, the transition to an electricity mix dominated by renewable energy would imply an important challenge for the integration of intermittent production: the combined power of solar and wind would reach (and surpass for scenario D) half the total production by 2050 (see Supplementary Figure 4).

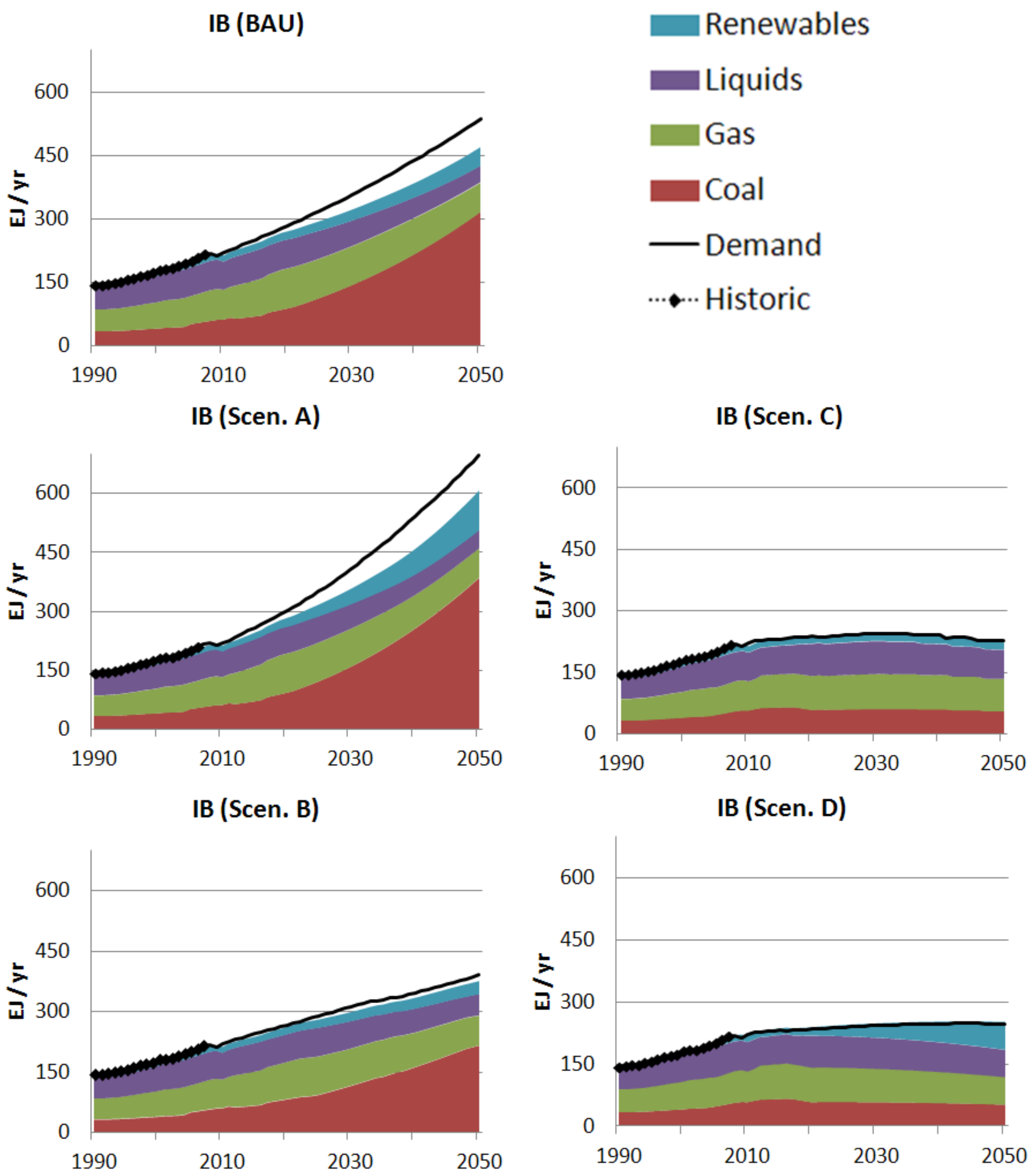


Supplementary Figure 3: Electricity generation and demand (TWh/yr) by fuel source for each scenario.



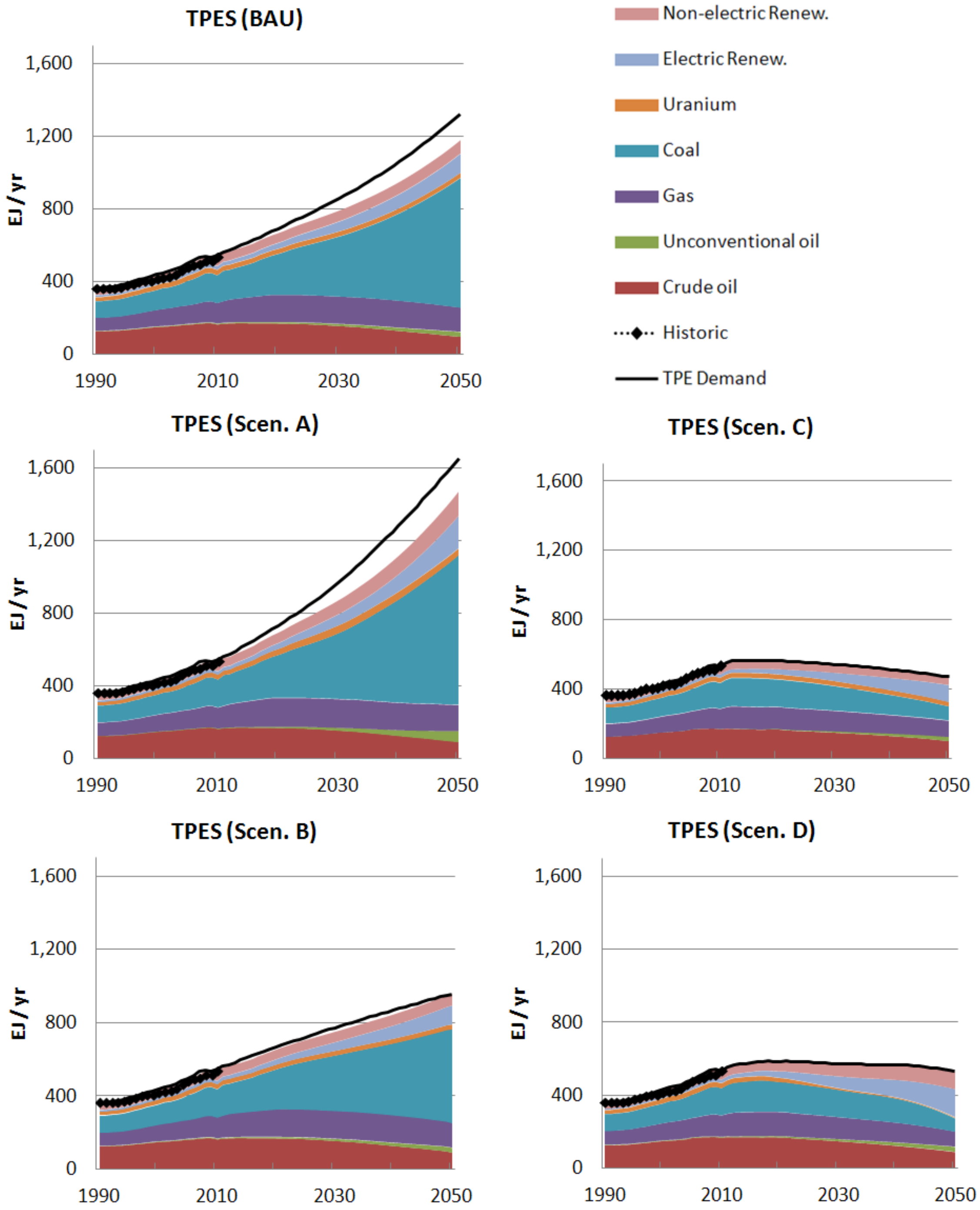
Supplementary Figure 4: For each scenario, (a) Proportion of combined wind and solar electric generation vs. total and (b) Proportion of the investment in electric renewable related to total GDP. In terms of investment, all scenarios show a first maximum (related with the maximum wind rate installation), followed by a second related to solar.

Industrial and Buildings (IB) (Supplementary Figure 5): In the "growth + coal" scenarios, the participation of coal in the Industry and Buildings sector grows from the current 35% share to more than 60% in 2050. In scenario C, the current trends could be maintained, while in scenario D the penetration of the renewable energies progresses at a significant pace.



Supplementary Figure 5: Industrial and Buildings Residential (IB) Primary energy demand and supply by source fuel (EJ/yr) for each scenario.

<u>Total Primary Energy Supply (TPES)</u> (Supplementary Figure 6): The extraction of TPE continues its exponential trend in the scenarios BAU and A, reaching 1,300 EJ and 1,650 EJ respectively by 2050. However, significant divergences still appear between the energy supply and demand. Coal extraction grows in these scenarios at a pace very close to 2000-2013 average of +4% per year (BP 2014): +3.9% (BAU) and +4.3% (A), while it is lower for scenario B (+3.1%). In the "no-growth focus" scenarios, the combined effect of the cease of economic growth altogether with the transition to more efficient technologies and sources of energy in scenario D, allows for a reduction in the total TPE of around 10-20% for both C and D scenarios from current levels.



Supplementary Figure 6: Total Primary Energy Supply and demand by source fuel (EJ/yr) for each scenario. Historic consumption from World Bank.

Supplementary Figure 7 depicts the Gini index of some of the cases of countries currently being in the range of 12,000 US$ and/or 50-60 GJ per capita. For reference, some developed countries/regions are also shown:

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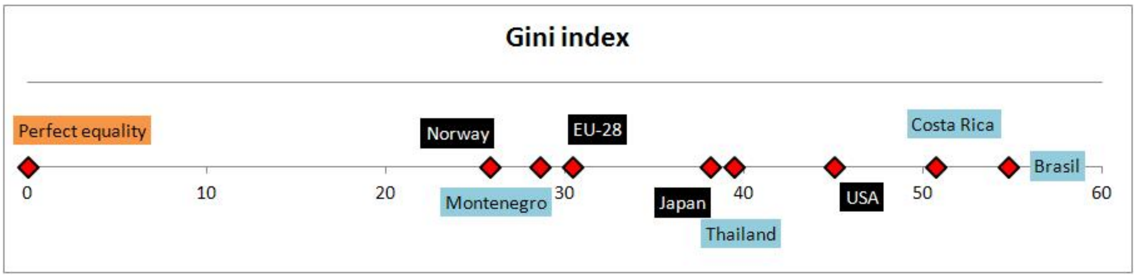

Supplementary Figure 7: Gini index by countries (Eurostat 2013; World Bank database 2014).

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