World Limits Model (WoLiM) 1.5
Model Documentation

Technical Report

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Summary

This document documents the "World Limits Model" version 1.5 (WoLiM 1.5), reporting the methods, rationale and hypothesis applied. This model is an energy-economy-environment simulation system dynamics model that focus on future energy resource availability and its implications for human socioeconomic systems at world aggregated level. In this version, it aims to describe the relationship Economy-Energy-Environment focusing on biophysical limits and deployment potential of renewable and non-renewable energies, as well as on anthropogenic Climate Change.

This report documents an updated version of the model applied in the published papers Capellán-Pérez et al (2014a) and Capellán-Pérez et al (2015), and documented in the previous Technical Report (Capellán-Pérez et al., 2014b). The main changes in this model version and documentation include:

- Correction of minor errors, improvement of modelling structures and update of the model to more recent data.
- Improved and expanded documentation (within the model and in this Technical Report).
- More depletion curves of non-renewable resources available for simulation.
- Disaggregation between conventional and unconventional gas.
- Inclusion of offshore wind resource.
- Consideration of the potential of all renewable sources (bioenergy, geothermal and solar) for other uses than electricity which allows the confrontation of its supply and demand.
- Rough estimation of the overcapacity required to integrate intermittent renewable energy sources in the electricity sector.
- Consistent behavior under scenarios of GDP reduction.
- Implementation in VENSIM and excel interface to run customized simulations (without requiring to install the VENSIM proprietary software).

For illustrating the introduced changes and for the purpose of comparison, the 5 scenarios simulated in Capellán-Pérez et al (2014a) with WoLiM 1.0 are re-run. Finally, the main limitations and further developments of the model are reported.

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Abbreviations

- AEI: Annual Efficiency Improvements
- ASPO: Association for the Study of Peak Oil
- BEV: Battery electric vehicles
- CCS: Carbon capture and storage
- Cp: Capacity factor
- CSP: Concentrating solar power
- CTL: Coal-to-liquids
- DICE: Dynamic Integrated Climate-Economy model
- EJ: Exajoule
- EROI: Energy return on energy invested
- EV: Electric vehicle
- GDP: Gross Domestic Product
- GDPpc: GDP per capita
- GEA: Global Environmental Assessment
- GHG: Greenhouse gases
- GTL: Gas-to-liquids
- IB: Industry & Buildings
- IEA: International Energy Agency
- IEO: International Energy Outlook
- IPCC: Intergovernmental Panel on Climate Change
- IR: Inferred resources
- LCA: Life-cycle analysis
- LDV: Light Duty Vehicle
- MEDEAS: Modelling sustainable Energy system Development under Environmental And Socioeconomic constraints
- Mha: Mega hectare
- MSW: Municipal Solid Waste
- NEA: Nuclear Energy Association
- NGLs: Natural gas liquids
- NGV: Natural gas vehicle
- NPP: Net Primary Productivity
- OECD: Organisation for Economic Co-operation and Development
- PES: Primary Energy Supply
- PHEV: Plug-in hybrid vehicle

- PV: Photovoltaic
- RAR: Reasonably assured resources
- RES: Renewable Energy Sources
- RES: Renewable Energy Sources
- RURR: Remaining ultimately recoverable resources
- SD: System Dynamics
- TPE: Total Primary Energy
- TPE: Total primary energy
- TPED: Total primary energy demand
- TPES: Total Primary Energy Supply
- TPES: Total primary energy supply
- UNEP: United Nations Environment Programme
- URR: Ultimately recoverable resources
- US EIA: US Energy Information Administration
- USA: United States of America
- WEO: World Energy Outlook
- WoLiM: World Limits Model

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1. Introduction and objectives

WoLiM, which continues previous work performed by the Group of Energy, Economy and System Dynamics of the University of Valladolid (de Castro, 2009; de Castro et al., 2009; Mediavilla et al., 2013), is a biophysical energy-economy-environment model (Dale et al., 2012a). It is a structurally-simple and transparent tool which compares data from many different sources and helps viewing global panoramas. This model aims to deal with complex and non-linear systems subjected to constraints such as the human development within the natural ecosystems. In order to achieve it, we face different issues:

- *Interdependence among subsystems*: since human activities unfold into natural ecosystems, feedbacks will be a key feature of the functioning of the whole system.
- *Multidisciplinarity*: to address the interdependence between systems the integration of knowledge from different fields is required (e.g. economy, climate, geology, engineering, etc.)
- *Uncertainty*: in such complex systems, predictions become infeasible and modelers have to adopt specific methodologies such as working with projections and scenarios.

System Dynamics (SD) is a useful tool to deal with these issues and has already successfully been applied to investigate the interactions in the energy-economy-environment interface (Dale et al., 2012a; de Castro, 2009; de Castro et al., 2009; Fiddaman, 2002; García, 2009; Leopold, 2016; Meadows et al., 2004, 1972; Mediavilla et al., 2013).

While depletion studies for individual fossil fuels are relatively abundant in the recent literature, few analyses offer an integrated perspective of all energy sources considering potential future developments, and even less include the energy demand from the socio-economic system. Although many global energy-economy-environment models have been developed (e.g. IPCC's Assessment reports and UNEP's Global Environmental Outlook), few of those models explicitly consider constraints to energy expansion assuming that the demand of energy in the future will be supplied without significant supply restrictions (Capellán-Pérez et al., 2014a).

Geology imposes certain physical constraints to the extraction rate of non-renewable energy resource stocks. For example, oil and gas are extracted by creating pressure gradients within the reservoir that cause the oil and/or gas to flow through the interconnected pores to one or more extraction wells. In most oilfields the pressure gradients are maintained by injecting another fluid (usually water) into the reservoir through injection wells. The injected water displaces the oil and occupies the pore space that it originally occupied. By contrast, gas fields are normally exploited simply by reducing the pressure at the extraction well using compressors. The gas in the reservoir expands as the pressure drops and thus flows to the extraction well (Muggeridge et al., 2014). Thus, technology can help regulate the extraction rate levels but cannot force them to reach any value. In the words of the geologist J. Laherrère (2010, p. 6), it is not *"the size of the tank"* (stocks) that matters, but rather *"the size of the tap"* (flows). This means that the limiting factor changes from the recoverable in-place resource to the time it takes to make it available for human use. In this context, "peak oil" as a concept was coined in 2002, when C. Campbell and K. Aleklett founded ASPO (Association for the Study of Peak-Oil). Its early members used a curve-fitting method developed by fellow petroleum geologist K. Hubbert, who postulated in the mid-20th century that the maximum extraction rate of crude oil from all wells of a region follows the same logistic growth function as the rate of discoveries in that region (Hubbert, 1956). The potential future evolution in fossil fuel resources extraction has been the subject of numerous studies in recent years, particularly in reference to oil. However, the studies differ in the dates and nature of the eventual decline of extraction, ranging from present times to the year 2020-25 (Aleklett et al., 2010; ASPO, 2009; Campbell and Laherrère, 1998; de Castro et al., 2009; EWG, 2008; Höök et al., 2009; Miller and Sorrell, 2014; Robelius, 2007; Skrebowski, 2010; Sorrell et al., 2009). Other fossil energy resources have been to date less studied, but similar depletion curves to those for oil have been also proposed for gas and coal (EWG, 2006, 2007; Höök and Aleklett, 2009; Laherrère, 2006; Mohr and Evans, 2009, 2011; Patzek and Croft, 2010; Tao and Li, 2007).

On the other hand, even in the presence of aggressive promotion policies, the diffusion of alternative technologies is limited by several technical, institutional, behavioural, and social factors. Models focusing on optimization procedures (that are the majority in the literature as noted in (Capellán-Pérez, 2016, chap. 2)) may include these restrictions, although in practice they are often not implemented in their standard versions (Iyer et al., 2015; Li and Strachan, n.d.; Staub-Kaminski et al., 2014). In fact, exploratory works have shown that these factors have sizeable impacts on the feasibility and mitigation costs of achieving stringent climate stabilization targets. Moreover, the study of previous energy/technological transitions shows that they are slow, in the order of decades (Fouquet, 2010; Smil, 2010).

However, few energy-economy models explicitly recognise that geological constraints might limit the extraction rates of non-renewable fossil fuels. As a result, future energy transitions are usually modelled as demand-driven transformations, i.e. without accounting for potential supply constraints, such as the models applied by the IEA (WEM, (IEA, 2015)) or the IMF (Aleklett et al., 2010; Benes et al., 2015; Höök and Tang, 2013; Kumhof and Muir, 2012). The projections of oil consumption during the 2000s decade by the US EIA constitute a paradigmatic example (Figure 1). At that time, their forecasts exhibited an almost continuous decline between 2001 and 2010, with the forecast for 2020 declining by over 20%, or 25 million barrels per day. In fact, these forecasts were based on the simple notion that the supply would be available to satisfy any demand, so these forecasts essentially only considered the drivers of demand at a time when the peak of conventional oil production was reached (Benes et al., 2015).

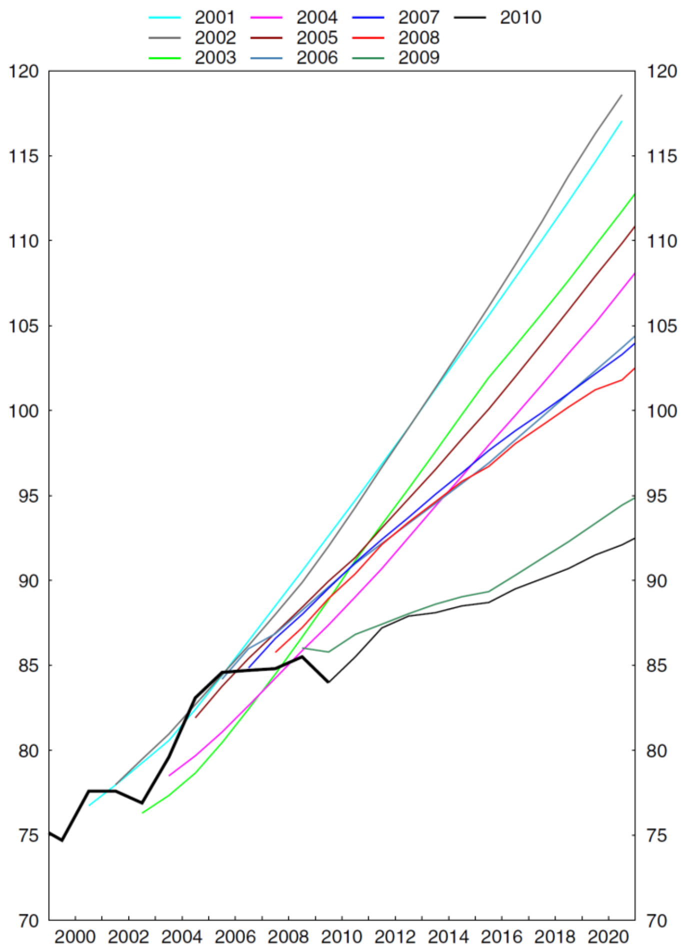

Figure 1 (Benes et al., 2015): EIA forecasts of oil production (2001-2010). EIA definition of world total oil supply: crude oil plus Natural Gas Liquids and other liquids, plus refinery processing gains.

Hence, few models explicitly recognise that geological constraints might limit the extraction rates of non-renewable fossil fuels by Nel and Cooper (2009), de Castro (2009), de Castro et al. (2009), and Dale et al., (2012b). However, recently even the IEA through the WEO (2016) has acknowledge the possibility of a supply gap in the near future (Figure 2).

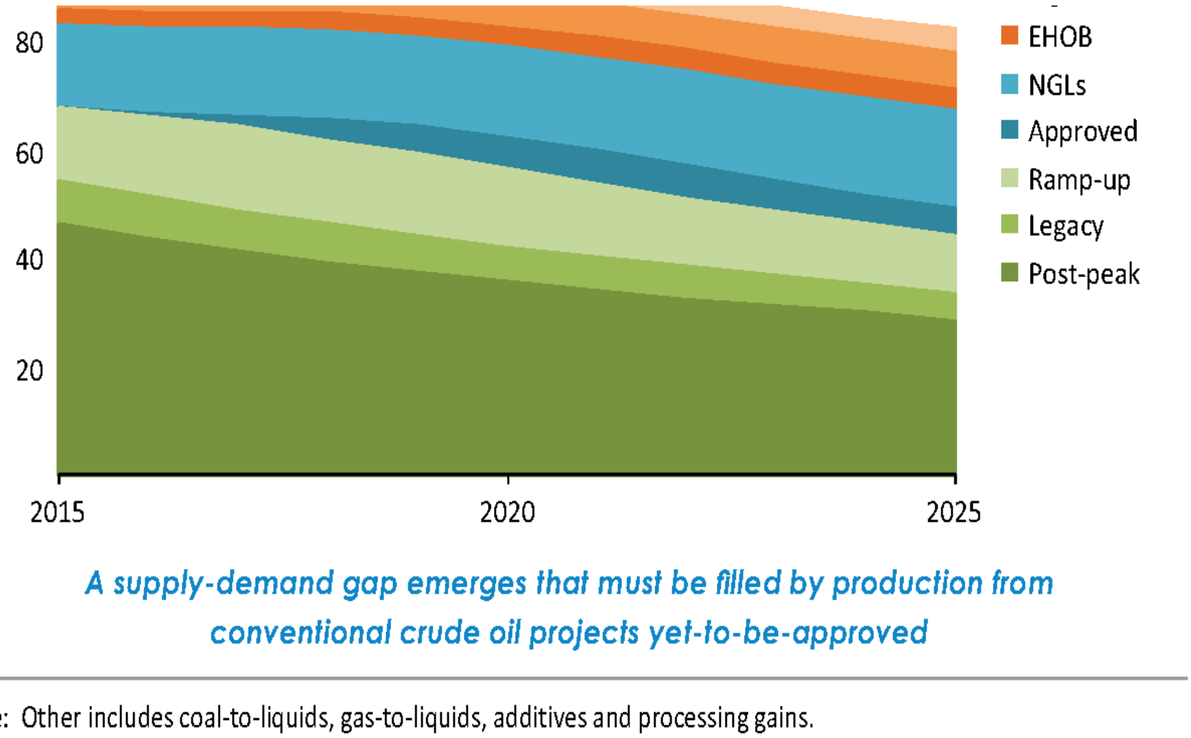

Figure 2 (WEO, 2016, fig. 3.16): Global supply outlook from selected sources in the New Policies Scenario.

WoLiM includes the exhaustion patterns of non-renewable resources and model their replacement by alternative energies considering estimations of development and market penetration, the energy demand of the goblal 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. 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 several characteristics that significantly reduce their sustainable potential (Capellán-Pérez et al., 2014a; de Castro et al., 2011, 2013b, 2014; Smil, 2008; Trainer, 2007).

This model version allows exploring the energy system and its climate change implications in detail. However, important features as feedbacks between the subsystems, the EROI consideration and other limits (e.g. water, minerals) are not included and are subject of current research.

This model version is implemented in Vensim and can be run using Vensim Reader (freely available software). WoLiM 1.5 is available for download in this link: http://www.eis.uva.es/energiasostenible/?page_id=2056&lang=en. All the equations of the model are available in the document: "Annex to WoLiM1.5 TR-equations.pdf".

This technical report is organized as follows: section 2 overviews the model, section 3 documents its main assumptions, the scenarios simulated are described in section 4 and the obtained results in section 5. Finally, the limitations and future developments of the model are briefly reviewed in section 6.

2. Overview of WoLiM

WoLiM 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 energies by alternative energy sources,
- The energy demand of the World's economy under different socio-economic scenarios,
- The sustainable potential of renewable energy sources.
- The net CO_2 emissions and concentrations in the atmosphere.

WoLiM is based on a sequential structure (see Figure 3) which starts by considering a scenario framework that consists of a set of socioeconomic and technological assumptions and policies that are integrated in a coherent and sensible way. Socio-economic assumptions drive global energy demand[1] evolution over time (2010-2050). This demand is then disaggregated according to the different end-use sectors (electricity, industry, transport, etc.), and the energy demand of each sector is disaggregated into demand by types of energy sources (liquid fuels, gas, electricity, etc.). These demands are compared to the supplies of each particular resource (oil, gas, uranium, etc.), which are limited by the geology-based peaks and the rates of technological substitution. Finally, the net CO_2 emissions and concentration levels are computed.

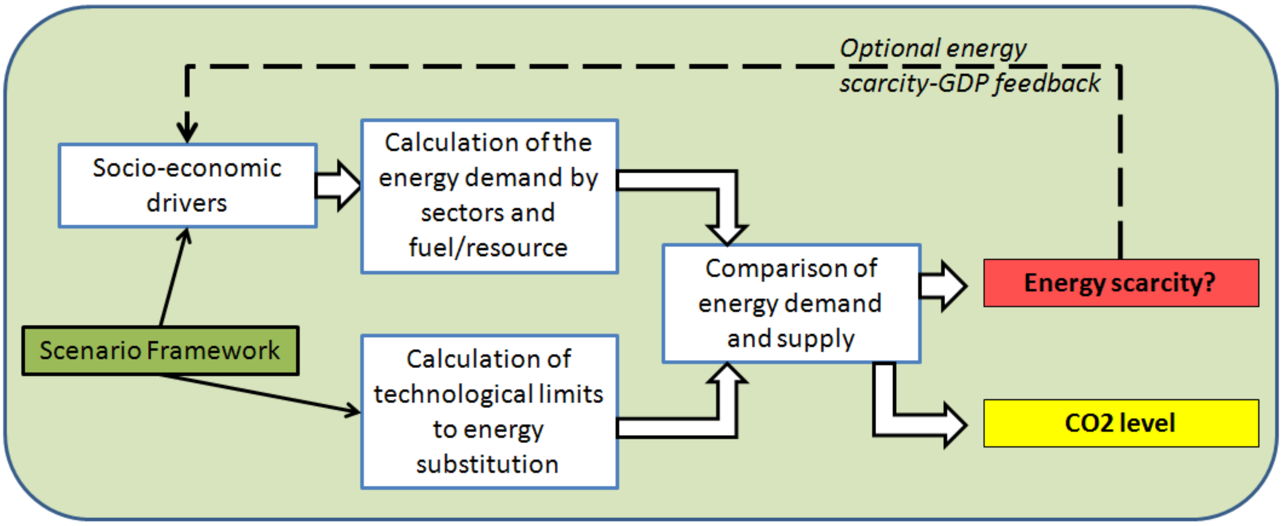

Figure 3: Basic logic functioning of the WoLiM model. See Appendix D for the modeling of the optional energy-scarcity-GDP feedback. See footnote 1 for a comment about the "supply" and "demand" terminology.

In the standard version of WoLiM the model outputs will only be valid as far as they do not lead to an important disequilibrium between demand and supply in any sector. Once this disequilibrium takes place, the system could evolve in a variety of ways and from that point in time on the results would not be robust enough. Thus, the main contribution of the model would be its capacity to detect, for each scenario and fuel/sector, the point in time when the supply might not meet the demand (i.e. "scarcity points").

The key exogenous variables of the model (variables which are set by the scenario methodology, while endogenous variables are calculated within the model) are:

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[1] Although in this report we use the terms "supply" and "demand" for the sake of simplification, we are aware that from an economic point of view this terminology is incorrect. In fact, both supply and demand functions depend on prices, which are not modelled in this framework. Instead, "supply" should be interpreted as "availability of energy resources" and "demand" as the "estimation of the consumption". This inconsistence will be corrected in further versions.

- 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 (IB).
- 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.

Given these, the following magnitudes can be derived:

- Energy intensities of each economic sector: transportation, electricity and IB.
- 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).
- Stocks that describe the infrastructure of renewable energies (solar, wind, hydroelectric, etc.) whose growth is determined by the policies applied.
- Stocks that represent the introduction of the alternative policies (biofuels, EV, efficiency, etc.).
- CO_2 emissions and concentration levels related to fossil fuel use.

The main assumptions and hypotheses considered in the model are the following:

- Non-renewable resources extraction rates are subject to geological constraints.
- Technological changes, such as the replacement of non renewable by alternative energies or efficiency, require time. Their transition growth ratios are determined based on the tendencies observed in past decades (and 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).

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 3).

Once a scenario is set, the estimation of the energy demand is calculated as the product of the exogenous GDP by energy intensity. We interpret GDPpc not as a welfare indicator[2], but as a driver of economic activity that requires energy and materials. In fact, the world socioeconomic system has been unable even to approach absolute decoupling between GDP and resources (e.g. (Bithas and Kalimeris, 2013;

[2] We recall that GDP was not designed to measure social or economic welfare (Kubiszewski et al., 2013). The limitations of GDP as welfare indications are well known (e.g. (Jackson, 2009; van den Bergh, 2009)).

Peters et al., 2011; UNEP, 2011)). Demand is organized into three aggregated sectors: Transportation,[3] Electricity and IB (Industrial and Buildings, without electricity). Each sector's energy demand is generated through sectoral energy intensities (see section 3.2). These energy demands are divided into demands of different energy sources 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 section 3.1.1.1). The model includes the estimations of expansion of several technologies (electricity from renewable energy sources, bioenergy, nuclear, coal-to-liquids (CTL), gas-to-liquids (GTL), etc.). Each scenario considers different policies for the expansion of each technology. Finally, CO_2 emissions and concentration levels to 2050 and the end of the century are computed.

Priority is given to renewable energy sources (once the infrastructure is built, all the energy generated is used), and the rest of the demand is divided between the non-renewable energy sources maintaining past shares (20-year average values from *International Energy Outlooks*). This allows us to compare demand and supply 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 at global level (e.g. (WEO, 2012)), we consider this analysis valid in the medium term (~2050). The model runs on a 1-year time step.

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.

- **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. In order to deal with these divergences a set of indicators is set (see Section 5). 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.

Different scenarios and a wide range of alternative policies can be applied when running the model (see circled variables in Figure 4) by varying: sectoral energy-efficiency improvement, promotion of electric transportation, renewable production (electric, thermal, biofuels), non-renewable maximum extraction curves, nuclear expansion, GTL and CTL.

Thus, this model enables to explore different scenarios of energy transition from a fossil-based system to a renewable energy one in the medium-term (until 2050), approximate date we consider the hypothesis employed are consistent. This model permits to focus into resource limitation, transition rhythms by identifying reasonable and feasible policies while ruling out others.

[3] Including aviation, Road (freight and passenger), Rail, Pipeline transport, domestic navigation and world marine bunkers.

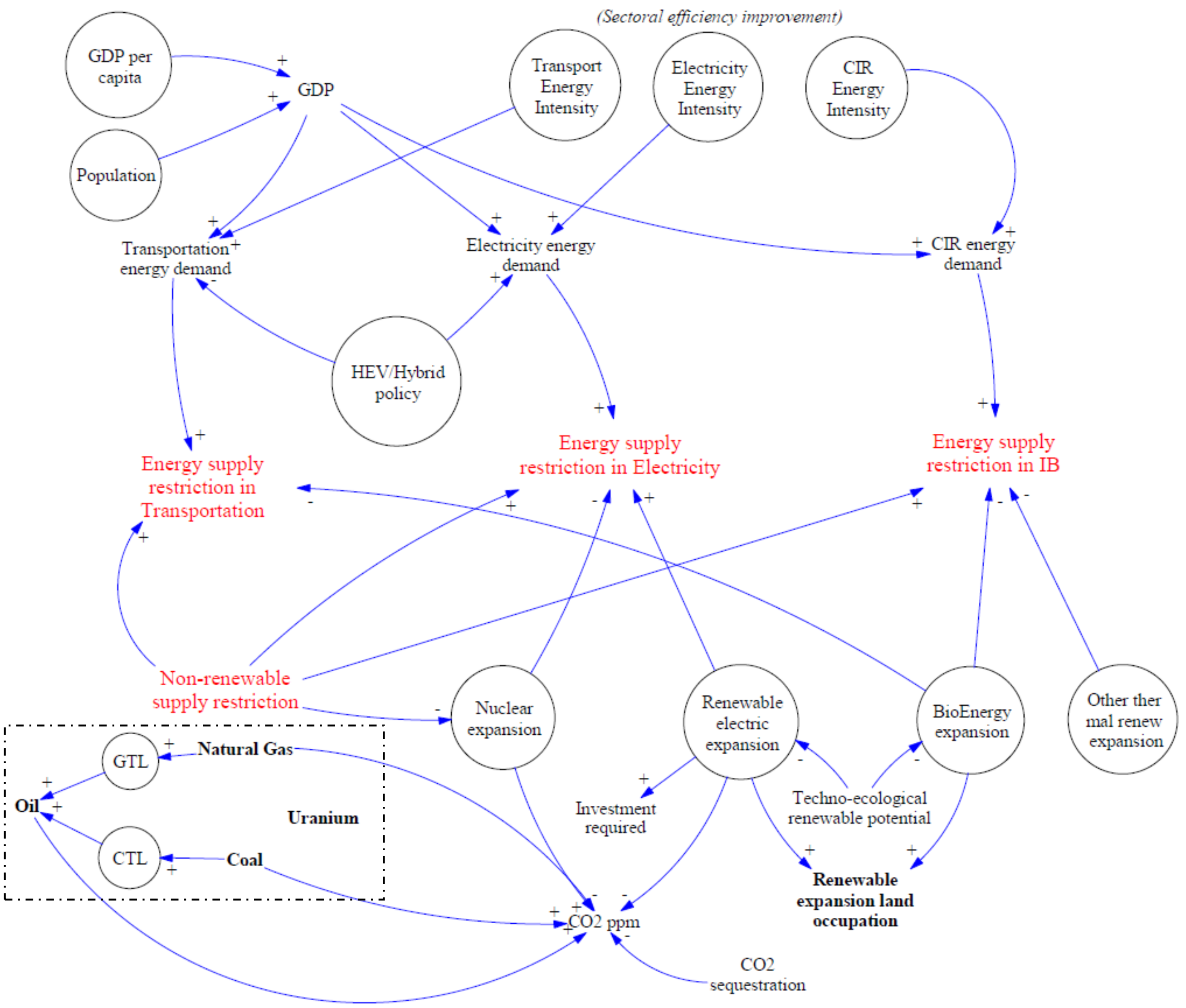

Figure 4: Causal loop diagram of the model WoLiM 1.0 with its basic elements. Scenario elements and policies are circled. IB: Industrial and Buildings sectors.

The current framework presents some limititations due to its operation in terms of primary energy (instead of net energy), the non-inclusion of material limits and other non-energetic renewable sources or the absence of feedback between its main subsystems (e.g. climate impacts) or other subsystems that are not included (e.g. biodiversity loss) (see section 6 on "Limitations and future developments of the model"). One of the most critical relationships relates the energy scarcity to the economy, which could impact economic growth (Ayres et al., 2013; Hamilton, 2009; Hirsch, 2008; Kerschner et al., 2013; Murphy and Hall, 2011; Tverberg, 2012). However, there is not a well-developed and widely accepted theory on this topic, most macroeconomic models paying very little attention to natural resources and, from our point of view, overestimating the capacity of technological substitution (Capellán-Pérez et al., 2014a; Huesemann, 2003).[4] In this context, it is possible to implemented a feedback that allows to dynamically adjust the energy

[4] Interestingly, this is also the conclusion reached by researchers analyzing the technological change rates in the transition pathways proposed by integrated assessment models of climate change to mitigate climate change, e.g. (Pielke et al., 2008) (conventional resource economics does not acknowledge for the existence of absolute physical boundaries to the extraction of resources on this century, thus in their reference/baseline scenarios without explicit climate policies the transition to renewable sources is not a requirement to sustain economic growth).

demand to the supply through decreasing the GDPpc in order to build feasible and consistent scenarios (Capellán-Pérez et al., 2015) (see Appendix D).

WoLiM integrates *large amount of data within a simple structure,* which makes it very transparent tool. 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).

3. Main hypotheses

3.1. Modelling of energy resources availability

This section documents the modeling of the energy resources availability in WoLiM (non-renewable resources in section 3.1.1 and renewable-resources in section 3.1.2). The model operates in terms of primary energy (direct equivalent method[5]).

3.1.1. Non-renewable energy resources

WoLiM considers the following non-renewable primary energy resources:

- Conventional oil: refers to crude oil and NGLs.
- Unconventional oil: includes heavy and extra-heavy oil, natural bitumen (oil sand and tar sands) and oil shales. Biofuels, CTL, GTL and refinery gains are modeled separately (see sections 3.1.1.5 and 3.1.2.1).
- Conventional gas.
- Unconventional gas: includes shale gas, tight gas, coal-bed methane (CBM) and hydrates.
- Coal: includes anthracite, bituminous, sub-bituminous, black, brown and lignite coal.
- Uranium.

We assume that the technologies that claim they could increase the fisible material by 50 to 100 times, like fast breeders and the so-called fourth generation reactors, will not be available in the next decades (Cellier, 2009). 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]

3.1.1.1. Modeling of primary non-renewable energy resources in WoLiM

It is assumed that the availability of non-renewable energy resources depends upon two constraints:

- Stock (available resource in the ground), ie. energy,
- Flow (extraction rate of this resource), ie., energy/time.

Figure 5 illustrates the depletion over time of a non-renewable resource stock (cumulative extraction, grey dashed line) through flows (depletion curve, black solid line) in the absence of non-geologic

[5] There are three alternative methods predominantly used to report primary energy. While the accounting of combustible sources, including all the fossil energy forms and biomass, is unambiguous and identical across the different methods, they feature different conventions on how to calculate primary energy supplied by non-combustible energy sources, i.e., nuclear energy and all renewable energy sources, except biomass. The direct equivalent method counts one unit of secondary energy provided from non-combustible sources as one unit of primary energy, that is, 1 kWh of (useful) electricity or heat is accounted for as 1 kWh = 3.6 MJ of primary energy. For more information see Annex II of (IPCC, 2011).

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

restrictions. The maximum flow rate is reached much earlier than the full depletion of the stock, at half the time assuming that the extraction rate follows a logistic curve.

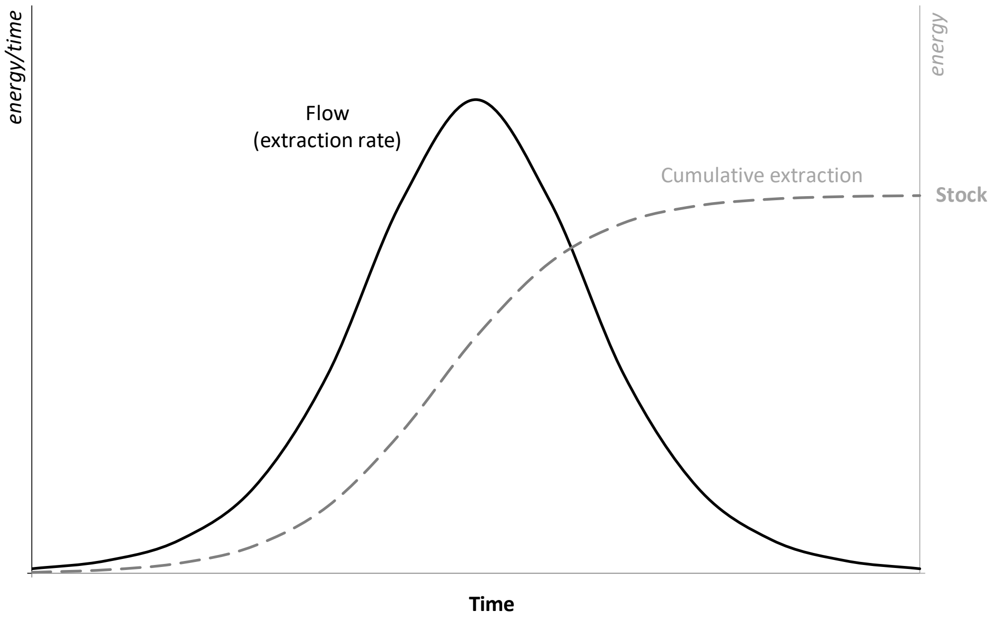

Figure 5 (Kerschner and Capellán-Pérez, 2017): Simplified representation of the depletion of a non-renewable resource in the absence of non-geologic constraints. Stocks and flows of energy relative to time.

The available stock of a resource is usually measured in terms of ultimately recoverable resources (URR), or remaining RURR (RURR) if referenced to a given year. The RURR in a given time t is defined as the difference between the URR and cumulative extraction in time t (see eq. 1):

$$RURR_t = URR - cumulative\_extraction_t \qquad \text{eq. 1}$$

In order to estimate the future availability of fossil fuels, we have reviewed the studies providing depletion curves for non-renewable energy resources taking into account both stocks and flow limits. These studies provide depletion curves as a function of time based on dynamically estimating the likely extraction rate of wells and mines globally (Aleklett et al., 2010; ASPO, 2009; EWG, 2006, 2007, 2008, 2013; Höök et al., 2010; Laherrère, 2006, 2010, Maggio and Cacciola, 2012, 2012; Mohr, 2012; Mohr et al., 2015; Mohr and Evans, 2009, 2009, 2011; Patzek and Croft, 2010; Zittel, 2012). These curves (see Figures 7-14) should not be interpreted as projections of the extraction of a given fuel, but instead represent curves of maximum possible extraction given the geological constraints (ie., assuming no demand or investment constraints).

The depletion curves of non-renewable energies reviewed in the literature represent extraction levels compatible with geological constraints as a function of time. Thus, to be incorporated as inputs in the model, these depletion curves must be transformed, since demand is endogenously modelled for each resource. We assume that, while the maximum extraction rate (as given by the depletion curve) is not reached, the extraction of each resource matches the demand. Actual extraction will therefore be the minimum between the demand and the maximum extraction rate (see Figure 6a). To do this, the depletion curves have been converted into maximum production curves as a function of remaining resources. In these curves, as long as the remaining resources are large, extraction is only constrained by the maximum extraction level. However, with cumulated extraction, there is a level of remaining resources when physical limits start to appear and maximum extraction rates are gradually reduced. In this way, the model uses a stock of resources (the RURR) and it studies how this stock is exhausted depending on production, which is in turn determined by demand and maximum extraction (see Figure 6b).

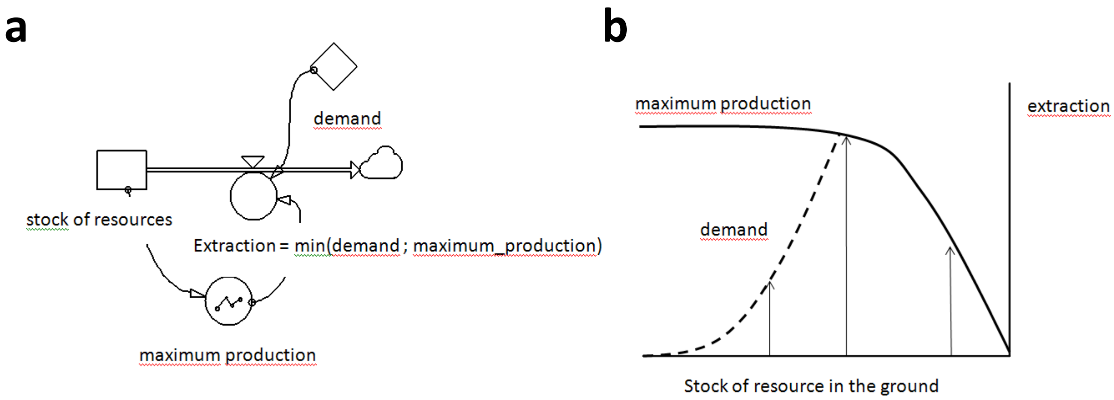

Figure 6 (Mediavilla et al., 2013): Integration of depletion curves in the model. (a) SD model. (b) A curve of maximum extraction (solid) compared with the demand (dashed).

As illustration, Figure 7a shows the depletion curves as a function of time and Figure 7b the associated curves of maximum extraction as a function of the RURR as applied in (Capellán-Pérez et al., 2014a).

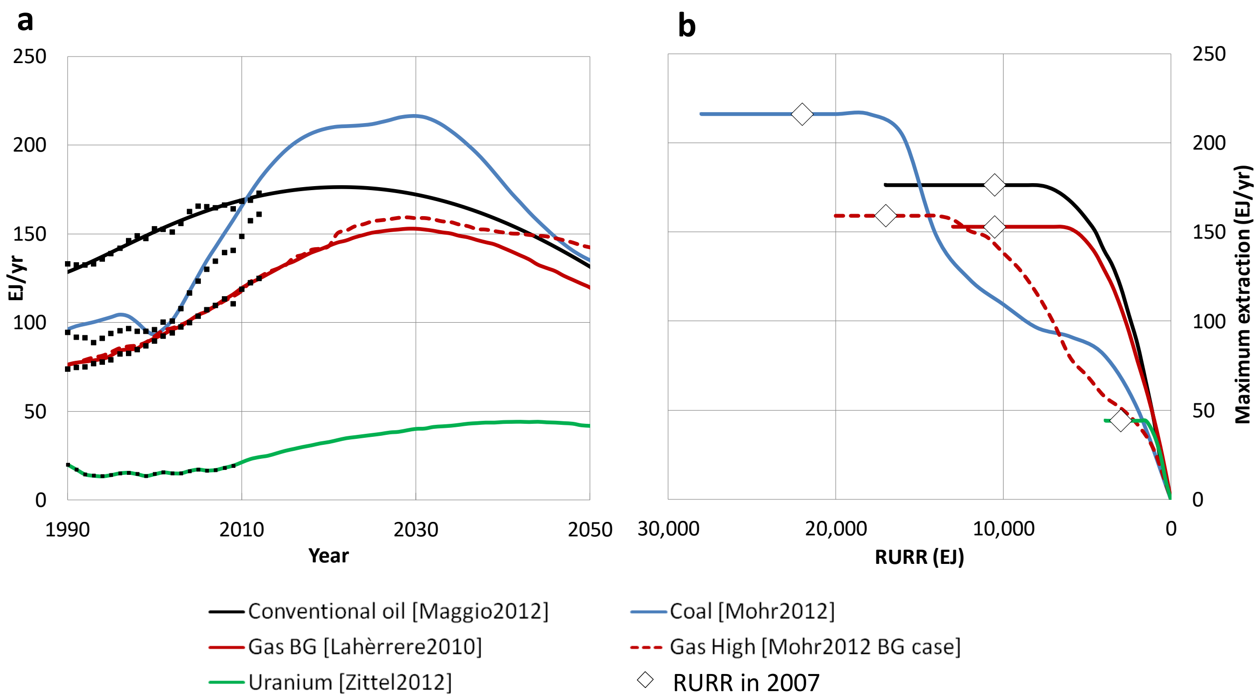

Figure 7 (Capellán-Pérez et al., 2014a): Non-renewable primary energy resources availability: (a) depletion curves as a function of time from the original reference; (b) curves of maximum extraction in function of the RURR as implemented in the model. The y-axis represents the maximum achievable extraction rate (EJ/year) in function of the RURR (EJ). For each resource, the extreme left point represents its URR. As extraction increases and the RURR fall below the point where the maximum extraction can be achieved, the extraction is forced to decline following the estimations of the studies selected (panel (a)). The RURR in 2007 for each resource is represented by a rhombus.

Each study follows it own assumptions to derive the depletion curves of each fuel, and these should be carefully assessed before applying a depletion curve in the model by the users. The following subsections review the depletion curves of non-renewable energy resources found in the literature by fuel together with a brief discussion: oil (section 3.1.1.2.1), natural gas (section 3.1.1.2.2), coal (section 3.1.1.2.3) and uranium (section 3.1.1.2.4). WoLiM allows selecting a diversity of depletion curves for each fuel (as well as considering a customized one or assuming the unconstrained extraction of the fuel).

The maximum extraction curve does not allow capturing the flow constraints when the peak rate of a fuel has not been reached. For this reason, unconventional oil & gas extraction is subject to an additional constraint that limits the maximum annual growth extraction rate to avoid unrealistic growth extraction rates (see section 3.1.1.4).

3.1.1.2. Literature review of depletion curves by fuel

The following subsections review the depletion curves of non-renewable energy resources found in the literature by fuel together with a brief discussion: oil (section 3.1.1.2.1), natural gas (section 3.1.1.2.2), coal (section 3.1.1.2.3) and uranium (section 3.1.1.2.4). See also (Wang et al., 2016) for a recent and comprehensive review. Additionally, the projections from the World Energy Outlook "Current Policies scenario" (WEO, 2012), essentially following the energy demand-driven paradigm, are represented for comparison.

3.1.1.2.1. Oil

Figure 8 shows the depletion curves for oil found in the literature compared with the projection of the Current Policies Scenarios of the IEA (WEO, 2012). Due to the lack of standardization, we have collected projections from solely conventional oil to total oil (ie., including unconventional oil). Among the depletion curves, the main foreseen trend is that global oil extraction will reach a peak followed by an irreversible decline in the next years (e.g. (ASPO, 2009; EWG, 2008, 2013; Laherrère, 2006; Maggio and Cacciola, 2012)), whereas few estimates find profiles that follow an undulating plateau (Aleklett et al., 2010; Skrebowski, 2010). Analyses do not expect to substantially exceed the maximum of 90 Mb/year. In turn, only the IEA estimates that future oil extraction will be growing by the year 2035. The estimate of Laherrère (2006) applying logistic models is the highest and exceeds the historic data since about 2005, although it is the most accurate in relation to the most recent data of total oil extraction.[7] Aleklett et al., (2010) critically assessed the global oil production forecast of the IEA's WEO (2008), producing an alternative estimate by introducing correction factors to account for geological factors not included in the report. Maggio & Cacciola (2012) provide three estimates associated to three different URR levels; its lower projection is similar to that of ASPO (2009). EWG projections are the most pessimistic among the set analysed, projecting a step decline from the date of the assessment.

[7] It is noteworthy that the last published projection from J. Laherrère from May 2015 (http://aspofrance.viabloga.com/files/JL%5fHubbertlineraization24May) is very much alike to that of the year 2006.

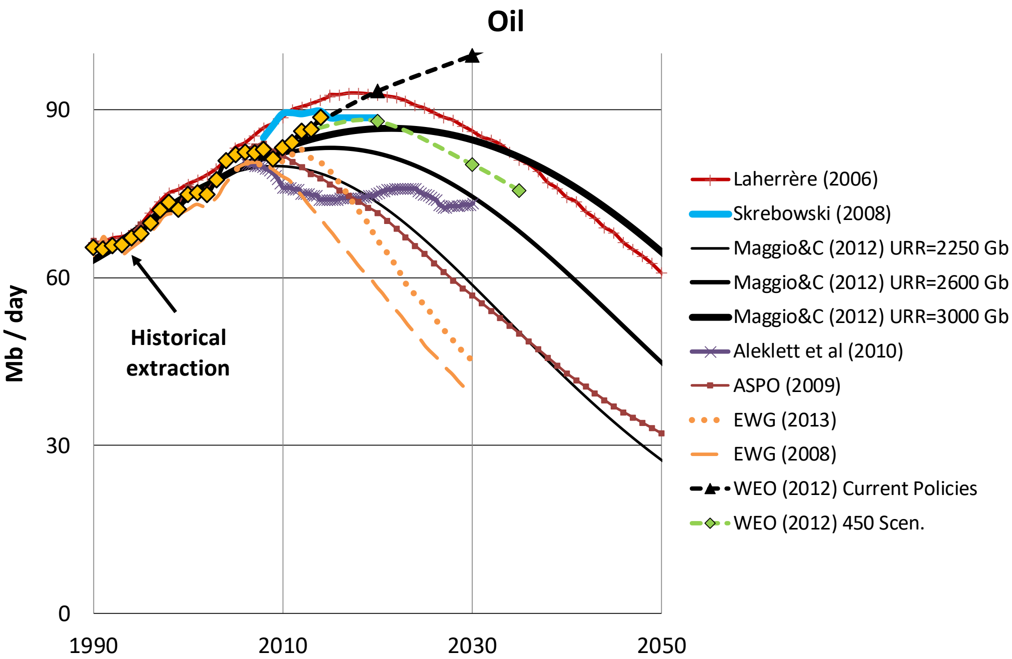

Figure 8: Depletion curves for oil by different authors and comparison with (WEO, 2012) scenarios "Current Policies" and "450 Scenario". Historical data (1990-2014) from BP (2015). There is a lack of standardization in the literature. For each study, "oil" refers to only crude oil (including NGLs) (Maggio 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, 2015) historical data (1990-2014) include crude oil, shale oil, 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.

While the estimations for conventional oil tend to converge for similar patterns, the highest uncertainty is on the future development of unconventional oil (Mohr and Evans, 2010). Its main issue is that what extent technological improvements will be able to compensate the fact that, due to the viscosity and physical properties of unconventional oils, pumping becomes more energy consuming and slower. As an example, Mohr et al (2015) analyze 3 scenarios with (very) different RURR levels (see Figure 9). Although the numbers vary at the end of the century, the difference in extraction levels in 2050 between the highest and the lowest case is just around 20% (54 vs 66 EJ/yr). However, given the current obstacles to the global-scale deployment of unconventional oil even Mohr et al (2015)'s lower scenario may prove too optimistic (Murray, 2016).

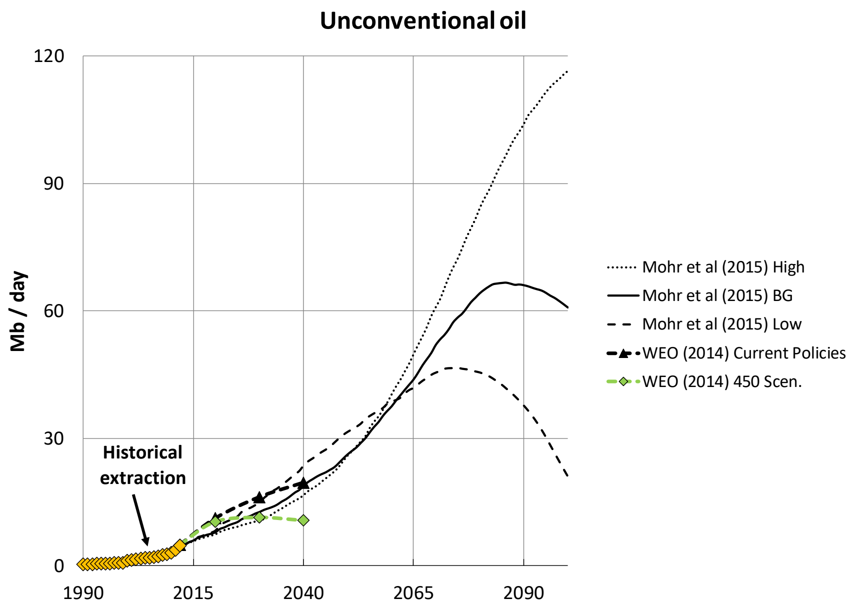

Figure 9: Depletion curves for unconventional oil from Mohr et al. (2015), WEO (2014) projections and historical extraction (1990-2012) from Mohr et al (2015).

3.1.1.2.2. Natural gas

Figure 10 shows the results of collecting estimates for total natural gas (ASPO, 2009; Laherrère, 2010; Maggio and Cacciola, 2012; Mohr, 2012; Mohr et al., 2015; Mohr and Evans, 2011) compared with the projection of the Current Policies Scenarios of the IEA (WEO, 2012). We observe that ASPO (2009)'s projection for the last years is below recent historical data of extraction, and coincides with the lower case from Maggion & Cacciola (2012). Maggio & Cacciola (2012) found that, for different RURR levels, the maximum extraction rate would not trespass 140 TCF/year, reaching its peak before the mid-century. Mohr (2012)'s projections for natural gas (which are very similar to Mohr and Evans (2011)'s), offer a wide range between their "low case" and "best guess", although both depict a peak at around 2025-2030 between 130 and 150 TCF/year. Lahèrrere's (2006) estimate broadly falls between Mohr (2012) two lower cases, although with a greater steepness after reaching the peak. The "high case" from Mohr (2012) assumes that very large amounts of unconventional gas (coal bed methane, shale gas and tight gas) will be available in the future (RURR of 11 ZJ) in comparison with the other estimates (e.g. RURR of 2.1 ZJ considered by Lahèrrere (2006)). Mohr et al (2015) updated Mohr (2012)'s analysis, including methane hydrates and updating the RURR for different types of unconventional gas. As a result, the RURR for total natural gas was substantially increased in the best guess (+55%) and high scenarios (+70%). Both cases (as well as the high case from Mohr (2012)) reach maximum extraction levels that are well above the range of the rest of forecasts. These are the only cases which the projections of the IEA are consistent with. Mohr et al BG (2015) reaches a plateau at around 180 TCF/year that lasts several decades, while the high scenario assumes that natural gas extraction might increase during the next decades until a maximum extraction close to 300 TCF/yr around 2075.

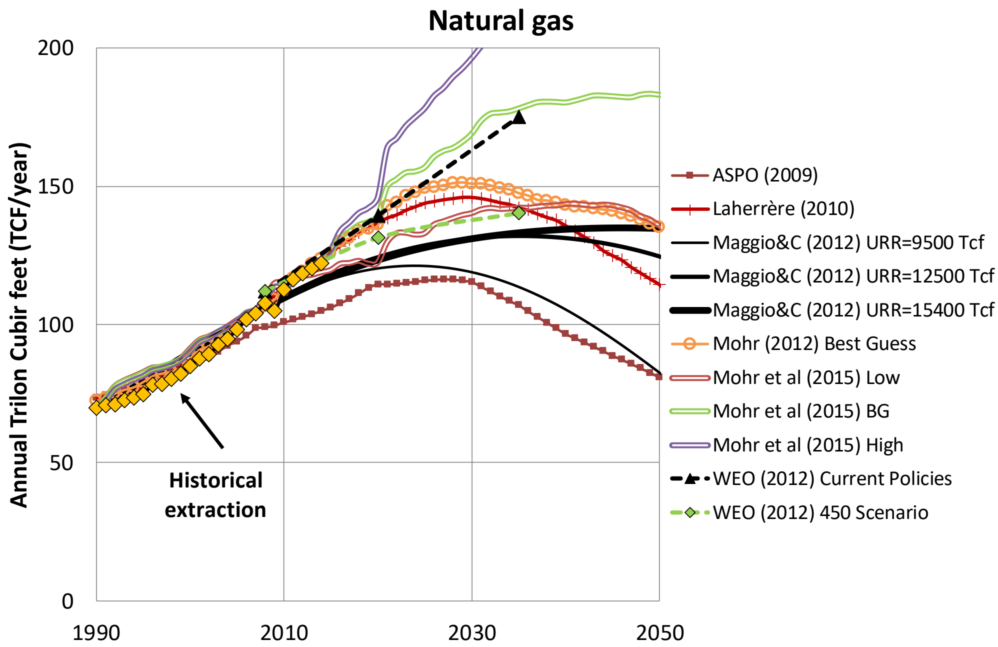

Figure 10: Estimations of total natural gas extraction by different authors and comparison with (WEO, 2012) scenarios "Current Policies" and "450 Scenario". Historical data (1990-2014) from BP (2015).

As for unconventional oil, few studies have focused on unconventional gas. **Figure 11** shows the low, best guess and high depletion curves from Mohr et al (2015).

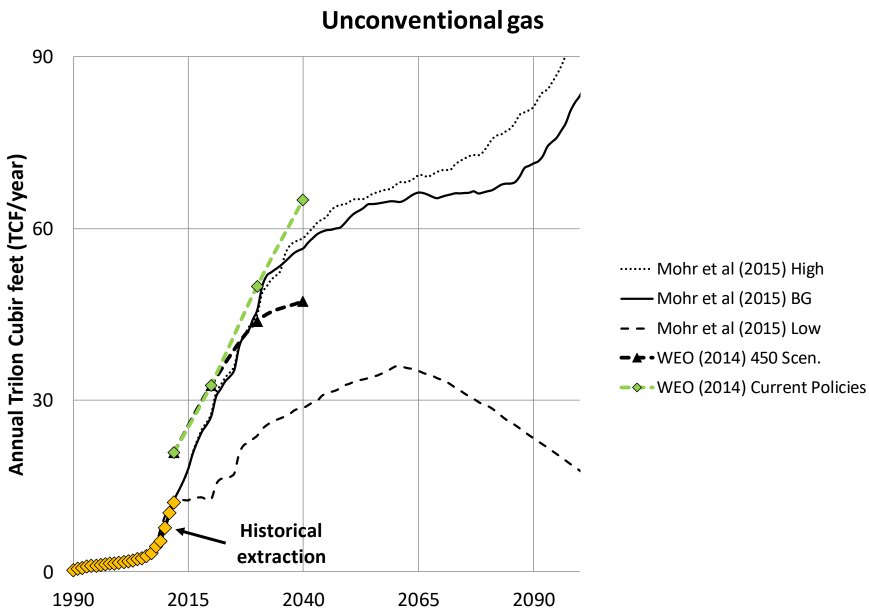

Figure 11: Estimations of unconventional natural gas extraction from Mohr et al (2015), WEO (2014) projections and historical extraction (1990-2012) from Mohr et al (2015).

Natural gas energy content per volume

Gas reserves are usually reported in volume units (e.g. tcf[8]). However, and similarly to oil, different agencies apply different energy equivalence attending to different composition of the gas, etc.

	Original conversion given	**1 bcf in Mtoe**
(ASPO, 2009)	1 bcf = 166 Mboe	22.1
(EIA US, 2014, chap. Appendix G)	1 cf = 1,022 Btu	25.8
(BP, 2013)*	324.6 bcf = 3,034 Mtoe	25.6
(IEA, 2013)	3,435 tcm = 2,787 Mtoe	23.0
(Mohr and Evans, 2011)	133 tcf = 140 EJ	25.1

*Table 1: Equivalence between volume and energy applied by different agencias and authors. *Equivalence used by de Castro (2009).*

In this model we have adopted the equivalence from the *US Energy Information Administration* since we used their data to estimate the regressions from the sectoral energy demand (cf. section 3.2). We note that it is in the low range of bcf/Mtoe, i.e. it is in the highest range of useful energy per volume extracted.

3.1.1.2.3. Coal

Figure 12 shows the different estimates for coal production that have been collected from the literature (EWG, 2007, 2013; Höök et al., 2010; Maggio and Cacciola, 2012; Mohr, 2012; Mohr et al., 2015; Mohr and Evans, 2009; Patzek and Croft, 2010). The first remark is that most of the proposed depletion curves are not consistent with the recent surge in coal extraction globally. In fact, most of the studies are based on logistic curves similar to the ones used for oil. The liquid nature of oil makes fast extraction in mature fields impossible, no matter how much infrastructure is used. Coal is a mineral and, therefore, more infrastructure and extraction effort can replace the low quality of the resource. If the maximum extraction is higher, this means that, with the same amount of resource, the curve goes up more and then goes to zero faster (EWG, 2007, 2013; Höök et al., 2010; Maggio and Cacciola, 2012; Patzek and Croft, 2010). On the other hand, the analyses by Mohr and Evans (2009), Mohr (2012) and Mohr et al (2015) are based on a modelling methodology taking into account the particularities of solid mined resources.

Since different types of coal exist with different thermal equivalent (e.g. lignite, hard coal, etc.), we take the average value of the last 30 years as reported by (BP, 2013): 1Mt = 0,4844 Mtoe, as done by other studies (e.g.(Höök et al., 2010)).

[8] tcf: trillon cubic feet, that equals 10^3 bcf (1e9 cf).

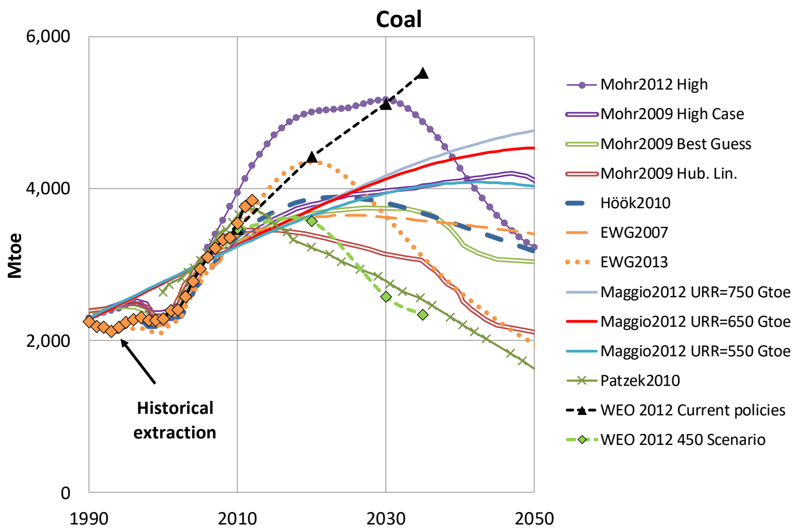

Figure 12: Estimations of coal extraction by different authors and comparison with (WEO, 2012) scenarios "Current Policies" and "450 Scenario". Historical data (1990-2014) from BP (2015). (1 Mt = 0.4844 Mtoe (Höök et al., 2010)).

Figure 13 represents the forrester diagram of coal extraction to illustrate the modelling of non-renewable energy resources extraction. "RURR coal" is the main stock, and "extraction coal EJ" is the main flow, which is compared with the "Total demand coal EJ".

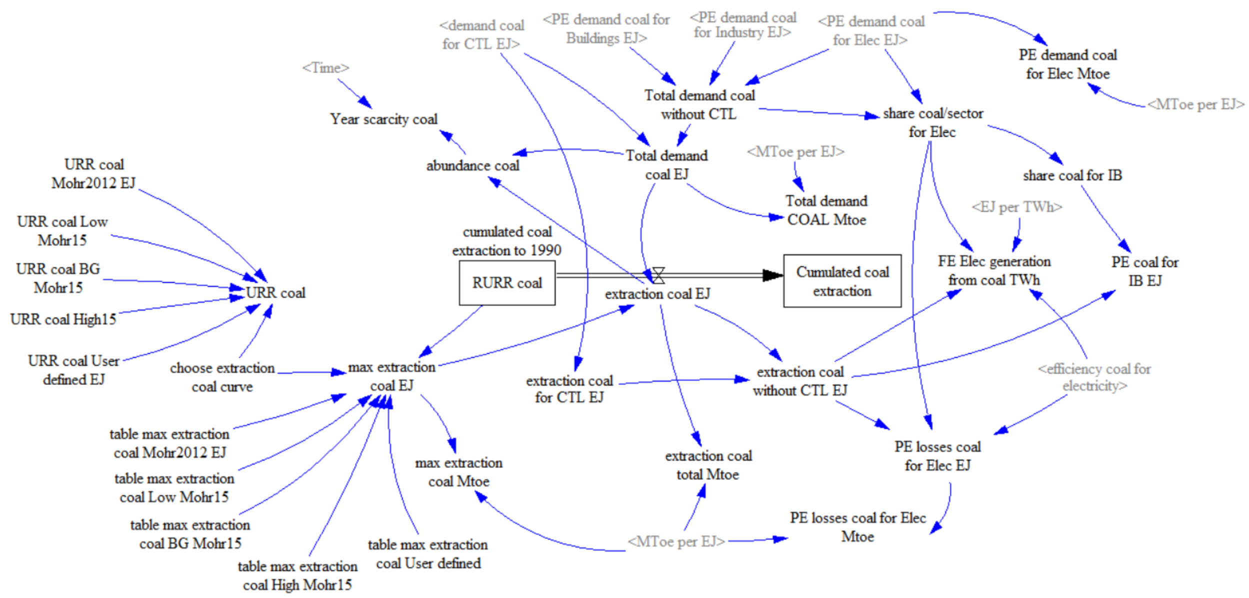

Figure 13: Forrester diagram of coal extraction.

3.1.1.2.4. Uranium – nuclear fuels

Figure 14 shows the uranium depletion curves found in the literature, which are in fact produced by the same research team (EWG, 2006, 2013; Zittel, 2012). In the most recent study (EWG, 2013) applies the most recent data from the Nuclear Energy Agency (NEA): individual country-specific extraction profiles are obtained, derived by mine-by-mine analysis of reserves and production. Especially for Kazakhstan the proposed time schedules for new mine openings is implemented. The reserves however have been adjusted by including uranium mining and preparation losses, depending on the extraction methods. In extreme cases these amounted up to 30% (personal communication).

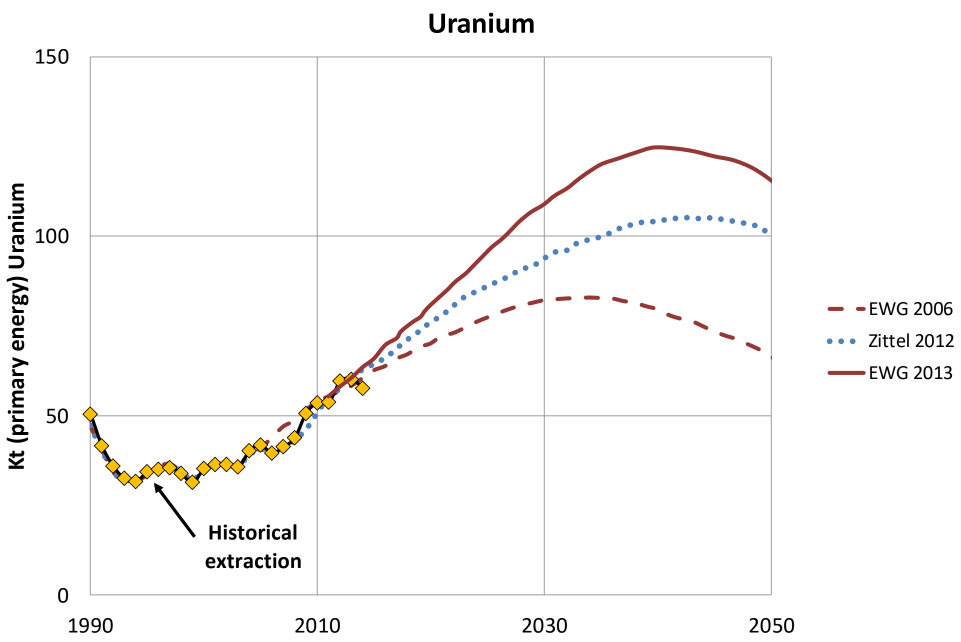

Figure 14: Estimations of uranium extraction by different authors. Historical data (1990-2014) from WMD (2016); conversion from kt U_3O_8 to ktU following EWG (2006).

3.1.1.3. Depletion curves available in WoLiM 1.5

Table 2 collects the depletion curves available in WoLiM 1.5:

Resource		**Reference**	**Description**	**URR**	
				(Mass)	(ZJ)
Oil	Total	(Laherrère, 2006)	Hubbert method (2,000 Gb of conv. + 1,000 Gb of unconv.)	3 Tb	16.7
	Conv.	(Maggio and Cacciola, 2012) [low; middle; high*]	Hubbert method	[2.3; 2.6; 3] Tb	[12.6; 14.5; 16.7]
	Unconv.	(Mohr et al., 2015) [low; BG; high] cases	Mining model extraction	[2.5; 2.7; 3.8] Tb	[5.8; 10.5; 22.1]
Natural gas	Total	(Laherrère, 2010)*	Hubbert method ("creaming curve")	13,000 tcf	13.6
		(Mohr, 2012) best guess*	Mining model extraction (12,900 tcf of conv. + 7,200 tcf of unconv.)	19,100 tcf	19.9
	Conv.	(Mohr et al., 2015) [low; BG; high] cases	Mining model extraction	[11.6; 13.8; 23.6] tcf	[11.1; 13.1; 22.5]

	Unconv.	(Mohr et al., 2015) [low; BG; high] cases	Mining model extraction	[2.9; 15.4; 25.3] tcf	[2.8; 14.7; 24.2]
Coal		(Mohr, 2012) high case*	Mining model extraction.	670 Gtoe	27.8
		(Mohr et al., 2015) [low; BG; high] cases	Mining model extraction.	[660; 1160; 1720] Gtoe	[14.5; 22.4; 31.6]
Uranium		(Zittel, 2012)*	Hubbert method, considering RAR (<260 $/KgU) and IR of NEA (2011)	8,900 ktU	3.7
		(EWG, 2013)	Hubbert method, considering RAR (<260 $/KgU) and IR of NEA (2012)	9,700 ktU	4.0

Table 2: Depletion curves of non-renewable energy resources implemented in WoLiM 1.5. The depletion curves applied in Capellán-Pérez et al. (2014a) are marked with an asterisk (*). Note that an exogenous constant growth was assumed for unconventional oil in Capellán-Pérez et al. (2014a).

Tb: terabarrels (10^{12} barrels); RAR: reasonably assured resources; IR: Inferred resources; NEA: Nuclear Energy Association.

For comparison, the meta-analysis of non-renewable energy resource estimates performed by (Dale, 2012) that review over 300 studies obtained the following URR values as medians: 13.2 ZJ (conventional oil), 10.5 ZJ (conventional gas) and 24.8 ZJ (coal). Thus, we are assuming values in the upper range of the literature. The studies that focus on non-conventional resources are much less abundant and (Dale, 2012) did not report significant statistical results.

3.1.1.4. Constraints to the (growth) extraction of unconventional fuels

The maximum extraction curve does not allow capturing the flow constraints when the peak rate of a fuel has not been reached. For this reason, unconventional oil & gas extraction is subject to an additional constraint that limits the maximum annual growth extraction rate to avoid unrealistic growth extraction rates.

Unconventional oil

As in the previous version of the model, we consider a "Best Guess" case, extrapolating the +4.5% annual growth past trends and an optimistic "High Case" of +6.6% annual growth as estimated by (Grushevenko and Grushevenko, 2012; Söderbergh et al., 2007). This assumption is consistent with the annual growth from the depletion curves projected by Mohr et al. (2015) for unconventional oil. Figure 15 shows that, after an initial very high growth extraction rate, the growth stabilizes at lower levels for the three scenarios (low, BG, high) at between +2.5 and +5% to 2050.

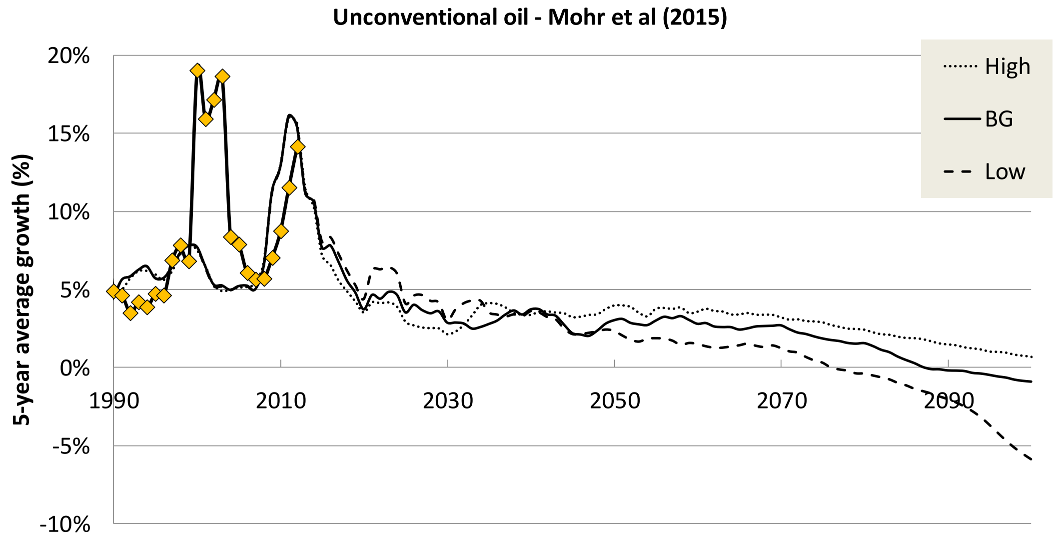

Figure 15: 5-year average growth (%) of unconventional oil for the high, BG and low scenarios from Mohr et al (2015). Historical extraction (1990-2012).

<u>Unconventional gas</u>

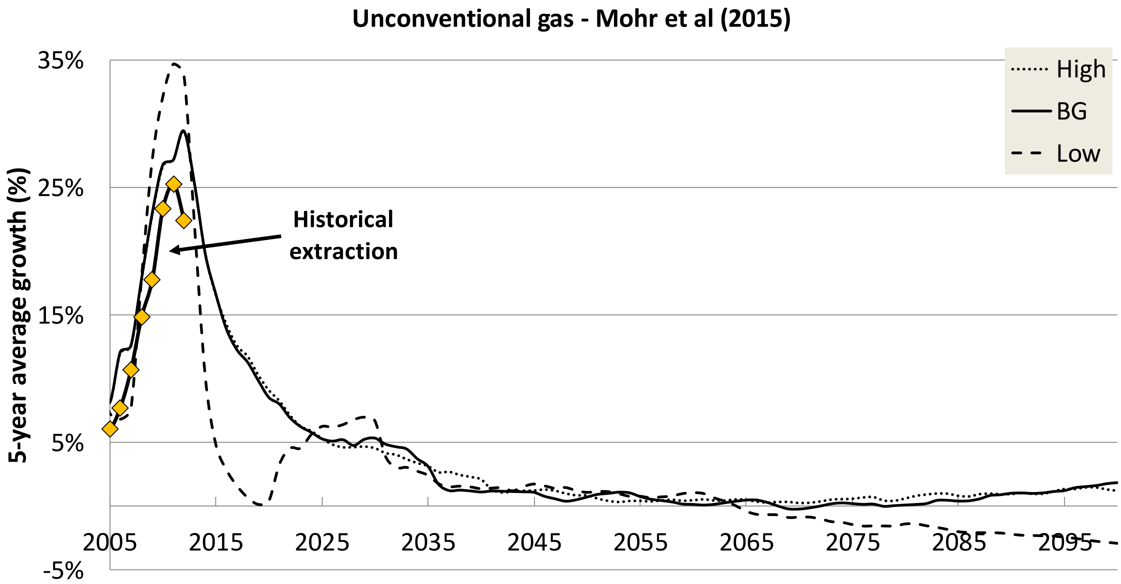

Figure 16: 5-year average growth (%) of unconventional gas for the high, BG and low scenarios from Mohr et al (2015). Historical extraction (1990-2012).

3.1.1.5. Refinery gains and other liquids (CTL and GTL)

Refinery gains are a correction applied to account for volumetric expansion of liquids during the refining process that typically represent betwteen 2 and 3% in energy terms. We asume that all the energy inputs required for achieving oil refinery gains come from natural gas.

CTL (*Coal-to-Liquids*) and GTL (*Gas-to-liquids*) refer to the transformation of coal and gas into liquid hydrocarbons. Different technologies currently exist,[9] mostly based on the Fisher-Tropsch process.

[9] It can be achieved through either coal gasification into syngas (a mixture of hydrogen and carbon monoxide), combined using the Fischer-Tropsch or methanol-to-gasoline synthesis process to produce liquid fuels, or through the less developed

However, all are characterized by low efficiencies: GTL conversion technologies are around 55% efficient and coal conversion between 27-50% (Greene, 1999; Höök and Aleklett, 2010; IPCC, 2007a). Their current production is exiguous: less than 0,3 Mb/d in 2014 (IEA, 2016a). Usually growth projections from international agencies are relatively modest (e.g. +11%/yr for GTL in the *New Policies Scenario* of (WEO, 2012)), due to their high cost and the common assumption that no significant liquids/oil restrictions will exist in the scope of their projections. WoLiM reacts to an eventual liquid scarcity by boosting these sources of energy.

CTL faces compelling challenges that limit its potential to significantly deploy at global level: very high capital costs (financing CTL projects can be difficult unless public incentives and subsidies are provided), a very low efficiency, significant related environmental impacts (Höök et al., 2013). In fact, the recent published works a considerable reduction in planned CTL plant capacity (Höök et al., 2013; WEO, 2012). Moreoever, any new CTL plant that would be planned to be built outside of South Africa (only country where the technology can be considered as mature) may behave more like an early mover (i.e. the cost penalty was estimated in more than a 50% (Williams et al., 2009)).

There are many ways to liquefy natural gas, and several pilot plants, trial projects and research initiatives exist. However, only two companies – Sasol and Shell – have built large scale commercial plants (>5,000 b/d capacity). The GTL industry is currently essentially immature and many important patents are held by relatively few companies (Wood et al., 2012). Unlike CTL plants, the construction and operation of large scale GTL plants is now a reality, with increasing momentum. After the experiences of Sasol's Mossgas GTL plant in South Africa and Shell's Bintulu plant in Malaysia the first decade of the 21st century has witnessed the construction and start of the Oryx 34,000 b/d GTL plant and the Pearl 140,000 b/d plant, both in Qatar. Moreover, a 34,000 b/d GTL plant was built in the Escravos region in Nigeria and started its operation in summer 2014. From 2000, the average global growth trend has been slightly over +16% per year (IEA, 2016a).

CTL and GTL are modeled as following in WoLiM: while the liquids supply is able to cover the demand, these technologies continue to deploy at the historical trends. However, when the supply is "close"[10] to be unable to cover the demand, a crash program is automatically activated in all scenarios that significantly increase the production from both GTL and CTL. The modeling is different attending to their different current situation: while GTL is assumed to be able to automatically increase its deployment level, CTL will face significant barriers in the first stages. Höök et al., (2013) report typical construction times of 4 to 5 years. For example, the worldwide crash coal liquefaction program modeled by Hirsch et al., (2005) assumes that the first coal liquefaction plant would begin to operate four years after the decision to proceed, assuming thereafter an increase of +38% per year (*ad hoc* assumption*)*. In our model, we will assume no lags in the implementation of the CTL crash program but setting its annual growth to +15-20% (similar to current GTL deployment growth levels) since higher values seem unlikely in the light of the current constraints of the technology and the likely proximity of the divergences between supply and demand in the liquids sector that activate in practice the crash programs in the model. In terms of efficiency, we assume that the CTL process will maintain the values of the past decades which average 31% (1971-2014). For GTL, we take the average between 1985 and 2014 of 52% (IEA, 2016a).

However, these crash programs for both CTL and GTL are critically dependant on the availability of coal and gas, respectively. That is, these programs are active while it is possible to increase the extraction rate of coal and gas, respectively, i.e. while the maximum extraction level has not been reached (see Figure 7). However, if the maximum extraction level is reached (or, in other words, the parameter abundance lower than 1, cf. Section 5), the crash program is stopped since at that point it is assumed that the remaining fossil fuel resources would be instead used in their most efficient ways to prevent energy scarcity.

direct-coal liquefaction technologies in which coal is directly reacted with hydrogen (WEO, 2012).

[10] When the parameter abundance is lower than 1 (see section 5).

3.1.2. Renewable energy sources

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 (de Castro et al., 2011; 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 (Lenzen, 2010; Smil, 2008, p. 362; Trainer, 2007), their lower energy density (de Castro et al., 2011, 2013b, 2014; Smil, 2008, pp. 383–384), most have lower EROI 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 (de Castro et al., 2013b; García-Olivares et al., 2012), and their associated environmental impacts (Abbasi and Abbasi, 2012; Danielsen et al., 2009; Keith et al., 2004; Miller et al., 2011), which all together significantly reduce their sustainable potential (Capellán-Pérez et al., 2014a; de Castro et al., 2011, 2013b, 2014; Smil, 2008; Trainer, 2007).

In this section we discuss the techno-ecological potential of renewable energies considered in the model. Special attention is devoted to the land requirements of RES technologies given that the transition to RES will intensify the competition for land globally (e.g. (Scheidel and Sorman, 2012)), in a context where the main drivers of land-use are expected to continue to operate in the next decades: population growth, urbanization trends and shift to more land-intensive diets (FAO, 2009; Kastner et al., 2012; Smith et al., 2010). Renewable resources can be used to obtain thermal (section 3.1.2.2) and electric energy (section 3.1.2.3). For clarity we start by documenting the assumptions in relation to bioenergy in the model (section 3.1.2.1).

3.1.2.1. Bioenergy

Biomass is limited by a total terrestrial net primary productivity of roughly 60 TW (humans already appropriate indirectly 20-50% in an unsustainable way (Cramer et al., 1999; Haberl et al., 2007, 2013; Imhoff et al., 2004; Imhoff and Bounoua, 2006; Smil, 2008; Vitousek et al., 1986). 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.). We follow WBGU (2009) approach and divide bioenergy resources into 3 categories: traditional biomass, dedicated crops and residues:[11]

1- <u>Traditional biomass</u>: It is the biomass used by large populations in poor-countries. There is much uncertainty around the amount of traditional biomass currently used: WEO (2010) estimates that 2.5 billion people used 724 Mtoe in 2008, while WBGU (2009) cites 47 EJ (i.e. 1,120 Mtoe). We asume the consumption ratio constant over time (0.29 toe per capita) together with a reduction in the number of people dependant on traditional biomass from around 40% of global population in 2008 to around 25% in 2035 following WEO (2010) and IPCC SRRES (IPCC, 2011). After 2035 the decreasing (linear) trend is maintained, however we introduce a minimum threshold of 15% of global population dependant on traditional biomass. However, this threshold is not reached before 2050 (see Figure 17). Since most of the traditional biomass is extracted in an unsustainable way, we assume that the reduction in traditional biomass use do not increase the techno-ecological potential of bioenergy.

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[11] 4th generation (algae) is not considered due to the high uncertainties of the technology and the long-term of its eventual commercial appearance (Janda et al., 2012).

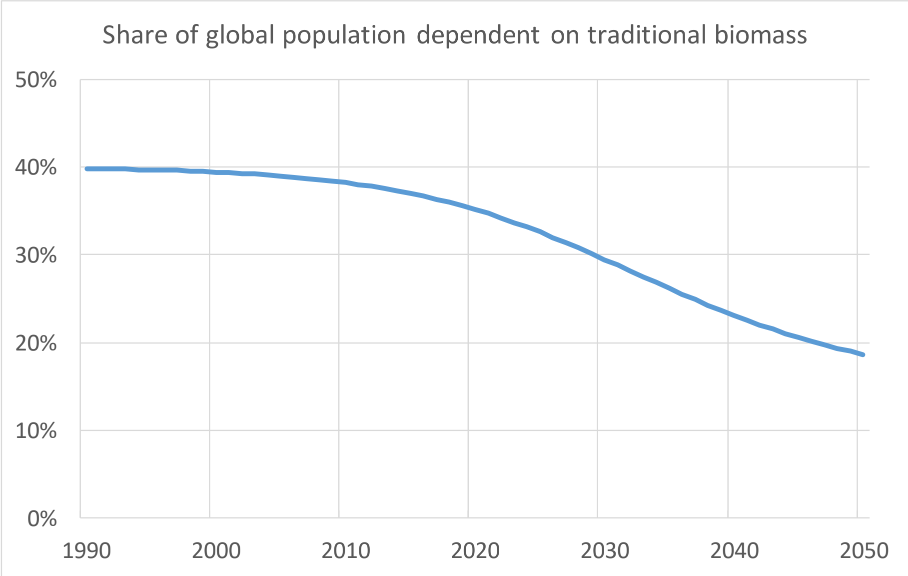

Figure 17: Share of global population dependent on traditional biomass in WoLiM 1.5 (exogenous assumption).

2- Dedicated crops in marginal lands and land subject to competition with other uses. We assume that these dedicated crops for bioenergy will be mainly used for biofuel production as it currently the case (2nd -current bioethanol and biodiesel) and given that previous work found that liquids would likely be the first final energy source to face scarcity (e.g. (Capellán-Pérez et al., 2014a)). It is assumed that the 3rd generation biofuels (cellulosic) do not require additional land, but instead substitute the 2nd generation when the technology is available at a rate depending on the scenario. We assume an improvement of +15% in the power density in relation to the 2nd generation (WBGU, 2009).

3- Residues (agricultural, forestry and MSW). Currently, only MSW exists at commercial level. The 3rd generation biofuels (cellulosic) are still in R&D and doesn't appear in the standard version of the model before 2025 (Janda et al., 2012). Agricultural and forestry uses will be assumed to be mostly used in thermal applications, as it currently happens (IPCC, 2007a, 2007b). The rest is modeled as biofuels and as additional potential to be used as an electrical generation technology in MSW.

The approach followed in WoLiM to estimate the techno-ecological potential of marginal lands and dedicated crops is to exogenously set a potential land availability (hectares) for each one, and subsequently derive the energy potential taking into account the corresponding power density. For those technologies that currently do not exist at commercial level, we assume that their output in the first years will follow the historic deployment rates of 2nd generation biofuels (2000-2014).

The estimation of land availability for each category is a sensitive and difficult task. The foreseeable additional demand of land for food for the next few decades (due to population and affluence growth) is projected to be 200–750 MHa (Balmford et al., 2005; FAO, 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. Humans also use biomass for other uses such as livestock feed (including grazing), fibre, material, etc. 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)). Moreover, it is estimated that current and future crop yields will be affected negatively by climate change (IPCC, 2014a), offsetting potential productivity gains from technological innovation. According to FAOSTAT, there were 1,526 MHa of arable land and permanent crops in 2011 (FAOSTAT, 2015).

However, the new land that we could convert to agriculture is 200-500MHa (FAO, 2009; Schade and Pimentel, 2010), or 386MHa in a sustainable way, converting abandoned agricultural land (Campbell et al., 2008; Rockström et al., 2009). This means that it may be not possible to meet the current trends of demand for food if the degraded land continues to grow, as more than 350MHa will be lost if present trends continue

(Foley et al., 2005; Pimentel, 2006). Thus, in view of the current situation, and considering that currently almost 15% of the world population is undernourished (FAO, 2012), a very large surface for bioenergy (or other land-intensive RES such as solar, see section 3.1.2.3) at global level is not compatible with sustainable future scenarios.

Two types of land availability for bioenergy are taken into consideration depending on the competition with other uses:

- **Marginal lands**: they do not imply a competition with current crops. The model considers the analysis from (Field et al., 2008) who find that 27 EJ of NPP can be extracted from 386 Mha of marginal lands avoiding the risk of threatening food security, damaging conservation areas, or increasing deforestation. They expect that the average NPP in biomass energy plantations over the next 50 years is unlikely to exceed the NPP of the ecosystems they replace.

- **Land subject to competition with other uses**, which is to be defined exogenously by each scenario. We consider that only the dedicated crops would require additional land. Related to the gross power density of 2nd generation biofuels under land competition, we will consider as reference the world average value given by (UNEP, 2009) based on real data (36 Mha occupied for 1,75 EJ in 2008) that estimates at 0,155 W/m2. Assuming a similar energy density for current production, almost 60 MHa are nowadays used (BP, 2016). However, the real occupied surface might substantially higher given that the methodology applied by the UNEP is conservative (see (de Castro et al., 2013a)), this number might in fact be closer to 100 MHa.

In relation to the potential land for dedicated crops for bioenergy, taking into account the future land requirements for food, urbanization and biodiversity conservation, the scenarios implemented in WoLiM standard version take two values: (1) roughly two-fold present occupation (taking as reference the conservative estimate) for the standard scenario (100 MHa) and (2) a high scenario considering up to 200 MHa (see Table 3). However, these values can be changed when implementing a customized scenario: for example (Doornbosch, 2007) estimates in 440 MHa the additional land potentially available for biofuels (mainly in Latin America and Africa). As a reference, since 2000 the area from Southern countries that has been bought or long-term rented by trasnationals and investment funds has been estimated to surpass 80 MHa (Anseeuw et al., 2012).

Since current conventional bioenergy use for heat (18 EJ/yr harvestable NPP (REN21, 2016)) surpasses sustainable levels (de Castro et al., 2013a; Foley et al., 2005; GFN, 2015; Pimentel, 2006), we assume that in the future better practices could be adopted allowing to increase the sustainable potential to 25 EJ/yr (NPP harvestable). An eventual reduced dependence on traditional biomass in the next decades might also allow to use bioenergy resources in a more sustainable and efficient way.

There is currently a controversial debate about the potential of the valuation of agricultural and forestry residues, because of its threat to soil fertility preservation in the long run, biodiversity conservation and ecosystem services (Gomiero et al., 2010; Wilhelm et al., 2007). We take the estimation of (WBGU, 2009) of 25 EJ NPP taking into account economic restrictions and we assume that most of it will be dedicated for thermal uses (50%), and the remaining for biofuels (25%) and electricity (25%).

Table 3 summarizes the potential for bioenergy for thermal uses considered in the model (for the biomass for electricity see next section):

	Reference	**Surface availability**	**Gross power density**	**Potential**		**Use in WoLiM**
				NPP harvestable	Final (gross) power	
		MHa	W/m2	EJ/yr	EJ/yr	

Conventional bioenergy		Own estimation	-	-	25	20	Heat
-	Marginal lands (no competition with current uses)	(Field et al., 2008)	386	0.033[a]	27	4.1	Biofuels
2nd gen.	Dedicated crops (competition with current uses)	(de Castro et al., 2013a)	100 (standard scenario)	0.155[b]	33	4.9	Biofuels
3rd gen. (from 2025)	Dedicated crops	(WBGU, 2009)	0[c]	0.18	+5.0[c]	+0.7[c]	Biofuels
	Agriculture & Forestry residues	(WBGU, 2009)	-	-	14	11.2	56% thermal
			-	-	4.75	0.95	25% electr.
			-	-	6.25	0.95	25% biofuels
Total					115	42.8	All uses

Table 3: Techno-sustainable potential of bioenergy by type. 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] *In reality, the global power density is less than 0.155 since it has been shown that the methodology applied by the UNEP is conservative. As a reference, 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).*

[c] *The 3rd generation of biomass is modeled without additional land requirements due to the assumption that it will replace previous land occupied by 2nd generation crops.*

Previous studies of the global potential of bioenergy have yielded a wide range of conclusions, spanning almost three orders of magnitude (Haberl et al., 2013). The sustainable technical primary potential of bioenergy considered in WoLiM amounts to around 115 EJ/yr (harvestable NPP) and ~43 EJ/yr of final gross power, and is located in the lower-medium range of the literature. Our comparatively low figure arises from the consideration given to the competing claims of other forms of land use and from the fact that some other estimates have assumed unrealistically high yields and do not take into account the biophysical limits. Haberl et al., (2013) estimated that the maximum physical potential of the world's total land area outside croplands, infrastructure, wilderness and denser forests to deliver bioenergy at approximately 190 EJ/yr. [12] The considered potential matches well with a recent analysis which found that the global sustainable technical primary potential of bioenergy amounts up to 100 EJ (Creutzig et al., 2014). Also, the current unsustainable use of many biomass resources implies that these trends cannot be maintained indefinitely in the future.

Figure 18 represents the Forrester diagram of the 2nd and 3rd generation biofuel production in land competing with other uses, as well as the biofuel production in marginal lands:

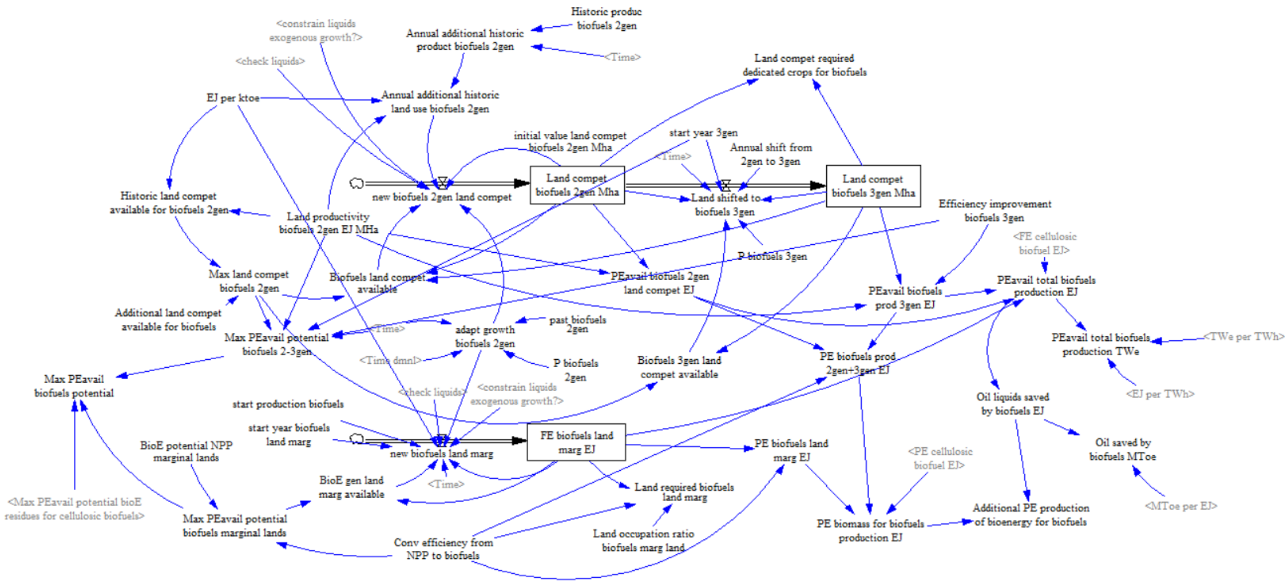

Figure 18: Forrester diagram of the modeling of the bioenergy in the WoLiM model.

3.1.2.2. Renewable energy sources for thermal power

The Industry and Buildings (IB) sectors are very complex sectors to analyze since they use all kinds of fuels and energy vectors in a great diversity of technologies. For the sake of simplicity, WoLiM maintains a high level of aggregation in the IB sectors and focus instead on the Transport and Electricity generation sectors. The thermal uses of renewable energies (solar, geothermal and bioenergy) are not explicit in the model, nor are they assigned to a concrete technology (except for the 3rd generation biomass residues, see section 3.1.2.1). Energy transition policies include a switch to renewable and efficiency improvements in a similar way as done in World3 (Meadows et al., 2004). These policies are modelled as target-policies of RES market penetration level for a given year (see section 3.3.3 for a description of the modelling).

However, the aggregated thermal Total Primary Energy (TPE) from renewable energies is tracked in the model in order to assist the design of scenarios, with the thermal renewable potential excluding bioenergy (see **Table 4**) estimated into around 1 TW_{th} (40 EJ/yr or around 950 Mtoe/yr). For geothermal, since currently around half of the resource is used for generating electricity and the other half for thermal

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[12] "At present, humans harvest ~230 EJ/yr worth of biomass for food, livestock feed (including grazing), fibre and bioenergy (a substantial fraction of which is derived from residues and waste flows). In order to produce that biomass, humans affect or even destroy roughly another 70 EJ/yr of biomass in the form of plant parts not harvested and left on the field and biomass burned in anthropogenic vegetation fires. Hence, some 800 EJ/yr worth of biomass currently remain in the aboveground compartment of global terrestrial ecosystems. Of this 800 EJ/yr, 48% grows in forest ecosystems, and much of the remainder in ecosystems which either cannot easily be exploited, such as tundra and drylands (28%), in national parks, conservation areas and wilderness or in cultivated ecosystems which are already heavily harvested (grazing lands, cropland). In order to meet their biomass demand, humans affect approximately three quarters of the earth's ice-free land surface [10] with huge implications for ecosystems and biodiversity." (Haberl et al., 2013)

purposes, we assume that the techno-ecological potential estimated by (de Castro, 2012) (0.6 TW_{th}) is shared equally between these two technologies (assuming a 1/3 efficiency conversion from heat to electricity).

	Reference	Techno-ecological potential (gross power)
		TWth
Geothermal	(de Castro, 2012)	0,3
Thermal solar	Own estimation (see Appendix C)	0,7
Total		1

Table 4: Techno-sustainable potential of non-electric renewable sources excluding bioenergy.

Thus, combining the data from Table 3 and 4 the techno-sustainable potential of thermal RES considered in WoLiM amounts to around 74 EJ/yr (20 EJ/yr conventional bioenergy, 14 bioenergy residues, 18 geothermal and 22 solar).

Figure 19 shows the Forrester diagram of the extraction of (primary energy) from thermal RES.

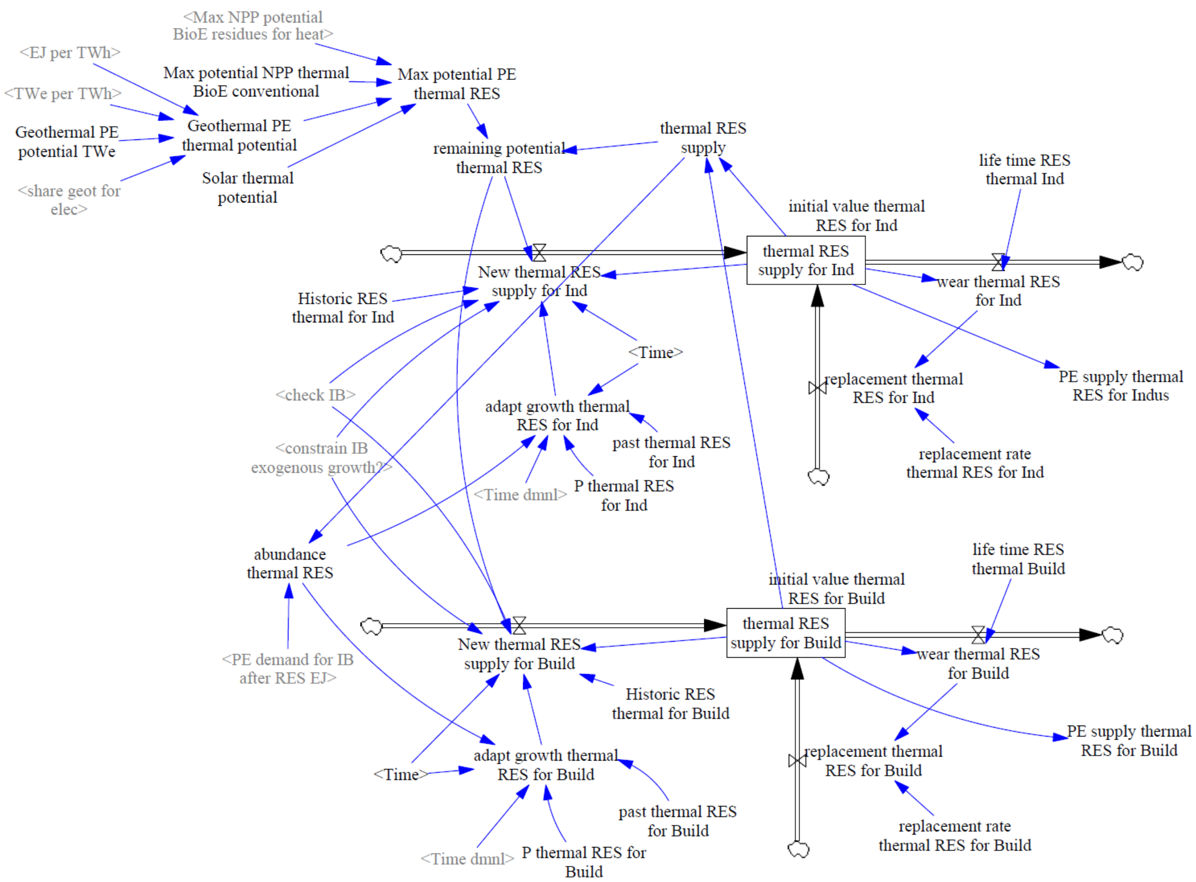

Figure 19: Forrester diagram of the extraction of (primary energy) from thermal RES.

3.1.2.3. Renewable energy sources for electricity generation

The most promising electric renewable energies are solar and wind (Smil, 2010). However, recent assessments using a top-down methodology that takes into account real present and foreseeable future efficiencies and surface occupation of technologies find that the potential of their deployment is constrained by technical and sustainable limits (de Castro et al., 2011, 2013b). The evaluation of the global technological onshore wind power potential, acknowledging energy conservation, leads to a potential of 30 EJ/yr (de Castro et al., 2011). In relation to offshore wind, in a back of envelope estimation, assuming a power density of net electricity delivered 1 W_e/m^2 and that 1% of the continental ocean platforms might be occupied by human infraestructures (the density of occupation by human infrastructure in land is 1-2% and entire platforms like Artic and Antartic are not accesible to human ocuppation), a rough potential of 0,25 TW_e is considered. 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 around 65-130 EJ/yr (2-4 TW_e[13]) (de Castro et al., 2013b) in 60-120 MHa.[14]

As discussed in the precedent section, we assume that bioenergy will be mainly used for thermal and liquids uses. For electricity uses, we arbitrarly assign a potential for waste (agrofuels, woodfuels, etc.) and MSW of 10 times the current production (0.1 TW_e). From 2025 (though this can be adjusted depending on the scenario), additional biomass is available trough the deployment of the 3rd generation biomass technologies (see Table 3). The additional potential would amount to 25% of the total NPP (25 EJ/yr) considering an average efficiency conversion of 20% (de Castro et al., 2014),[15] i.e. 1.25 EJ/yr (0.04 TWe). Sea waves on coasts and tidal resources are limited to a physical dissipation of 3 TW, hydroelectricity is limited by a total gravitational power of rain of 25 TW and geothermal renewable resources are limited by a total Earth dissipation of 32 TW (Hermann, 2006). Acknowledging the high dispersion of these resources and their role in the energetic and material fluxes of ecosystems, we estimate that less than 1 TW_e could be attained in a sustainable way by renewable energies other than solar and wind.

Following these considerations, the global techno-ecological potential of renewable energies for electricity generation is estimated at around 175 EJ per year (~5.35 TW_e/yr, see Table 5). 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 the Supplementary Material in (Capellán-Pérez et al., 2015) for a comparison and discussion.

	Techno-ecological potential	**Investment cost**	**Lifetime**	**Capacity factor**	**Power density**
References	(de Castro et al., 2011; de Castro, 2012; de Castro et al., 2013b) and	(Teske et al., 2011)	(IPCC, 2011) and conventional values	(Boccard, 2009; EIA, 2009; Prieto	(de Castro et al., 2013b; Smil, 2015)

[13] "TW_e" represents power electric production: 8760 TWh = 1 TWe, i.e. in one year 1 TW of capacity functioning with a 100% capacity factor produces 1 TWe.

[14] The potential in urban areas is greatly limited by the competition with the solar thermal technologies and the fact that the adaptation to the rooftop implies lower efficiencies. See Appendix C for more details.

[15] The MSW efficiency reported by the IEA is also in that range (22%): https://www.iea.org/publications/freepublications/publication/essentials3.pdf.

	own estimations					and Hall, 2013)	
Technology/Unit	TW_e	2011$/kW			Years	[ad.]	W_e/m^2
		2010	2030	2050			
Hydro	0.75	3,110	3,550	3,800	80	0.65 (2007) – 0.55 (2050)	4
Wind onshore	1	1,740	1,100	1,030	20	0.21	1 (regional level)
Wind offshore	0.25 (1% of ocean platforms)	3,340	1,680	1,500	20	0.27[c]	
Solar	3.3 (100 MHa)	4,110	1,180	1,030[a]	25	0.16	3.3
Biomass, waste & MSW	0.14	3,240	2,730	2,680	30	0.83	-
Geothermal	0.1	14,310	8,340	5,980	30	0.9	50
Oceanic	0.05	8,300	2,480	2,480[d]	40	0.9[b]	-
TOTAL	5.6						

Table 5: Data of electric renewable in the model. "TW_e" represents power electric production: TWh/8760. MSW: Municipal solid waste.

[a]The solar investment cost after 2030 is set to the same level than wind onshore, since we judge that it is unlikely that solar technologies will manage to be less expensive in the future than wind given their higher technological complexity. 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.

[b]No data was found since the oceanic technology is still under R&D. We arbitrarily assigned the same value as geothermal (0.9).

[c]We assume that offshore wind has a +30% higher Cp than onshore wind.

[d]The oceanic investment cost is maintained constant after 2030 since we judge too optimistic that these technologies might reach a low cost in the order of the ones of wind offshore.

We consider the power density of renewable in order to track their land occupation. We apply data based on studies that take into account real present efficiencies and surface occupation of technologies (de Castro et al., 2013b; Smil, 2015). For the capacity factor (Cp) of solar PV and wind, we apply a couple of studies that focus on the estimation of this parameter applying a top-down analysis of real-life systems in large areas rather than usual, laboratory values that happen to substantially overestimate this parameter in working conditions. Thus, Prieto and Hall (2013) estimate the Cp of solar PV in Spain, a country with good insolation and with a significant solar power installed. Boccard (2009) found that, although for more than two decades, the Cp of wind power measuring the average energy delivered has been assumed in the 30–35% range of the name plate capacity, the mean realized value for a region as Europe in the period 2003-2007 was below 21%. Arvesen and Hertwich (2012) confirmed the existence of a general tendency of wind power LCAs to assume higher capacity factors than current averages from real-world experiences. For the rest of sources we apply standard values from the EIA US (2008). Table 5 shows the energy techno-ecological potential, investment cost (without including operation&maintenance), lifetime, capacity factor and power density assumed for each renewable technology for electricity generation.

Below we represent the equations and Forrester diagram (Figure 20) of solar electric generation; all electric renewables are represented by similar structures.

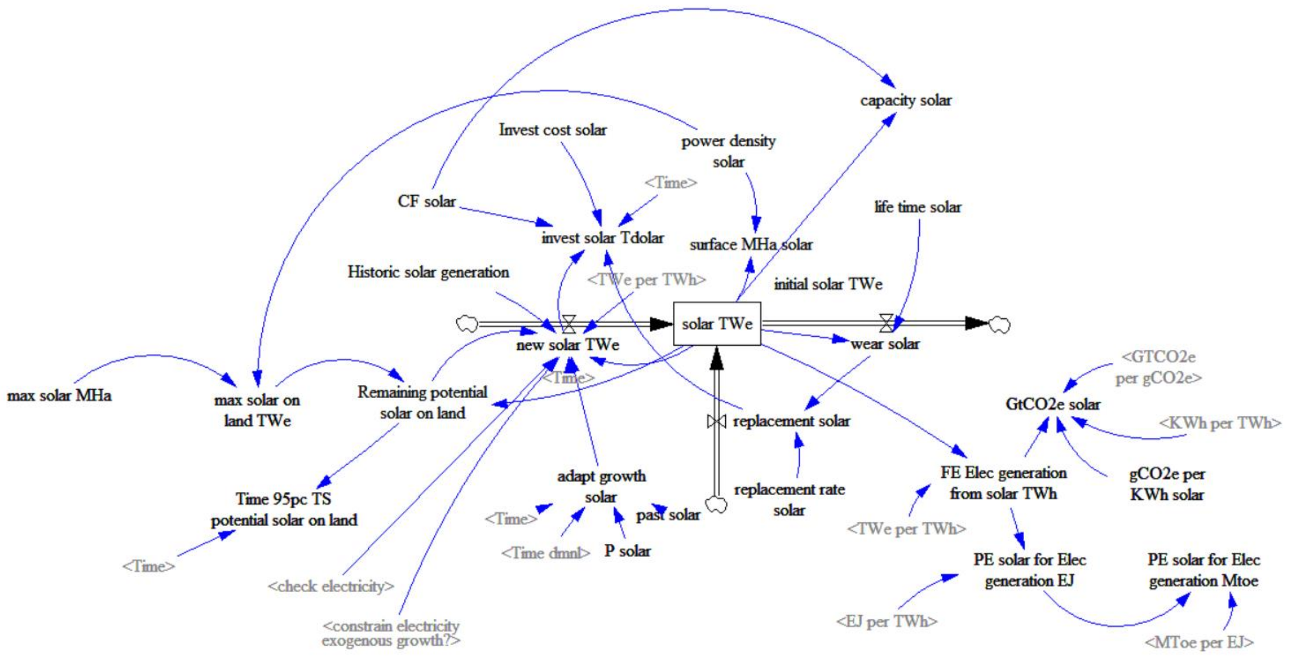

Figure 20: Structure of the renewable electric technologies. Here, we represent solar as example.

P1_solar represents the annual growth considered in each scenario (*past_solar* represents the past trends and *Adapt_growth_solar* models a soft transition between both during a period of 5 years). 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*, that in the case of solar comes from the potential land dedicated to solar power plants *max_solar_Mha*) reducing the exogenous growth initially set. As discussed in section 3.4, we apply a logistic curve (Höök et al., 2011), as shown by eq. 2:

$$New\_solar\_TWe(t) = Adapt\_growth\_solar(t) \cdot \left(\frac{\max\_solar\_TWe - solar\_TWe(t)}{\max\_solar\_TWe}\right) \cdot solar\_TWe(t) \qquad eq.\ 2$$

Solar_TWe accounts for the level of solar power accumulated, balanced between the new power installed (*new_solar_TWe*), the wear of infrastructure (*wear_solar*) and the replaced infrastructure (*replacement_solar*):

$$\frac{d(solar\_TWe)}{dt} = new\_solar\_TWe + wear\_solar\_TWe + replacement\_solar\_TWe \qquad eq.\ 3$$

Figure 21 shows the dynamics of the eq. 2 with an example to illustrate the behavior of exponential growth constrained by an exogenous limit (upper panel, annual variation of electric solar production; lower panel, total electricity generation from solar).

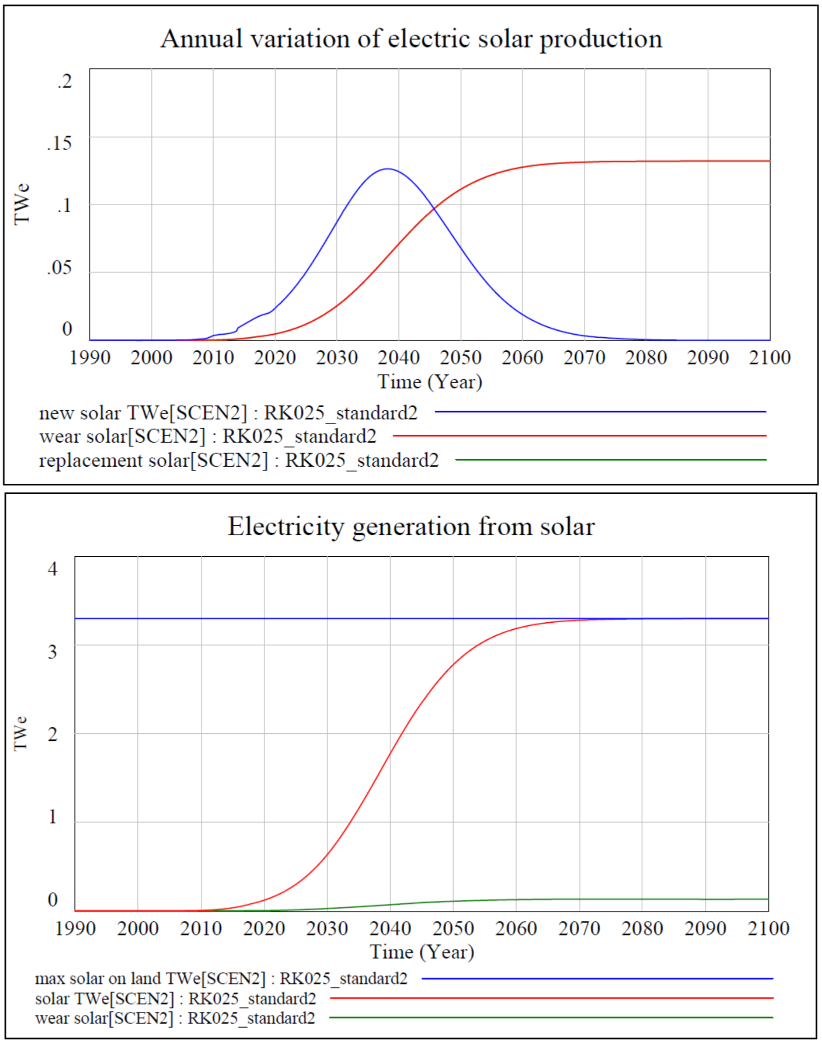

Figure 21: Total electric solar production (TWe). In this figure we represent the dynamics of eq. 2 considering a very rapid growth of solar (+19%, as in scenario 1). While being far from the potential limit, exponential growth drives the growth of new solar power. As the total solar power installed increases, the depreciation of infrastructures becomes significant. Finally, just 15 years after reaching the maximum installation rate, 95% of the potential is achieved in 2065.

Thus, we dynamically account for the electrical production (*solar_production_TWh*), the land occupied (*surface_MHa_solar*), the monetary investment needed (*invest_solar_Tdolar*) and the parameter abundance that tracks the relative proximity to the maximum potential (*abund_solar*, cf. Section 5):

The RES for electricity generation can be divided between "baseload", i.e. those sources that are able to give a constant and manageable load ("dispachtable") such as hydro, biomass and geothermal, and "variable" generation. The latter are characterized by differing levels of variability and limited predictability over various time scales, and include wind and solar. Integrating these resources in the electricity mix requires some level of overcapacity and storage and/or energy demand management. As a first approximation, we assume that as RES penetrate in the electricity generation, the system requires a higher capacity to operate (i.e. overcapacity). To prioritize the variables RES, which paradoxically are the most abundant (wind and solar), the overcapacity in the system is assigned to the baseload plants (both non-renewable and RES) through a reduction of the capacity factor of baseload plants as a function of the increasing level of penetration of the intermittent RES. We take as reference the study from NREL (2012) which estimated different scenarios of RES penetration (see Figure 22). We extended these scenarios until 100% RES penetration level with two methods (lineal and polynomial order 2), considering that at 100% penetration level of intermittent generation the Cp of baseloads plants would fall to zero. The polynomial curve provides a better fit and is therefore introduced in the model. For the sake of simplicity, in this model version the same reduction factor for all baseload plants is applied equally[16] and the required additional storage is not explicitely modelled.

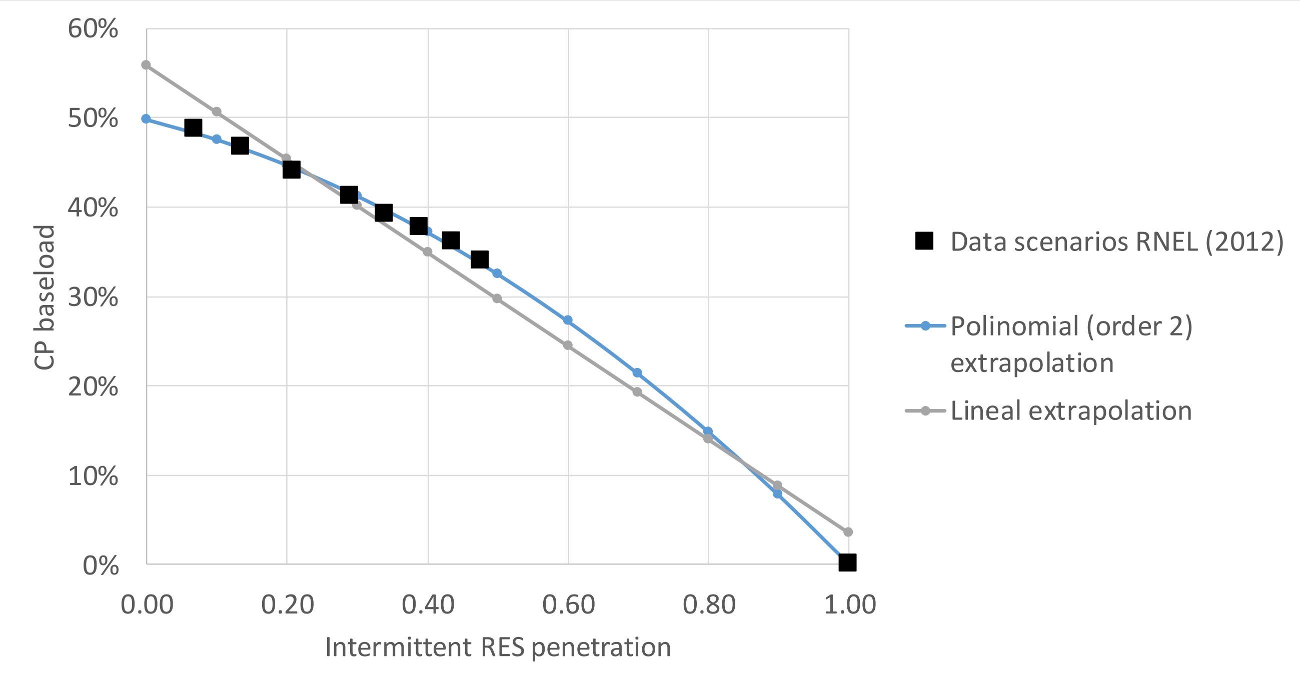

Figure 22: Decreasing capacity factor of baseload plants (including RES and non-RES power plants) as a function of the increasing level of penetration of the intermittent RES wind and solar from NREL (2012), and polynomial and lineal extrapolation until 100% (Cp baseload=0%).

The monetary investment for building new plants up to 2050 is computed following (Teske et al., 2011). We assign the same cost to new and repowering plants in order to be sure not to underestimate that cost, since the costs when replacing an old power plant are usually lower. Slight adjustments are made to represent the costs in 2011 US$ (2005-2011 consumer price index of 1.15 from http://www.measuringworth.com/uscompare/), and to represent it as a function of the delivered electricity instead of installed capacity through the capacity factor (see Table 5). Since solar FV investments cost have declined faster than projected by (Teske et al., 2011), we fitted their learning curve to actual developments.

The additional costs related to the variability of RES (increase of operating costs[17]) and the need of grid development (renewable energies are often located in remote areas) are modelled taking into account studies for wind. Grid reinforcement costs are, by nature, dependent on the existing grid. We use the median value calculated in (Mills et al., 2012) for 40 transmission studies for wind energy in the USA, which is, in fact, on the upper side of the comprehensive study made by (Holttinen et al., 2011): 300 $ 2011US/kW of wind installed. Assuming a capacity factor of 21% for wind (the mean value for Europe between 2003 and 2007):

[16] This was explicitely modelled only for RES sources and nuclear, since capacity for electricity generation from fossil fuel resources is not included in the model.

[17] Increase in reserve requirements is not computed since the investments for non-renewable electricity production are not modeled.

$$300\,\frac{\$}{kW} = 300\,\frac{T\$}{10^3 \cdot TW} \cdot \frac{1\,TW}{8760\,TWh \cdot CF} \cdot \frac{8760\,TWh}{1\,TWe} = 1.43\,\frac{\$}{We} \qquad eq.\ 4$$

Other costs, such as balancing costs, are also introduced into the model: (Holttinen et al., 2011) also concludes that at wind penetrations of up to 20% of gross demand (energy), the system operating cost increases arising from wind variability and uncertainty amounted to about 1–4 €/MWh of wind power produced. We assume here similar costs for the combined variable renewable producers -solar and wind- (see Table 6), extrapolating the cost until it reaches a maximum of 5 euros/MWh at 50% of total electricity share. This cost is assigned to the wind production, assuming that solar technologies might have more capacity to store energy in the future (e.g. CSP with thermal storage).

Combined variable renewable production share	Balancing cost [$ 2011US/MWh produced]
10 %	2.8
20 %	4.2
30 %	5.6
50 %	7
> 50 %	7

Table 6: Integration cost adapted from (Holttinen et al., 2011).

3.2. 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, we applied the Energy Intensity method, that has already been used in similar studies due to its simplicity and robustness (Furtado and Suslick, 1993; Hall and Klitgaard, 2012; Saddler et al., 2007). This model is 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 and technological improvement) dominate over the variations of fuel prices and its substitutes (de Castro, 2009; Furtado and Suslick, 1993; Saddler et al., 2007). In fact, prices and costs can falsely signal decreasing scarcity. Reynolds (1999) demonstrates that, when considering the size of the resource base as unknown (or ignored), it is possible to have several years of increasing production simultaneously with lower prices and costs until a sudden, intense price rise occurs with a huge cut in production, similar to the oil shock in 2007-08 (Hamilton, 2009). Another attractive feature of this methodology is the fact that, while energy and GDP per capita vary by more than one order of magnitude as one goes from developing to developed countries, the intensity does not change by more than a factor of 2, indicating that there are important commonalities among the energy systems of rather different countries (Goldemberg, 1996).[18]

[18] The use of a world aggregated indicator also allows outsourcing and carbon-leakage issues that may be significant at national level (e.g. (Baksi and Green, 2007)) to be avoided.

3.2.1. Estimation of sectoral Energy Intensities

Considering the sectoral Energy Intensity as energy used by a sector divided by the total GDP of the economy, 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 (estimated in this study applying econometric methods),

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 (eq. 5):

$$E_i = GDP \cdot I_i \qquad \textit{eq. 5}$$

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

A conventional way for characterizing the evolution of energy intensity is shown in eq. 6 (Schenk and Moll, 2007), which can also be written as in eq. 7, where annual Intensity (I_t) decreases each year at a constant rate (a=1-AIE) in relation to the previous year (I_{t-1}):

$$I_t = I_{t=0} \cdot (1 - AEI)^t \qquad \text{eq. 6}$$

$$I_t = I_{t=0} \cdot (1 - AEI)^t = (1 - AEI) \cdot I_{t-1} = a \cdot I_{t-1} \qquad \text{eq. 7}$$

AEI represents the Annual Efficiency Improvements.

Thus, the parameter "a" or (1-AEI) accounts for technological change, and by varying it, it is possible to explore different scenarios of sectoral technology-efficiency improvements.

The results of the sectoral energy intensity regressions are shown in Table 7 and Figure 23. Appendix A depicts the results of the statistics tests to validate the models. However, the estimated regression for the Electricity sector is non-stationary and an alternative assumption was required. The electricity consumption intensity has remained stable at around 250 TWh/2011 UST$ due to the massive transition of more developed economies to that (more efficient) source of energy (Fouquet, 2010). Thus, since historical data of the last decades have shown that the global relationship between GDP and Electricity consumption is roughly 1:1, we assume that the intensity of the electricity sector will remain at current levels during the simulations.

Energy sector	**Sectoral Energy Intensities**		**Period**
TPE demand	$I^{tot}{}_t = 0.988582 \cdot I^{tot}{}_{t-1}$ (R^2=0.999840)	EJ / UST$	1971-2010 (regression)
Transport PE demand	$I^{transp}{}_t = 0.993298 \cdot I^{transp}{}_{t-1}$ (R^2=0.999841)	EJ / UST$	1971-2007 (regression)
Electricity consumption[19]	Non-stationary model	TWh/ UST$	1980-2010 (regression)

[19] If instead considering the electricity generation we could have considered the consumed electricity. In that case, we would need to account for distribution and generation losses, which iIn the last 30 years have been in the range of 8-9.5% of the total electric generation (US EIA db, 2014).

IB PE demand	$I^{IB}{}_{t} = 0.995 \cdot I^{IB}{}_{t-1}$	EJ / UST$	1990-2010 (calibration)

Table 7: 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 document are in 2011 US$. PE: Primary Energy. We have used the (World Bank database, 2015) for the historical series of world GDP at constant prices in US2011 T$ and TPE demand, (IEA ETP, 2010) Transportation PE use and (US EIA db, 2015) 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).

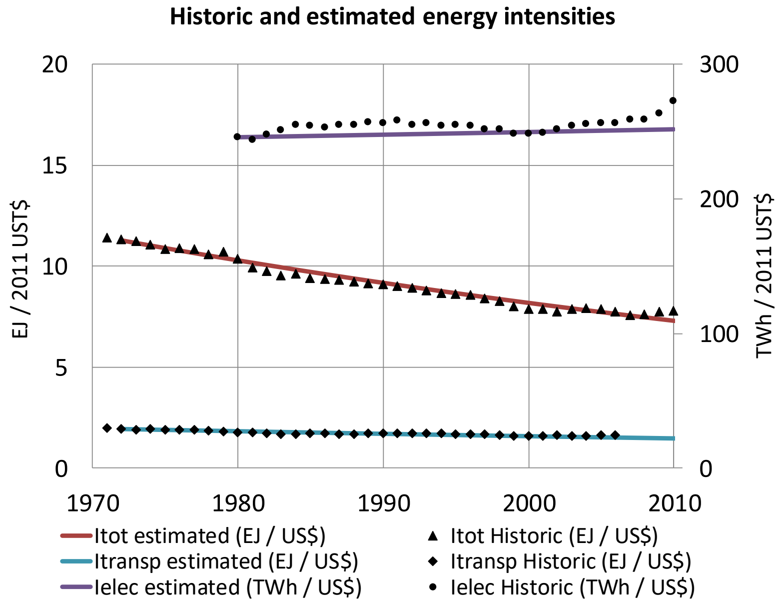

Figure 23: Historic and estimated energy intensities by sectors. Itot refers to Total Energy Primary intensity (EJ/UST$), Itransp to Transportation intensity (EJ/UST$), and Ielec to Electrical generation intensity (TWh/UST$). All dollars in the document are in 2011 US$.

Our results indicate that in the last 40 years, the world TPE intensity has improved at a yearly average rate of 1.15 % (Smil (2005) estimated 1% improvement for the 20th century). This evolution has not been uniform, and since the year 2000 its value has remained constant at around 8 EJ / 2011 UST$. As signaled and studied by Baksi and Green (2007), an important question for future scenarios is whether a 1% rate of decline in the global average annual energy intensity can be improved upon over the course of the 21st century. Or, alternatively, if it will become more difficult to maintain a 1% rate of decline, as the best improvements in energy efficiency, and the largest gains from sectoral output shifts, are ''used up''. Transport and Buildings primary energy intensities have also improved in the last decades, although at smaller rates (0.7% and 0.5% respectively).

3.2.2. Energy intensity scenario implementation

In order to account for the biophysical and thermo-dynamical limits in the substitution of inputs in production in medium and long-term scenarios (as stated by Ecological Economics, e.g. (Ayres, 2007; Ehrlich, 1989; Stern, 1997)), we modify the conventional expression of the energy intensity (eq. 8) as a physical indicator as proposed by Schenk and Moll (2007):

$$I_t = I_{min} + (I_{t=0} - I_{min}) \cdot a^t \qquad eq.\ 8$$

a represents indirectly the Annual Efficiency Improvements (a=1-AEI), while 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 4). As reference, we use the studies of (Baksi and Green, 2007; Lightfoot and Green, 2002) that analyze the potential efficiency improvements until 2100 taking into account physical and thermodynamic constraints in each sector, a methodology that helps to eliminate future energy intensity decline scenarios involving implausible values (e.g. (Pielke et al., 2008)). The next section illustrates the results obtained when applying this equation instead of the standard approach.

<u>Application of the Energy Intensity as physical indicator</u>

When applying energy intensity scenarios two hypotheses are assumed. At a world level, only regional convergence has been found, mainly among OECD members (e.g. (Liddle, 2010)). Also, due to the different development levels, efficiency margins that can be achieved vary for different countries. Due to the world-aggregation of the model, we decided to take maximum values of efficiencies, assuming that all countries would be able to reach these values (following a similar methodology to (Baksi and Green, 2007; Lightfoot and Green, 2002)). Thus, we consider this optimistic hypothesis so as to be sure not to minimize efficiency and potential technological improvements.

In order to illustrate the behavior of the Energy Intensity as physical indicator, we represent four future evolutions of the total energy intensity: the first two use the conventional formula (see eq. 7), while the third and fourth use the modified version (eq. 9). Baksi and Green (2007) demonstrated that, even when large efficiency improvements are assumed, physical and thermodynamic constraints appear and the yearly reduction rate of energy intensity is limited. In this section a reference scenario (-1.15% yearly decrease and horizontal asymptote at 30% from current levels) is compared with Baksi and Green (2007)'s most optimistic scenario (which they judge as unrealistic) of yearly improvements of 2% and a horizontal asymptote at 11% from 1990's levels. We also introduce the projections of WEO (2012) for comparison:

- "Conv(-1.15%)": conventional equation and extrapolation of past trends (-1.15% yearly).
- "Conv(-2%)": conventional equation and -2% yearly improvements.
- "Schenk(-1.15%; 30%)": alternative equation with extrapolation of past trends (-1.15% yearly) and I_{min} at 30% of 1990's levels (2.7 EJ/2011 UST$).
- "Schenk(-2%;11%)": alternative equation with -2% yearly improvement and I_{min} at 11% (~1 EJ/2011 UST$).

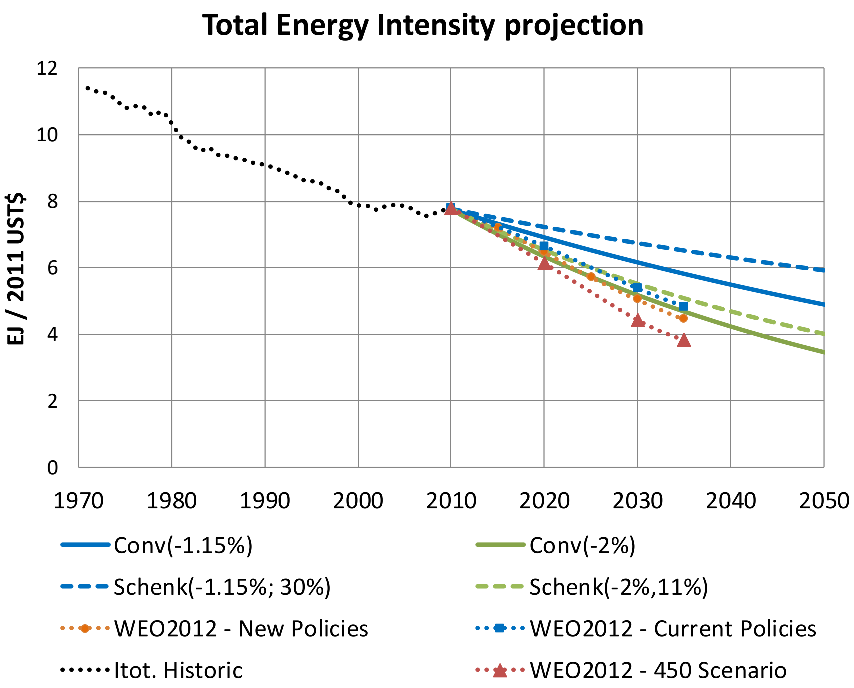

Figure 24: Examples of the application of the Energy Intensity as a physical indicator for forecasting future energy demand.

The first observation is that the projections forecasted by WEO (2012) imply total energy intensity improvements in the order of (or superior to) 2% per year, i.e., doubling the historical values and outside the range of the values identified by Baksi and Green (2007) as being realistic and achievable (0.9-1.22%). When comparing the modified expression with the conventional one, we observe that the fact of not limiting the improvements in the long-term implies significant reductions of intensity projection in 2050 for both scenarios: 1 EJ / 2011 UST$ in the reference and more than 0.5 EJ / 2011 UST$ in the most optimistic one.

As a reference for implementing the minimum value of energy intensity in the scenarios, we will consider the “likely” range estimated by Baksi and Green (2007) of 25%-35% (in relation to 1990 levels).

3.3. Modeling by sectors

We represent the economy by 4 sectors following the nomenclature of the *International Energy Outlooks* (IEOs) from the *US Energy Information Administration (US EIA):* Transportation, Electricity, Industry and Buildings (the latter as an aggregate of Commercial and Residential). This level of aggregation allows thus to explore the impact of the energy transition by sector. In order to calibrate the model we used the data provided by the IEOs *and the World IEA balances* (IEA, 2016a).

In this model version, we decided to focus in this study on the Transport and Electricity generation sectors, while maintaining a high level of aggregation in the Industrial and Building sectors, which are much more complex to model since they use all kinds of fuels and energy vectors in a great diversity of technologies. The approach will be detailed in **section 3.3.3.1**.

Figure 25 represents the PES of each sector considered in WoLiM: the Electricity generation (215 EJ), Industrial (165 EJ), Transportation (101 EJ) and Buildings (50 EJ). The Total Primary Energy Supply (TPES) in that year reached 536 EJ. Interestingly, the losses in the electricity sector (from both generation and distribution) account for almost as much as industrial sector with 150 EJ (28% of the TPES). In the last years, the electricity sector showed the greatest growth. As this figure illustrates, an electrification of the society without a shift in the generation mix would inefficiently spend large amount of resources.

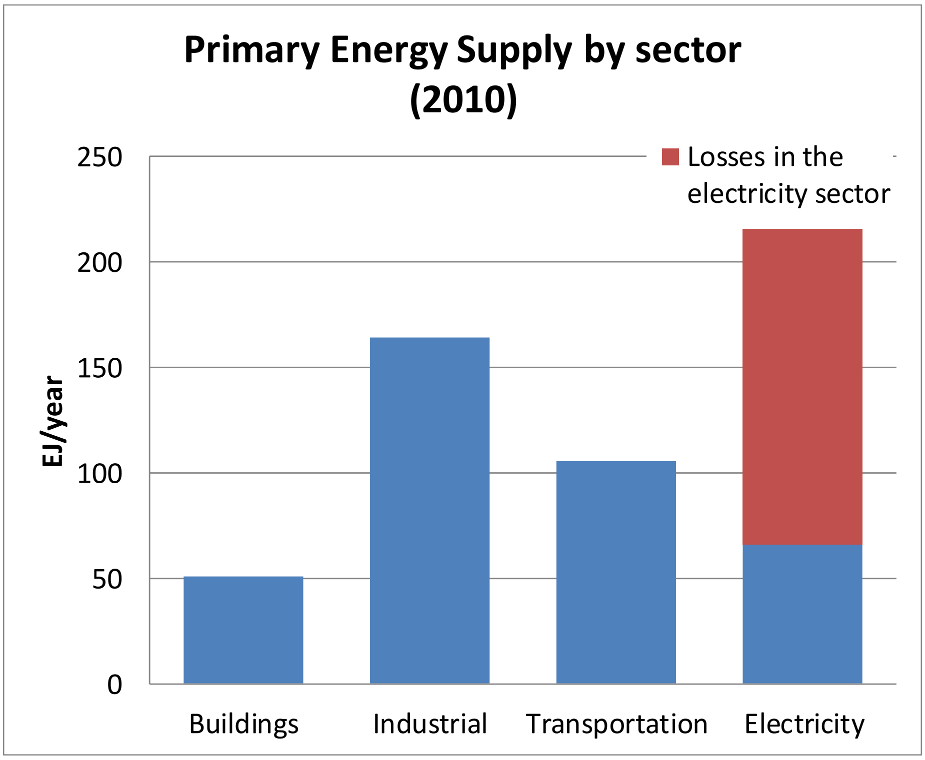

Figure 25 (IEO, 2013): Primary Energy Supply by economic sector modeled in WoLim. The losses for the rest of sectors are not showed since they are not explicitely considered in WoLiM.

Each sectoral energy demand evolution (E^i) is generated through the energy intensity method explained in Section 3.2 and is modeled following the eq. 9.

$$E^i{}_t = a^i{}_t \cdot I^i{}_{t-1} \qquad \text{i: economic sector} \qquad \textit{eq. 9}$$

In the next sections, the modeling of each sector is analyzed separately.

3.3.1. Electricity

The final electricity demand is generated from its energy intensity projection, which is assumed to correspond 1:1 with the evolution of GDP (see section 3.2). In order to account for the electricity generation demand, distribution losses must be added to the electricity consumption trends. An analysis of the period 1980-2010 reveals that these losses were approximatively 9.5% of the electricity consumed (Figure 26).

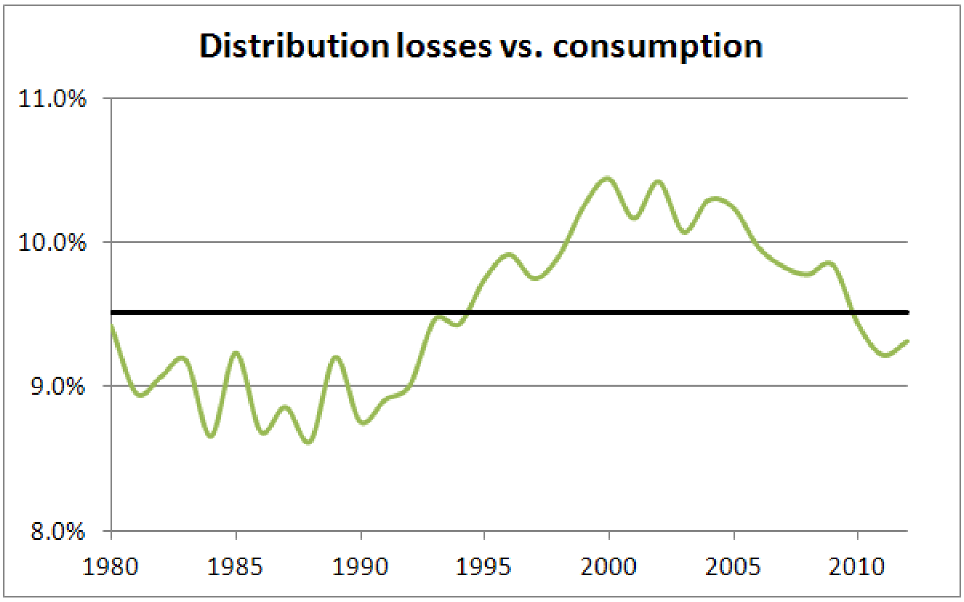

Figure 26: Distribution losses vs. consumption at global level (1980-2012) (US EIA db, 2015).

The electricity generation is estimated applying eq. 10. When checking this relation for the past years an error inferior to 1% was obtained.

$$E_{elec}^{gen} = E_{elec}^{cons} \cdot (1 + 9.5\%) \qquad eq.\ 10$$

The model also accounts for the additional energy due to the electrification of transportation (see section 3.3.2). The modelling of electricity generation in WoLiM is as following: priority is given to the evolution of exogenously variables (oil, nuclear and RES); the remaining is distributed equally between coal and gas following their share in 2014 (65% and 35% respectively). The following efficiencies are applied for the non-renewable electricity generation following the IEA Balances (IEA, 2016a):

Fuel	**Efficiency of power plant**	**Comment**
Nuclear	33%	Constant in the IEA balances
Coal	35.3%	Stable trend between 1971 and 2014, average of the period.
Oil	36.1%	Stable trend between 1971 and 2014, average of the period.
Natural gas	5% annual improvement growth from current values with an asymptote in 60%.	There has been a constant improvement in the efficiency of natural gas power plants, from 35% in 1990 to 44.3% in 2014.

Table 8: Assumptions for the efficiency of fossil and nuclear power plants.

The generation of electricity from RES, oil and nuclear are exogenously projected depending on the scenarios modelled.

3.3.1.1. Electricity generation from oil

The current generation of electricity is dominated by fossil fuels (75% in 2010 (WEO, 2012)), dominated by coal (46%) and gas (23%)). The contribution of oil is declining since the 70s and currently represents around 4%. We linearly extrapolate past trends assuming that oil, due to its high quality and increasing scarcity in the future, will be driven out from the electricity generation around 2025 to be used in more specific applications (see Figure 27).

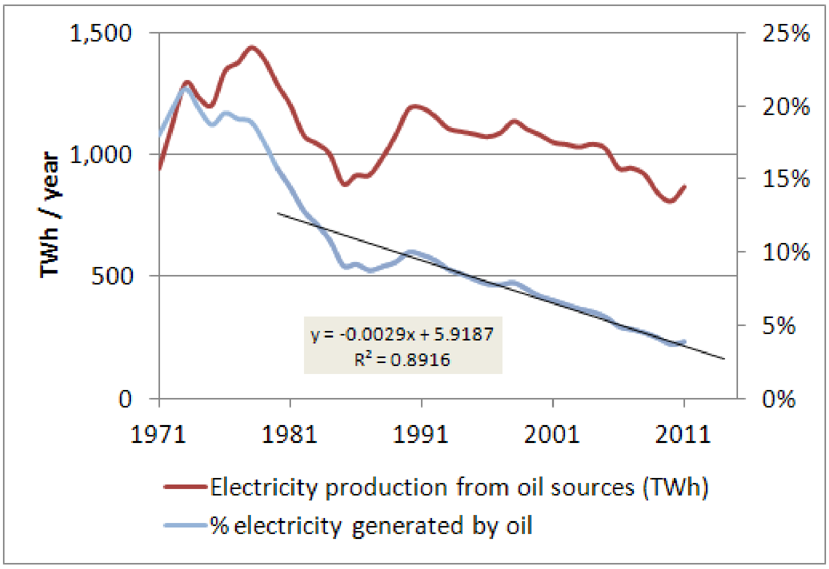

Figure 27 (own analysis from (World Bank database, 2015)): Electricity production from oil sources (TWh) and as percentage of the total electricity production.

3.3.1.2. Nuclear power scenarios

Due to the uncertainty in future nuclear deployment, we consider 4 possibilities in relation to nuclear fission power capacity:

1- Constant power (optimistic realist as argued by Schneider et al., (2012),

2- Assuming that the lifetime of nuclear reactors is maintained to 40 years in all countries, the progamed new reactors are built and a progressive shut-down of reactors in Germany,

3- PLEX (Plant Life Extension): as scenario 2 but considering the lifetime or reactors of 60 years,

4- Increase following the forecast from the World Nuclear Association (WNA) (+ 1-2%/year growth) for the coming decades (Dittmar, 2013; WNA, 2005).

Global nuclear power plant capacity is explicitely represented in WoLiM. Since nuclear power plants require a depletable input to operate (uranium), the electricity produced by uranium is modelled by three structures for representing: the exogenous demand of each scenario (TWh), the installed capacity (GW) and a submodule of uranium extraction similar to the ones for other non-renewable energy extraction (see Figure 12). Ultimately, the electricity generation is the minimum between the available uranium and the existing infrastructure.

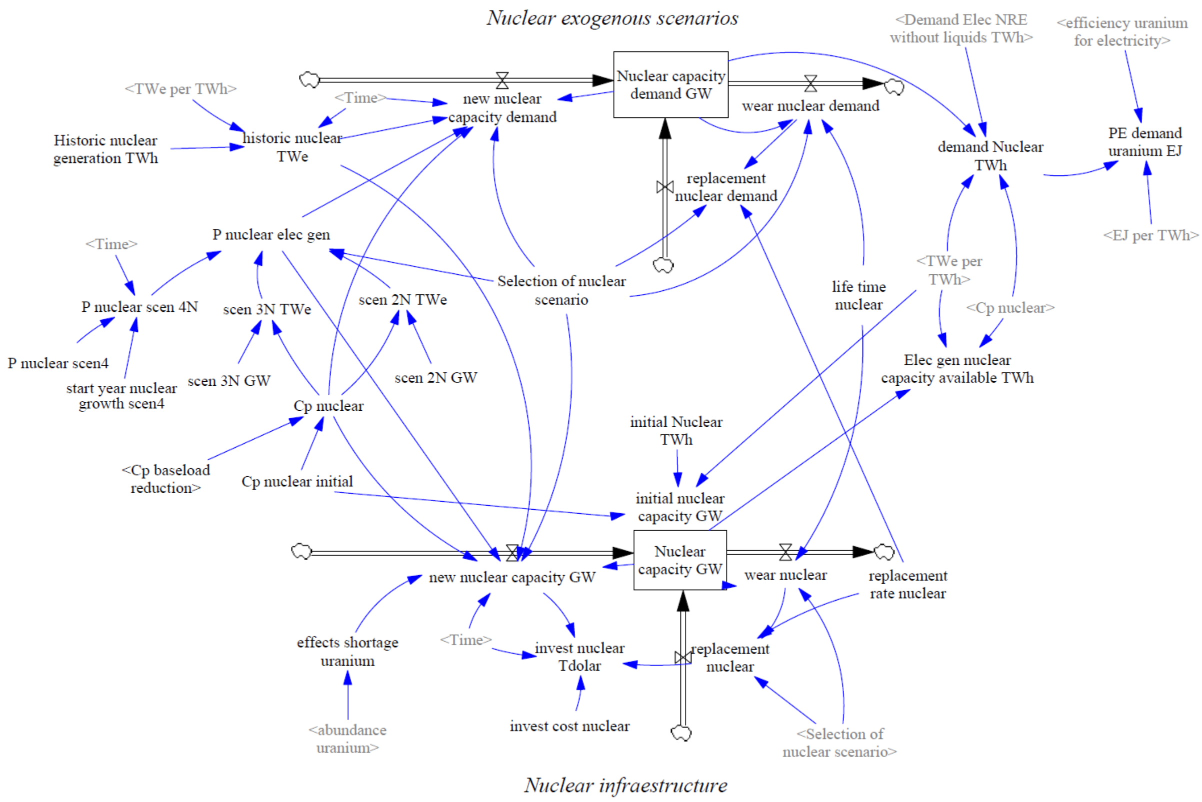

Figure 28: Forrester diagram of electric generation from nuclear power.

As a result, in those scenarios where the nuclear capacity is expanded, they may reach the limits in uranium extraction, eventually generating transitory problems of overcapacity. It is assumed that there are not new nuclear capacity additions when the demand of uranium exceeds its availability. For the sake of simplicity, in this model version it is assumed that decommissioned power is always replaced. Under this modeling, capacity constraints do not operate. However, as a result of the penetration of the electric intermittent RES the Cp of the nuclear plants falls which ultimately causes the decrease in the annual average output per installed capacity. Further versions of the model will consider the role of energy infraestructures more comprehensively.

Since the costs of nuclear have continuously upscaled since the deployment of this technology (Grubler, 2010), we take a conservative approach considering that future reactors would require the same investment as the recent Hinkley Point C nuclear power station in UK of 8,000 US$/kW (Schneider and Froggatt, 2014).

3.3.1.3. Electricity generation from RES

Among the renewable energies, hydroelectricity continues to be the largest contributor due to its early historical deployment; however the new renewable energies show a strong growth in the decades (e.g. solar +44%, wind +30%, see **Table 9**), while reaching (or close to) grid-parity costs in many locations (REN21, 2014).

	Reference	Annual averaged growth over the period	Period
Hydro	(US EIA db, 2015)	+2.4%	1990-2012

Wind onshore	(BP, 2016) & (IRENA db, 2017)	+24.3%	1990-2015
Wind offshore	(IRENA db, 2017)	+46.6%	2000-2014
Solar	(BP, 2016)	+43.8%	2000-2015
Geothermal	(US EIA db, 2015)	+3.0%	1990-2012
Biomass & MSW	(US EIA db, 2015)	+6.8%	1990-2012
Oceanic	(IRENA db, 2017)	+4.1%	2000-2014

Table 9: Historical generation of electricity by RES technologies: annual averaged growth over the period.

However, still the new renewable energies reached less than 4.5% of the world electric generation in 2011 (US EIA db, 2015). In 2007, over 95% of the power generation capacity under construction worldwide was for fossil fuel and hydro power production (WEO, 2008, fig. 6.4). But the in less than a decade the trend has radically changed: the capacity additions of renewable technologies in 2013 reached the same level than for the rest of technologies (Liebreich, 2014).

3.3.2. Transportation

Consumption in transport covers all transport activity (in mobile engines) regardless of the economic sector to which it is contributing including: road (passenger and freight), aviation, rail, marine bunkers and domestic navigation and pipeline transport. Transportation largely relies (95%) on liquid fuels; and 55% of the world total liquid fuels are dedicated to the Transportation sector.

As much of the global vehicle market is already covered by fuel-economy standards, the need for additional abatement from the transport sector is comparatively lower than for the power and industry sectors (WEO, 2014).

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

3.3.2.1. Electric vehicles

The prospects for electric vehicles (EVs) are highly uncertain, as the breakthrough to fully commercial models has yet to come and consumers would have to adjust to the characteristics of the new vehicles. WoLiM considers BEV (battery electric vehicles) and PHEV (plug-in hybrid vehicle) that are the types of electric vehicles that represent the bulk of the electric transportation for light duty vehicles (IEA, 2016b). By 2015, there were 1.25 million of EV vehicles in the world (mostly in advanced capitalist economies and China), which have to be compared with the 1,200 million motor vehicles currently existing in the world

(World Bank database, 2015). And usual projections foresee that the number of vehicles on the world's roads will reach 2,400 by 2040 (WEO, 2014).

One of the most important limitations of electric cars is their low functionality in terms of the capacity of accumulation of energy: 15 times less storage, according to (FTF, 2011), even taking into account the greater efficiency of electric motors and battery technology that can be expected in the next decade. Owing to this low accumulation capacity, only lighter vehicles are normally considered as candidates to be purely electrical, and even in those texts, where purely electric vehicles are considered for freight transport, such as (IEA, 2009), the goals are very low and are restricted to "light commercial and medium-duty freight-movement". The consumption of light vehicles takes up practically half the oil used for transport (IEA, 2009). This means that around 30% of the world oil consumption can be substituted by electric (or hybrid) cars.

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

Another limit that should be taken into account when studying electric cars is that of the materials needed for the batteries. The most promising batteries at the moment are lithium-ion batteries, and it is thought that each electric vehicle will need between 9 and 15kg of lithium mineral per vehicle. Lithium reserves are estimated as being 4.1Mt, although some authors claim that 11Mt could be exploited (Hacker et al., 2009). (Angerer, 2009) estimates 6Mt of global reserves and, according to his data, if lithium consumption for applications unrelated with electric vehicles continues to rise at the present rate, by 2050, 2Mt of lithium will have been consumed. Assuming that this lithium will not be recycled, this would leave between 2Mt and 9Mt for electric vehicles, which could maintain a total of between 222 and 1,200 million vehicles, assuming 9 kg lithium per vehicle (current fleet size is 800 million), which would be sustainable if the lithium in electric vehicles could be recycled at rates close to 100%.

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

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

Given the high upfront cost of the EVs, substantial deployment levels are currently dependent on policy, i.e. subsidies (WEO, 2014). Different analyses project different developments for the EVs. The EVI, which is "a multi-government policy forum dedicated to accelerating the introduction and adoption of electric vehicles worldwide" is on the optimistic side and seeks to "facilitate the global deployment of at least 20 million passenger car EVs by 2020" and "100 million by 2030" (IEA, 2016b). The target for 2030 would mean that by 2030, around 5% of the vehicles would be electric globally. Other analyses such as the WEO (2014) are less optimistic and project that the electricity's share of total transport energy demand still reaches only 2.4% by 2040, compared with 1% at present –mainly tran- (New Policies Scenario): "sales of plug-in hybrids and electric vehicles increase to 5.7% of total passenger LDV sales in 2040, from less than 0.2% today, helped by subsidies in several countries: they displace almost 800 thousand barrels per day (kb/d) of gasoline in road transport by 2040".[20]

[20] The report acknowledges that: "our projections point to only modest growth in the EV fleet, but a breakthrough in battery and recharging technology could revolutionise road transport in the longer term" (WEO, 2014).

These two analyses are taken as references for the "high" (extrapolation of +34% annual growth in share penetration in 2015-2030 from EVI, i.e. reaching full penetration in the market of LDV by 2050[21]) and "low" (1.5% share of EVs by 2040 by WEO (2014), i.e. +9% annual growth) assumptions regarding the development of EVs in WoLiM, estrapolating the trends up to 2050. Targets have been changed to expected annual share growth rather than market penetration rates by 2050 to avoid inconsistencies due to the assumption of paralization of the promotion of electric transport in the case there would be scarcity in the electricity sector and the dependence on the market share of the energy demand of the transportation sector. The share penetration of EVs is limited by the fact that only around 47% of motor vehicles are LDVs.

As for the CTL and GTL crash programs, the policy promoting electric and hybrid vehicles is frozen if the abundance of electricity decreases below the value 1 (cf. Section 5). For more details see (Mediavilla et al., 2013).

3.3.2.2. Natural Gas Vehicles (NGVs)

Differently to BEV&HEV, natural gas can cover almost the whole spectrum of vehicles. Natural gas can be used in a compressed (CNG) or liquid (LNG)[22] state in several modes of transport, including road transportation, off-road, rail, marine and aviation (IEA, 2010). Generally, CNG is more commonly used for lighd duty vehicles (LDVs) while heavy duty vehicles (HDVs) require more energy to run and tend to use LNG to maintain an acceptable range (IEA, 2010). Due to the strong growth in the past decade (+22% per year in number of vehicles, +17% share growth per year), by end-2012 there were 16.7 million NGVs (http://www.iangv.org/current-ngv-stats/). Still, this number pales in comparison to a total worldwide number of around 1,170 million motor vehicles that year (World Bank database, 2015) – i.e. 1.4% of total.

CNG vehicles are currently slightly less efficient than equivalent gasoline vehicles while diesel vehicles enjoy a small net advantage. In the future, however, estimated improvements in spark ignition engines will bring all technologies much closer together (IET JRC, 2014). Thus, for the sake of simplification, we will consider that the tank-to-wheel (TTW) factors of NGVs, diesel and gasoline are equivalent.

The world gas consumption in transport is expected to increase from 20 bcm in 2010 up to 40-45 bcm in 2030 (IGU & UN ECE, 2012). (WEO, 2014) projects that an expansion of 5.1% per year in gas energy use for transportation, from 40 bcm in 2012 to 160 bcm in 2040. Economic analysis indicate that natural gas can compete with gasoline in all scenarios where gas transmission and distribution grids are present (IEA, 2010). Especially, this growth is expected to remain strongest in the regions that are also currently leading in NGV market development (Asia-Pacific and Latin America). Also, due to the foreseen liquids scarcity along the first half of the century, it seems plausible to expect a high growth in the order of the past decade (+20% per year) of NGVs in the coming years.

The NGVs in WoLiM are modeled in a similar way to the BEV&HEV by an exogenous growth driven by the market penetration level assumed to be reached in the future. The development cost of retail infrastructure, that is estimated to be significant (WEO, 2012), is not modeled for the sake of simplicity.

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[21] This scenario is more optimistic than (WEO, 2016), which foresees in its more optimistic scenario 715 million of electric vehicles by 2040, vs. over 1,100 extrapolating EVI's projection 2015-2030.

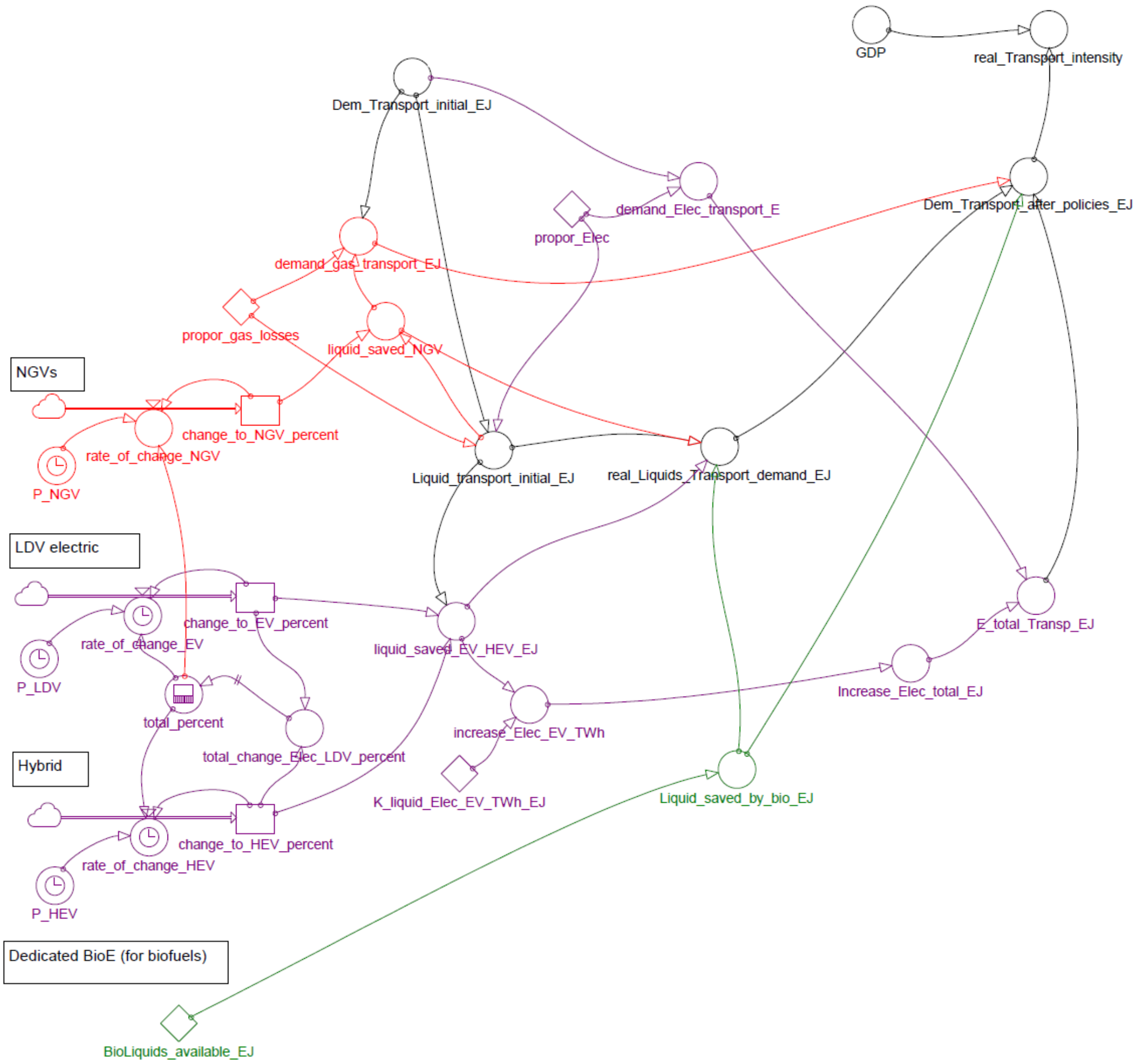
[22] At atmospheric pressure and temperature, natural gas has an energy content of around 40 MJ/m3 or 50 MJ/kg, as compared to gasoline (35 MJ/L) and diesel (39 MJ/L). In order to reach an acceptable range, gas needs to be stored in a way that increases the energy density. There are currently three technologies for this. The most common are CNG and LNG. CNG is gas that is compressed to a pressure of usually 200 bar, after which it is stored in cylinders. LNG is gas that has been liquefied by cooling it to below its boiling point of -163 °C (at atmospheric pressure) and subsequently stored. There are two standards for dispensing LNG: saturated LNG (8 bar and -130 °C) or cold LNG (3 bar - 150 °C) (IEA, 2010).

As for the BEV&HEV, the policy promoting NGVs is progressively constrained when the abundance of natural gas decreases below the value 1 (cf. Section 5).

3.3.2.3. *Biofuels for transportation*

The substitution of oil liquids by biofuels was explained in Section 3.1.2.

Figure 29 depicts the simplified Forrester diagram of the Transportation sector. An initial demand of energy for transport is generated through the energy intensity approach (*Dem_Transport_initial_EJ*). Subsequently, this demand is distributed by fuel shares following the historical trends. These trends are modified by the policies applied in terms of electric, hybrid and NGVs market penetration[23] as well as by the rhythms and potential of bioenergy deployment. The additional electricity required is added to the initial electricity demanded (*Increase_Elec_total_EJ*). Finally, the real energy intensity of the Transportation sector is calculated after the policies (*real_Transport_intensity*).



[23] An additional condition is considered: HEV&EV and NGVs only deploy while there is not scarcity of electricity and gas, respectively. This scarcity is measured through the parameter "abundance", as explained in **Section** 5.

Figure 29: Forrester diagram of the Transport sector in the WoLiM model.

Transportation is a key sector, which has a strong dependency on oil and is essential for most industrial processes and services, and increasingly also for the food sector (Lassaletta et al., 2014). The lack of energy for transportation is expected to have an impact on all of the other sectors, especially in a strongly globalized economy.

3.3.3. Industry and Buildings sectors

As explained in the section 3.2, the energy demand of Industry and Buildings sectors (IB sector) (*PE demand for IB initial_EJ* in Figure 30) is generated in aggregate form following the energy intensity method for both Industrial and Buildings sector. This is mainly due to the difficulty to find open source time series of data for each sector, but it is consistent with the approach of building a world aggregate model that contributes to the main dynamics of the energy-economy interaction. The Industry and Buildings sectors are much more complex sectors to model since they use all kinds of fuels and energy vectors in a great diversity of technologies. Consequently, we decided to focus in this version of the model on the Transport and Electricity generation sectors, while maintaining a high level of aggregation in IB sectors.

Since the share of both Industry and Buildgins in the IB aggregate has remained fairly constant over the last decades (*IEOs*), we assume that in the middle-term this proportion will hold (75% for industrial, 25% for buildings). The structure of this sector has been changed from the last model version given that in the current version the potential of thermal RES has been estimated (see section 3.1.2.2), wich has allowed to replicate in the IB sector the structure build for other sectors. For the sake of simplicity, the total thermal RES potential is considered as an aggregate (geothermal, solar and bioenergy), and different policies project different growth trends constrained by this total aggregate potential. Thus, thermal uses of renewable energies are not explicit in the model, nor are they assigned to a concrete technology (except for the 3rd generation biomass residues detailed previously in section 3.1.2.1). The replacement of fossil fuels in the IB sectors is made assuming a primary energy conversion of 1 to 1. As a reference, Table 10 shows the growth trends of solar and geothermal.

Thermal	
Solar[1]	Geothermal
(SHC, 2012)	(WEC, 2010)
+ 21 %	+ 13 %
2000-10	1995-08

Table 10: Renewable technologies for thermal generation by source growth rates (yearly average) . [1]All types.

Figure 30 shows the forrester diagram of the demand of energy in the Industry and Buildings sectors. As for other sectors in WoLiM, the renewable generation (thermal) has priority over the fossil fuels, which are assumed to maintain the last share from historical data (IEA balances).

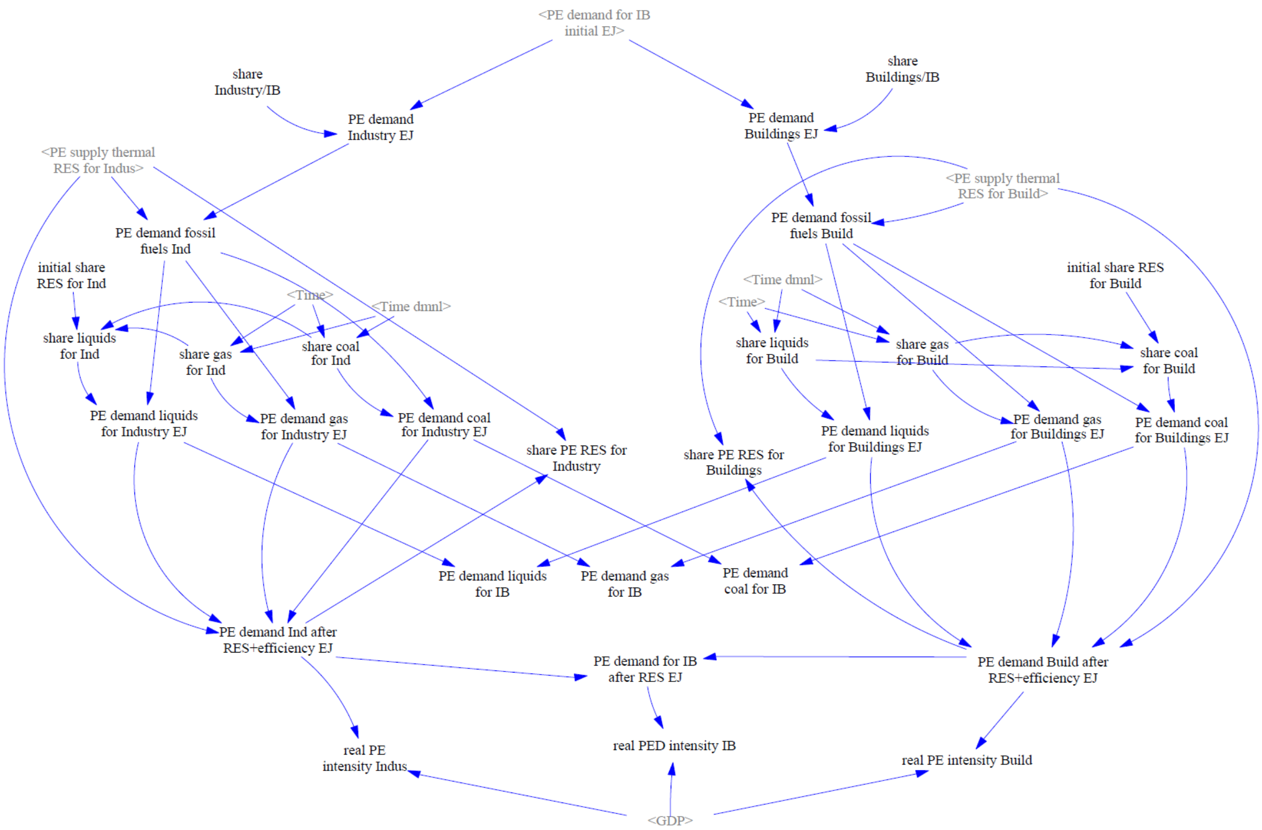


Figure 30: Forrester diagram of the representation of the Industrial sector and the policies applied.

For both sectors, the historical shares of RES, liquids, coal and gas from WoLiM 1.0 are maintained (Capellán-Pérez et al., 2014b).

3.3.3.1. Industry

This sector includes both manufacturing industries (food, paper, chemicals, refining, iron and steel, nonferrous metals, and nonmetallic minerals, among others) and nonmanufacturing industries (agriculture, mining, and construction), excluding the electricity. Chemicals, iron and steel, nonmetallic minerals, paper, and nonferrous metal manufacturing account for the majority of all industrial energy consumption. This sector accounts for around 50% of the world total final energy consumed, with a growing trend during the last decade. Interestingly, it is also the most sensitive sector (in terms of energy demand) during economic shocks, as seen in the 2007-2008 crash (IEO, 2011).

The industrial sector is dependent on a diversity of energy resources: liquid fuels, gas and coal amount each between 23% and 30%. In the last years, there has been an important growth of the renewable energy share reaching 7% by 2007, while the share of the oil has tend to slightly decrease in favor of coal and gas (IEO, 2010). In the period 1990-2007, RES have grown at a +7.4% average annual level. Among renewables, the most prominent source is the biomass&MSW, which currently provides around 90% of all the renewable energy in this sector.

3.3.3.2. Buildings

This sector is an aggregate of the sectors “Commercial” and “Residential” from the IEOs since their energy use patterns roughly correspond for most regions (IEO, 2011): lightning, coking, heating, etc. Thus, natural gas accounts for 40% and 30%, and the electricity for 51% and 32%, respectively. Also, as depicted in the Figure 25, it is the smallest sector in terms of energy consumption, representing around 15% of the total energy demand. In the period 1990-2007, RES have grown at a +2.4% average annual level. However, in countries where large shares of the population still depend on the use of traditional biomass show a very different pattern (36% of the world population in 2008). We model the use of traditional biomass following the assumption of (WEO, 2010), that projects a reduction of these share to 25% in 2035 and a linear trend thereafter.

In general, more potential for the penetration of alternative energies is given to the Buildings sector as usually considered (e.g. 20-20-20 from Europe Union).

3.4. Modeling policies: predictive growth curves

Many variables of the model are projected following a growing trend over time, such as the electric renewables, CTL and GTL crash programmes, electric and hybrid vehicles market penetration, savings in the Industrial and Buildings sectors, etc. A variety of growth curves exist (for an overview see (Höök et al., 2011)), however for most of the variables involved in the energy transition there are not enough past data to perform significant regressions and statistical analysis. In the policy realm, two types of policies are usually set: on the one hand, when a target is set for a year Y the annual effort is usually translated into annual (constant) percentage improvements, which translates into an exponential type of growth (eq. 11). Another possibility is to connect the initial and final point by a line, i.e. a linear growth. This is highly simplistic since real developments are usually non-linear, although it might be valid as an approximation in the short-term.

$$y_t = y_{max} \cdot e^{kt} \qquad \text{eq. 11}$$

Finally, sigmoid curves grow slowly in the beginning and end stages (asymptotically striving towards a maximum), being generally easier to fit to actual implementation of technology and market introduction dynamics. All growth rates are largely dependent on the initial (almost exponential) growth rate parameter k that governs the growth pattern before limitations begin to dominate. The growth rate slows down when the technology reaches a substantial level of deployment (i.e. point of inflection). This is due to a combined set of constraints, such as finantial limitations or industry-level limitations in the fabrication of components that make impossible to maintain the exponential growth and to the existence of an eventual limit. As reference, we take a logistic curve that is an S-curve with an inflection point reached at a 50% of the limitation (Sterman, 2000) (eq. 12).[24]

$$y_t = \frac{y_{max}}{1+e^{-k \cdot \Delta t}} \qquad \text{eq. 12}$$

Figure 31 shows the normalized linear, exponential and logistic growth curves:

[24] When confronting with past data (or equivalent data from another region or country), different systems may reach the point of inflection at different points. For example, comprehensive studies of giant oil fields, typically holding the majority of oil in many regions, have shown that they peak when approximately 40% of the URR has been extracted (Höök et al., 2011).

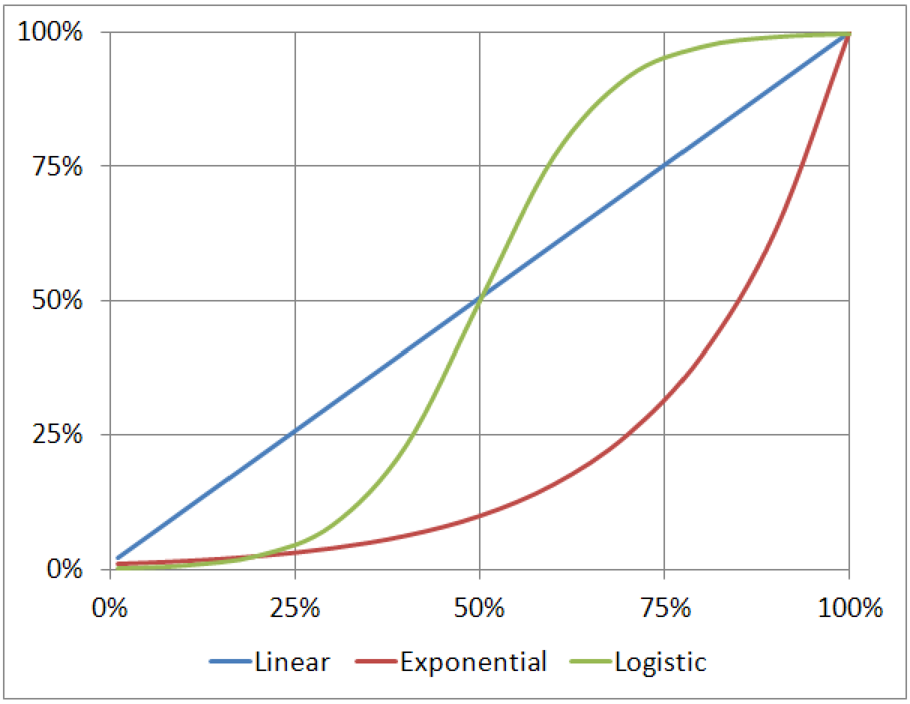


Figure 31: Comparison of the normalized linear, exponential and logistic growth curves.

Due to these advantages, we apply the logistic curve as predictive growth curves by default in the model. The upper limit is not the policy target in the year Y, but the actual physical limitation to the growth of this variable (e.g. the techno-sustainable potential of renewable energies (see Figure 20), the horizontal asymptote in the efficiency improvements, the market share of LDV to be sustitued by electric and hybrid vehicles, etc.).

3.5. CO_2 emissions and climate submodule

The model computes the CO_2 emissions associated with the use of fossil fuels: coefficients from (BP, 2013, p. 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.

Resource		Reference	Emission coefficient [tCO_2 / 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 11: CO_2 emissions for non-renewable resources used in the model.

Shale oil emissions are 6.14 tCO_2/toe vs. 3.84 for unconventional oil. Since we have all unconventional oils in an aggregated manner, a function corrects the emissions related to total unconventional oil assuming that shale oil would follow the share in relation to total unconventional oil as estimated by (Mohr and Evans, 2010) (Low Case) for 2050 and 2100 (linear interpolation). Thus, the emission factor for unconventional oil considering shale oil higher emissions would be:

$$Emission\ factor_{unconventional\ oil} = 3.84 + (6.14 - 3.84) \cdot share_{shale\ oil} \qquad eq.\ 13$$

See below (Figure 32).

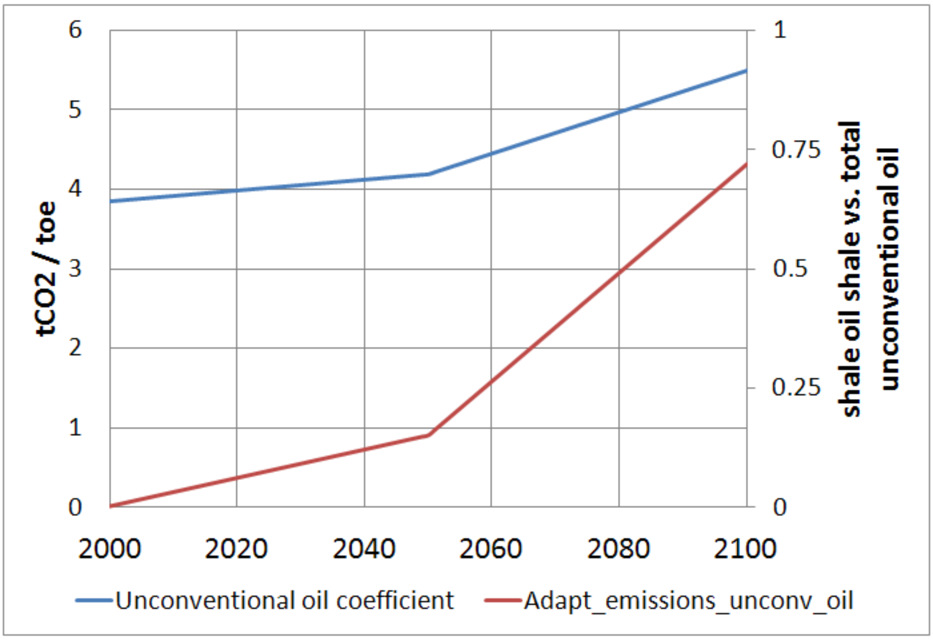


Figure 32: Evolution of the shale oil share in relation to total unconventional oil as estimated by (Mohr and Evans, 2010) and the associated emission coefficient for total unconventional oil production.

In the case the user introduces a depletion curve of total oil and total gas, then it assumed that emissions from unconventional fuels represent a fixed share of the total extraction. In the case of unconventional gas, it is assumed that they follow the share in relation to total natural gas as estimated by (Mohr and Evans, 2011) (BG) for 2050 and 2100. Similarly, for unconventional oil we assume the share from the BG scenario from (Mohr et al., 2015).

In this model version we implement the afforestation as the only CO_2 sequestration policy. As reference we use the work from (Nilsson and Schopfhauser, 1995) that analyzed the changes in the carbon cycle that could be achieved with a large global afforestation program covering 345 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).

This model version includes a simplified representation of the climate (Figure 33). The climate submodel of DICE-1994 (Nordhaus, 1992, 1994) has been implemented (with updated parameters from the DICE-

2013R (Nordhaus and Sztorc, 2013) which allow to compute for CO_2 concentrations,[25] radiative forcing and temperature change. Exogenous assumptions for land-use change emissions and other GHGs are also considered.

3.6. Summary of the key variables of the model

Table 12 summarizse the main exogenous variables of the model.

	Exogenous variables	Description/input specification
Socioeconomic	GDPcap	GDP per capita
	Population	Population
Sectoral efficiency improvements	a_{Transp}	Annual improvement
	a_{elec}	
	a_{BI}	
	I_{min}	Horizontal asymptote that represents the minimum value of the energy intensity.
Resource availability	Non-renewables	Maximum extraction curves
	CTL, GTL	Coal-to-Liquids, Gas-to-Liquids (Annual growth)
Electric renewables	Solar PV&CSP	Annual growth, available potential (MHa/y)
	Wind	Annual growth, available potential
	Hydroelectric, Geothermal, Bioenergy&Waste	
	Oceanic	
Nuclear		Annual growth, restricted by uranium maximum extraction curve
BioEnergy	2nd generation	Annual growth, available potential (MHa/y)
	3rd generation	Annual growth, available potential (EJ/y)

[25] In comparison, the previous methodology based on assuming 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) is in good agreement with the DICE climatic submodel version up to 2050, however beyond the mid-century the discrepancies reach discrepancies of around 20%.

	Residues	
Thermal renewables & efficiencies	Industrial sector	Market share in time t
	Buildings sector	
Alternative transport	HEV & Hybrid	Market share in time t
	NGVs	Annual growth
Afforestation program		Global program (MHa/y available)

Table 12: Main exogenous variables in the model. y refers to year.

The main endogenous variables are:

- Fuel & sectoral scarcities measured with the parameter "abundance" (cf. Section 5),
- Climate outputs: CO_2 emissions and concentrations,
- Renewable energy for electricity investment & shares comparing to the total mix.

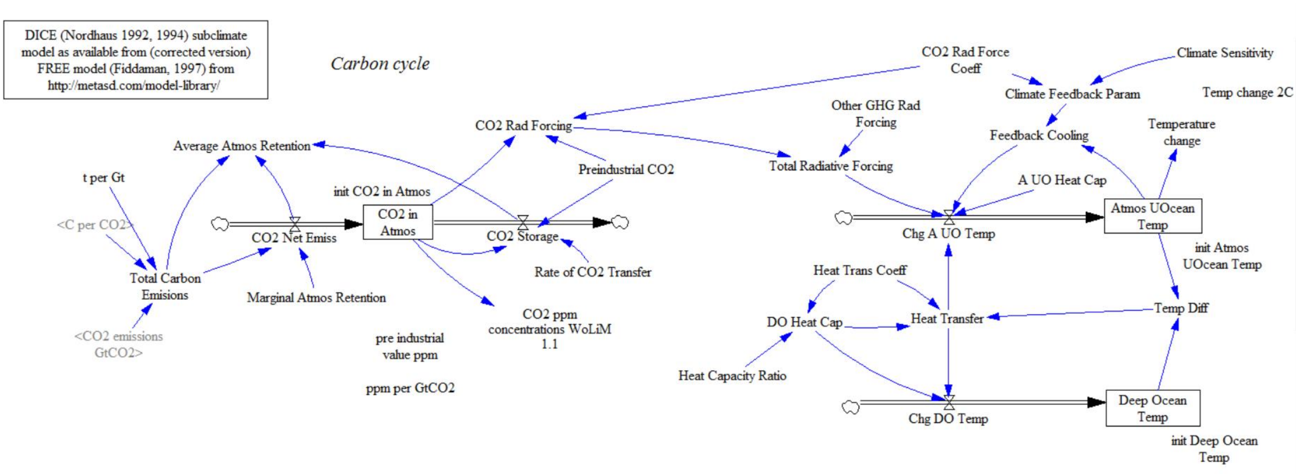


Figure 33: Carbon cycle and climate modeling in WoLiM

4. Description of scenarios

Different methods for exploring the future exist and have been applied in natural and social sciences (for an overview, see (Glenn and Gordon, 2009)). Prediction is possible if systems are well known and can be observed in controlled and reproducible situations. Unfortunately, this is not the case when complex causal relationships, limited knowledge and high level of uncertainty exist as in medium/long-term Economy-Energy-Environment modeling. Furthermore, these predictions are contingent on drivers that may be even more difficult to predict, such as human behavior. Scenario development offers one approach to deal with all this issues, focusing on an assessment of pathways of events under a set of key assumptions ('what if'?) (van Vuuren et al., 2012). Scenario methodology has become very popular in recent Global Environmental Assessment (GEA) (e.g. IPCC's Assessment reports (IPCC, 2001, 2007c; IPCC SRES, 2000), UNEP's Global Environmental Outlook (UNEP, 2012, 2007, 2004) or (MEA, 2005)) and has already several decades of history (Jefferson, 2016; Meadows et al., 1972).

In this Technical Report, we report the results of WoLiM 1.5 for 5 scenarios that have been shown to form the basis of many scenarios used in different environmental assessments (van Vuuren et al., 2012). The tested storylines are the same than the ones simulated for the previous version of the model WoLiM

1.0 (Capellán-Pérez et al., 2014b, 2014a, 2015), however adjustments have been made to adapt to the updated structure and available data.

4.1. Scenarios tested

This section describes the most important qualitative characteristics of the scenarios tested.[26] Table 13 summarizes the main assumptions and drivers of each scenario: a Business-as-Usual (used as reference and assuming that historical dynamics will also guide the future) and 4 alternatives:[27]

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'). A major risk of this scenario family is thus that the ecological and social systems are much more sensitive than assumed, as a result of which feedback becomes important (Cumming et al., 2005; Mediavilla et al., 2013).

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. A key issue in these scenarios is how such self-reliance is possible without becoming harmfully ineffective with respect to supranational issues of resource depletion and environmental degradation (e.g. (Friedrichs, 2010)). As for Scenario 1, ecological feedbacks could bring "bad surprises".

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 your own problems. In fact, although barriers for products are re-built, barriers for information tend to be eliminated. The focus is on finding regional

[26] 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).

[27] In reality, van Vuuren et al., (2012) identify 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 merge them for the sake of simplicity and reduce the number of representative scenarios.

solutions for current environmental and social problems, usually combining drastic lifestyle changes with decentralization of governance.

		BAU	1- Economic optimism with some market reforming[a]	2- Global SD	3- Regional competition	4- Regional SD
Economic development		Medium (historic trends)	Very rapid	Rapid	Slow	Medium
Population growth		Medium-Variant (UN, 2011)	Very low	Low	Similar to (UN, 2011) Medium-Variant	Similar to (UN, 2011) Medium-Variant
Technology development		Medium	Rapid	Ranging from mid to rapid	Slow	Ranging from low to rapid
Main objectives		Not defined	Various goals	Global sustainability	Security	local sustainability
Environmental protection		Both reactive and proactive	Mainly reactive	Proactive	Reactive	proactive
Trade		Weak globalization	Globalization	Globalization	Trade barriers	Trade barriers
Policies and institutions		Mixed	Policies to create open markets and reduce market failures	Strong global governance	Strong national governments	local steering; local actions
Examples in GEAs	(IPCC SRES, 2000)	-	A1	B1	A2	B2
	(MEA, 2005)	-	Global Orchestration	Techno-Garden	Order from Strength	Adapting Mosaic

Table 13: This table summarizes the main assumptions and drivers in very general terms. [a]We have merged the categories "Economic Optimism" and "Reforming Markets" because of their similarity for the sake of simplicity as justified by (van Vuuren et al., 2012). When a range was given, we have either referred directly to the quantification by (MEA, 2005) for socioeconomic inputs, or made our own interpretation as discussed in the text above.

4.2. Scenario implementation

Three main steps applied when implementing a scenario with the model are:

1- Selection (or self-construction) of a consistent (qualitative) storyline framework. For example, the storylines from the Global Environmental Assessments (e.g. IPCC, MEA, etc.).

2- Interpretation/quantification of the storyline. Some variables such as the socioeconomic inputs GDPcap and Population are available from the Global Environmental Assessments or institutional research agencies (e.g. IPCC, (MEA, 2005), United Nations, etc.).

3- For the rest of variables not explicitly available from GEAs, we have to interpret each storyline quantifying specific transition policies and technology aspects (cost, availability, etc.) to project the exogenous variables of the model.

The tested storylines are the same than the ones simulated for the previous version of the model WoLiM 1.0 (Capellán-Pérez et al., 2014b, 2014a, 2015), however adjustments have been made to adapt to the updated structure and available data (I_{min}, CTL/GTL growth, thermal RES growth and alternative transport policies). Table 14 shows the values for each key variable of the model for each scenario.

	SCENARIO - INPUT	BAU Projection of current trends	Scenario 1 Economic optimism with some market reforming	Scenario 2 Global Sustainable Development	Scenario 3 Regional competition	Scenario 4 Regional sustainable development
Socioeconomic (% 2015-2050)	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]	35 %	35 %	25 %	35 %	25 %
Resource availability	Non-renewables	Best Guess	Best guess (coal, conv. oil) High case (gas, unconv. oil)	Best Guess	Best Guess	Best Guess
	CTL, GTL[b]	Crash program (+15 %)	Crash program (+20 %)	Past trends	Crash program (+15 %)	Past trends
Electric RES	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 capacity		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 RES[28]	Industrial sector	Low (+7.4%)	Medium (+15%)	Rapid (+30%)	Low (7.4%)	Rapid (+30%)
	Buildings sector	Low (+2.4 %)	Medium (+5%)	Rapid (+15%)	Low (2.4%)	Rapid (+15%)
Alternative transport[b]	BEV&HEV	Low (+9%)	Medium (+22%)	Rapid (+34%)	Low (+9%)	Rapid (+34%)
	NGVs	Medium (+17)	Rapid (+25%)	Medium (+17%)	Low (+10%)	Medium (+17%)

[28] There was an error in this line in the Table 4 published in the paper (Capellán-Pérez et al., 2014a): the shares depicted represented the rough additional market share gain from 2008 levels, not the absolut.

Afforestation program	-	-	350 MHa	-	350 MHa

Table 14: 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 35% of the energy intensity levels of 1990 for scenarios BAU, 1 and 3, and at 25% for 2 and 4 following Baksi and Green (2007). [b] The CTL and GTL crash programs, as well as the "Alternative transport" policies are maintained while the "scarcity point" in the fuel inputs (e.g. electricity for BEV&HEV) and gas for NGVs).

5. Results[29]

Before reporting the results, we provide information on how the scarcity (i.e. the divergences between energy demand and available supply) is reported in WoLiM 1.5, since it is a model that does not automatically balance demand with supply. A parameter "abundance" [0;1] is defined for quantifying the relative scarcity by fuel and economic sector. While supply and demand are balanced, "abundance" is 1. However, when demand cannot be fulfilled abundance < 1 (the closest to "0" indicates a higher scarcity):

- By non-renewable fuel i: as a dynamic relation between the demand and the fuel demand (eq. 14):

$$Abundance(t)_i = 1 - \frac{Demand(t)_i - Extraction(t)_i}{Demand(t)_i} \qquad eq.\ 14$$

- By economic sector j: as a relation between each sectoral demand driven by each scenario and the energy effectively extracted to fulfill the demand for this sector j (eq. 15):

$$Abundance(t)_j = 1 - \frac{Demand(t)_j - Extraction(t)_j}{Demand(t)_j} \qquad eq.\ 15$$

Similarly, for characterizing the proximity of each RES to the techno-sustainable potential considered in the simulation, we define the "remaining potential":

- By renewable fuel i: is a relation between the potential considered and the current level extracted (TWe) (eq. 16):

$$Remaining\ potential(t)_i = \frac{Potential_i - TWe(t)_i}{Potential_i} \qquad eq.\ 16$$

5.1. Results of the simulations

Figures 34-42 report the main results of WoLiM 1.5 model up to 2050 with the scenarios described in the previous section.

GDPpc (exogenously) grows for all scenarios reaching between 15,000 and 30,000 2011 US$ by 2050 (Figure 34). This increase, in combination with the projected evolution of global population, drives the increase in the demand of energy for all sectors. These energy demands depend on the assumed exogenous evolution of sectoral efficiency improvements, as well as on the transition to specific technologies in each sector. For example, for the case of Transportation, the introduction of ambitious policies of transition to electric vehicles drives the evolution of its primary energy demand intensity down for the scenarios 2 and 4 (Figure 35). The aggregate contribution of all sectors is shown by the evolution of the total primary energy demand intensity, which decreases for all scenarios between 0.6%/yr (Scenario BAU) and 0.95%/yr (Scenario 4) in relation to 2015 levels by 2050 (Figure 35).

In terms of energy extraction, liquids reach a plateau at < 210 EJ (~100 Mb/d) between 2030 and 2050, and only Scenario 1 that assumes a higher extraction of unconventional oil in the next decades shows an increase in total liquids production over the studied period (Figure 36). For most scenarios, thus, the peak of conventional oil in the early 2010s determines a decline or stabilization of energy available for transportation. Biofuels, alternative electric, hybrid and gas transport, CTL&GTL (that does not develop significantly in any scenario (< 10 EJ/yr by 2050) 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, total oil abundance by 2050 is below

[29] The reported results have been run with Vensim DSS for Windows Version 6.4c (x32). The integration type was RK4 Auto with a timestep of 0.25 seconds.

0.8 for all the simulated scenarios (Figure 38). Natural gas reaches its peak in the 2020s, between 2023 (Scenario 1) and 2029 (Scenario 3), while coal reaches its extraction limits between 2032 (Scenario 1) and 2046 (Scenario 3) (Figure 36).

The use of renewable energies increases in all scenarios extraordinary in all scenarios, reaching an electricity production of 28,000-45,000 TWh, which is between 5 and 8 times current generation levels from RES (Figure 37). Although by 2050 there is no sign of electric RES reaching their biophysical sustainable potential, the low remaining potential for those scenarios with more ambituous policies of RES deployment (<15% for Scenarios 2 and 4), indicate that these trends could not follow in the second half of the 21st Century (see Figure 39). This model version allows to track the use of RES for other uses than electric (Figure 37), and the results shown that their limits are attained before the RES for electric (<0.05 in the 2040s for the Scenarios 2 and 4, see Figure 39).

These developments translate into an increasing total primary energy supply which reaches a plateau at different levels depending on the scenarios (between 700 EJ/yr amd 820 EJ/yr by 2030-2040) (Figure 40). Since total primary energy demand continues its increase, by 2050 the abundance of total energy lays between 0.5 and 0.8 depending on the scenario.

By sectors, both transportation and the aggregate of Industry and Buidings are the most affected by energy scarcity during the studied period (Figure 41).

Still, these developments have the potential to drive the system to dangerous levels of climate change surpassing 450 ppm and the 2°C threshold in the 2040s (Figure 42).

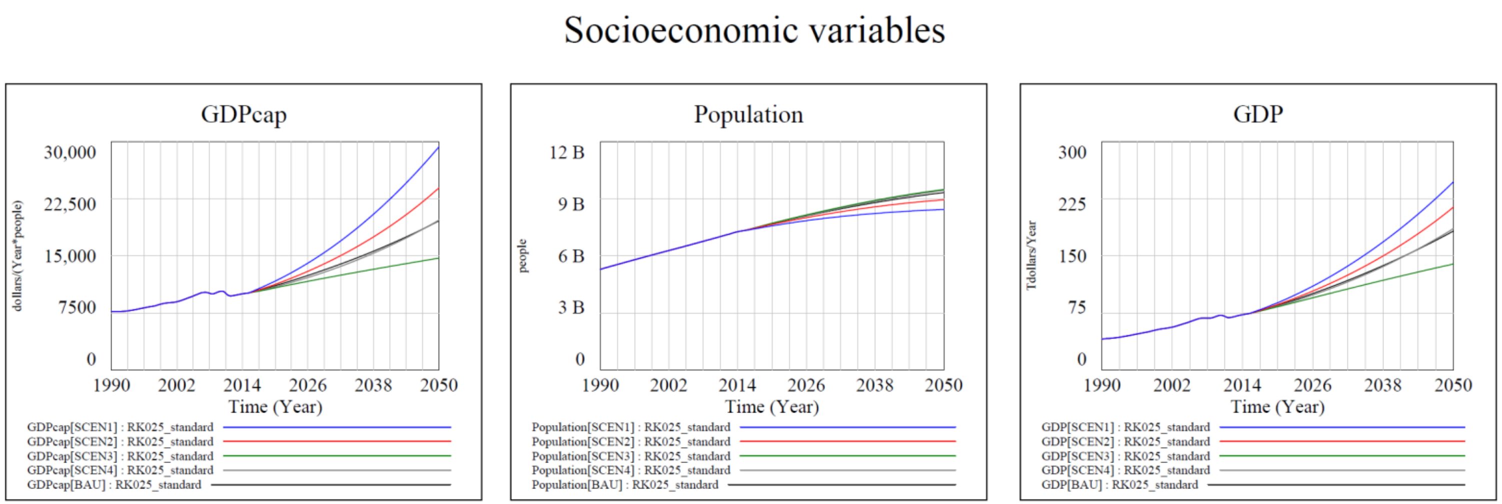


Figure 34: WoLiM 1.5 results: socioeconomic variables.

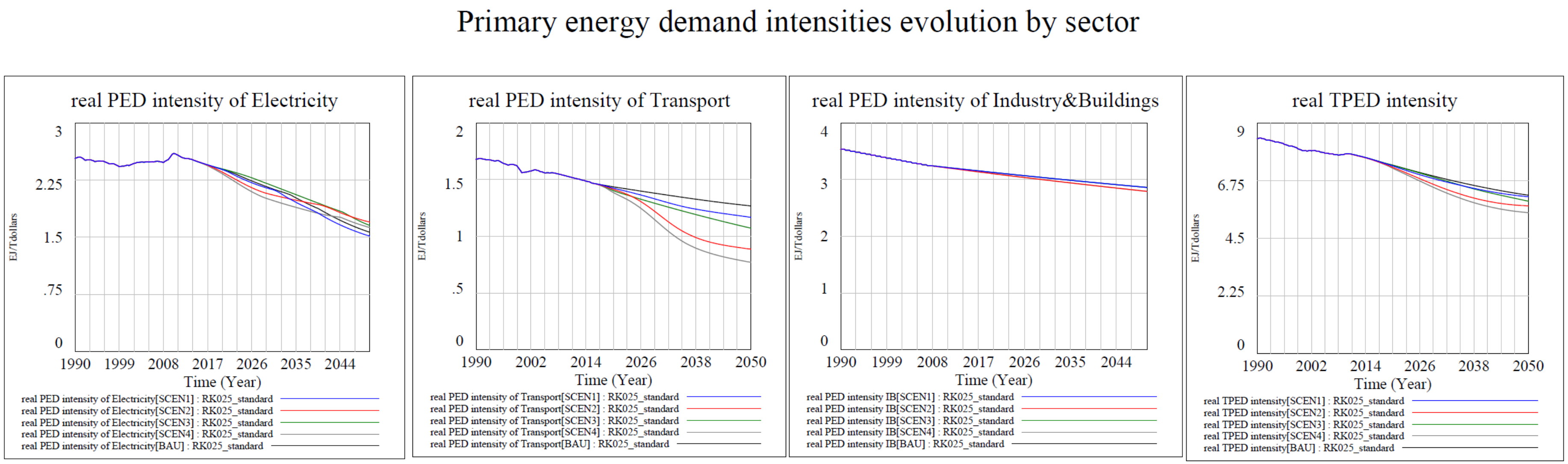


Figure 35: WoLiM 1.5 results: primary energy demand intensities evolution by sector.

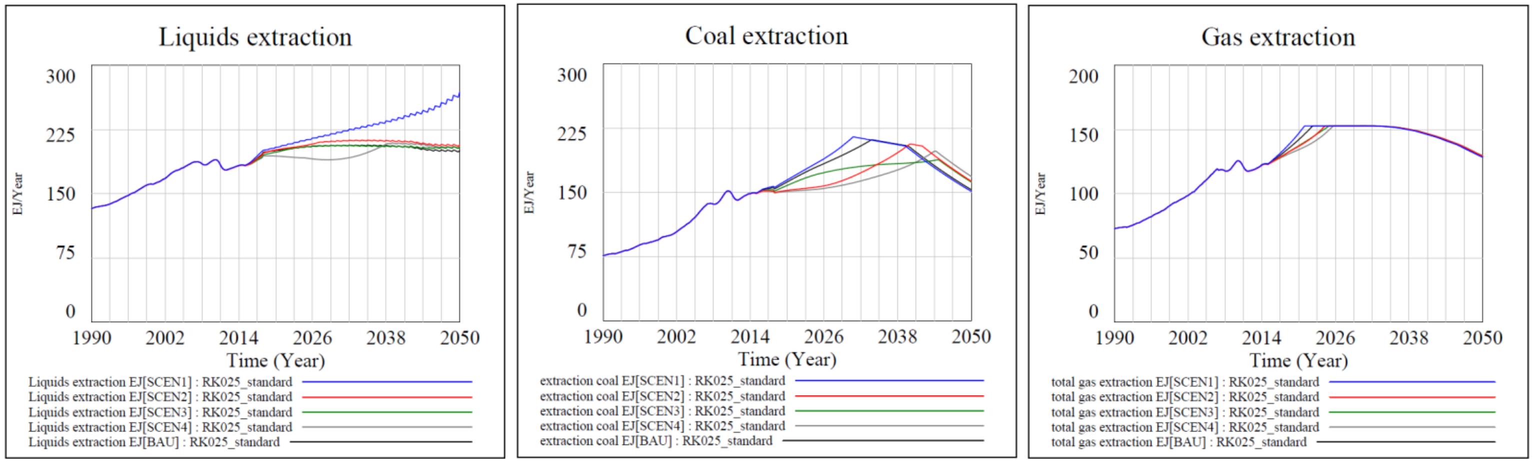


Figure 36: WoLiM 1.5 results: liquids (including oil, biofuels, CTL and GTL) coal and gas extraction.

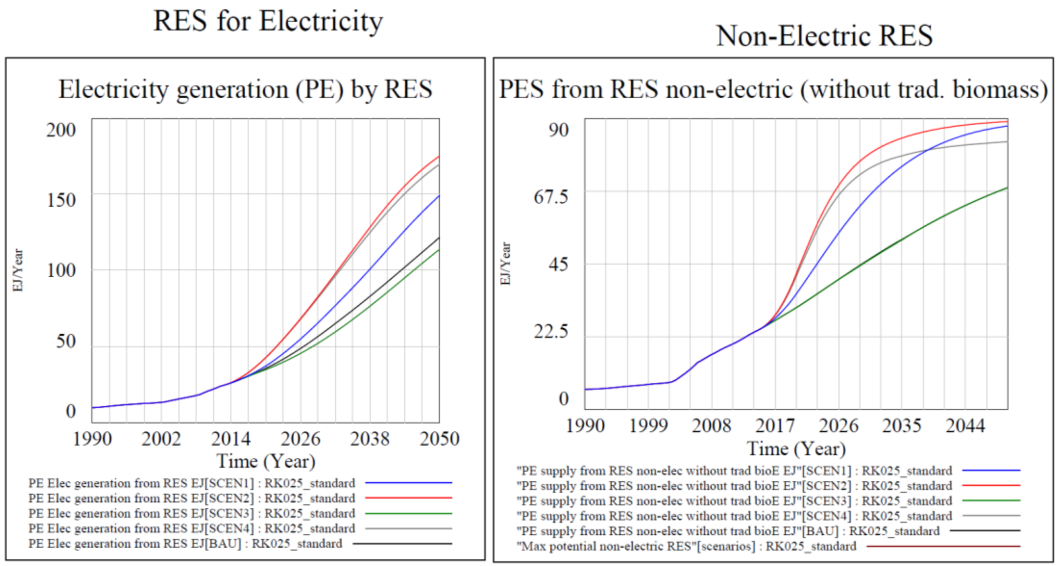


Figure 37: WoLiM 1.5 results: RES supply.

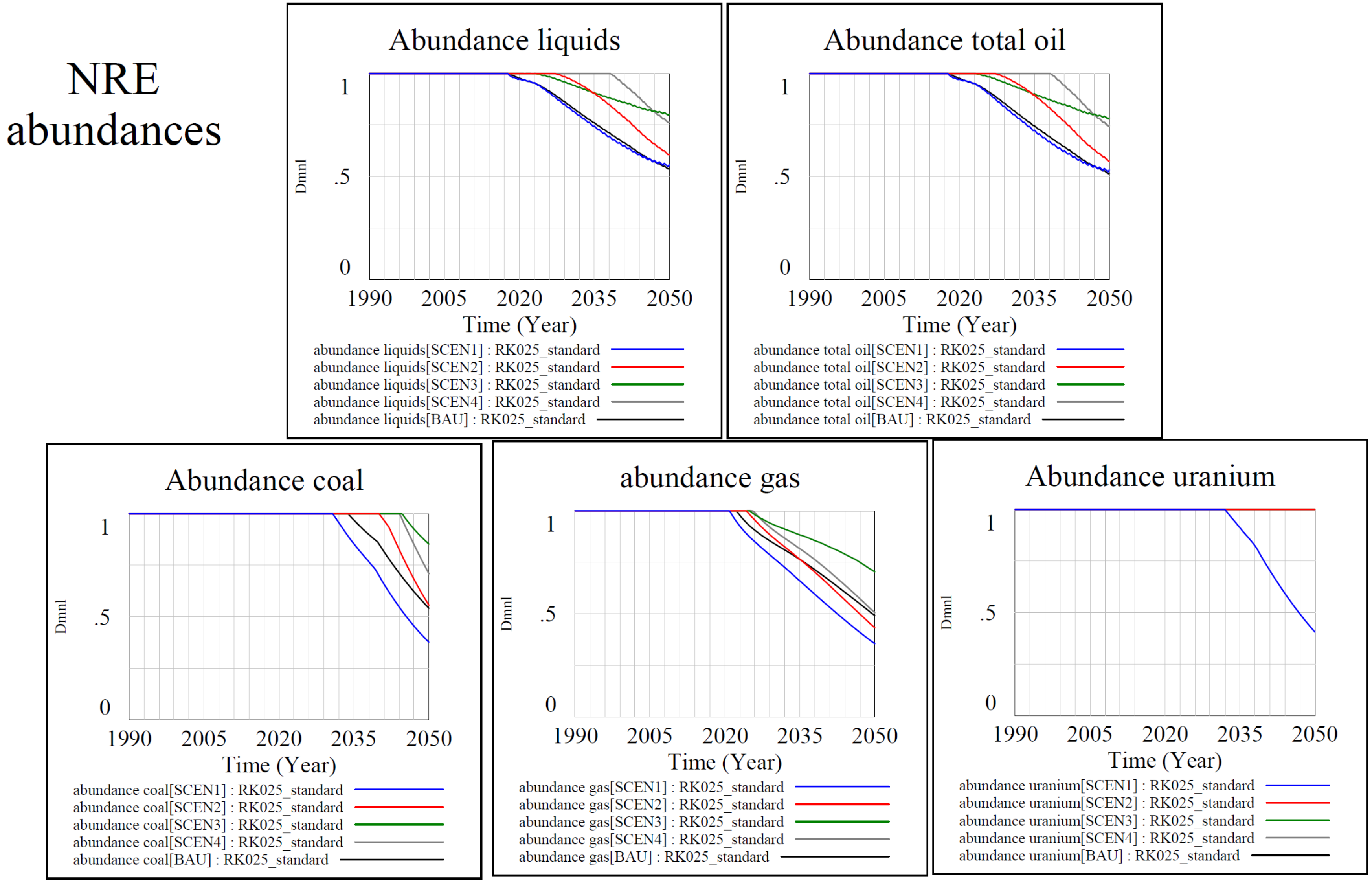


Figure 38: WoLiM 1.5 results: Abundances of non-renewable energy resources.

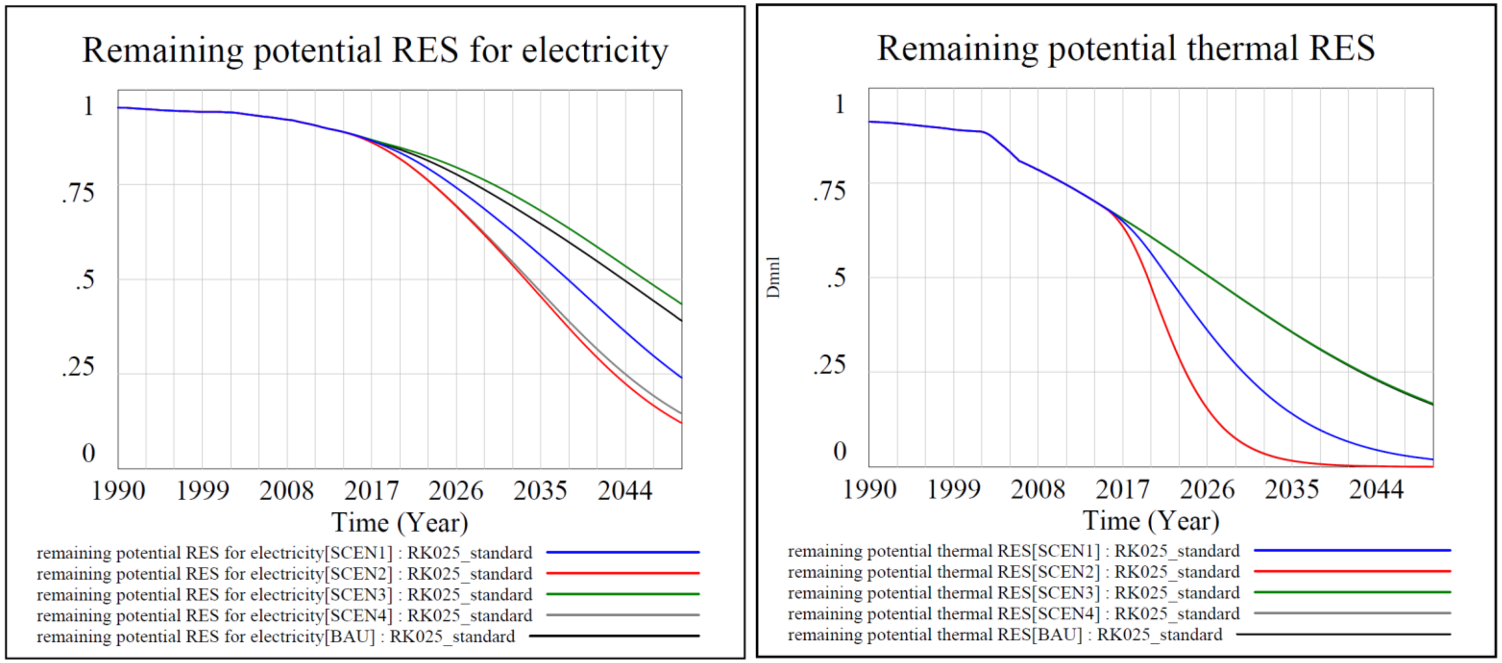


Figure 39: WoLiM 1.5 results: remaining potential of renewable energy sources.

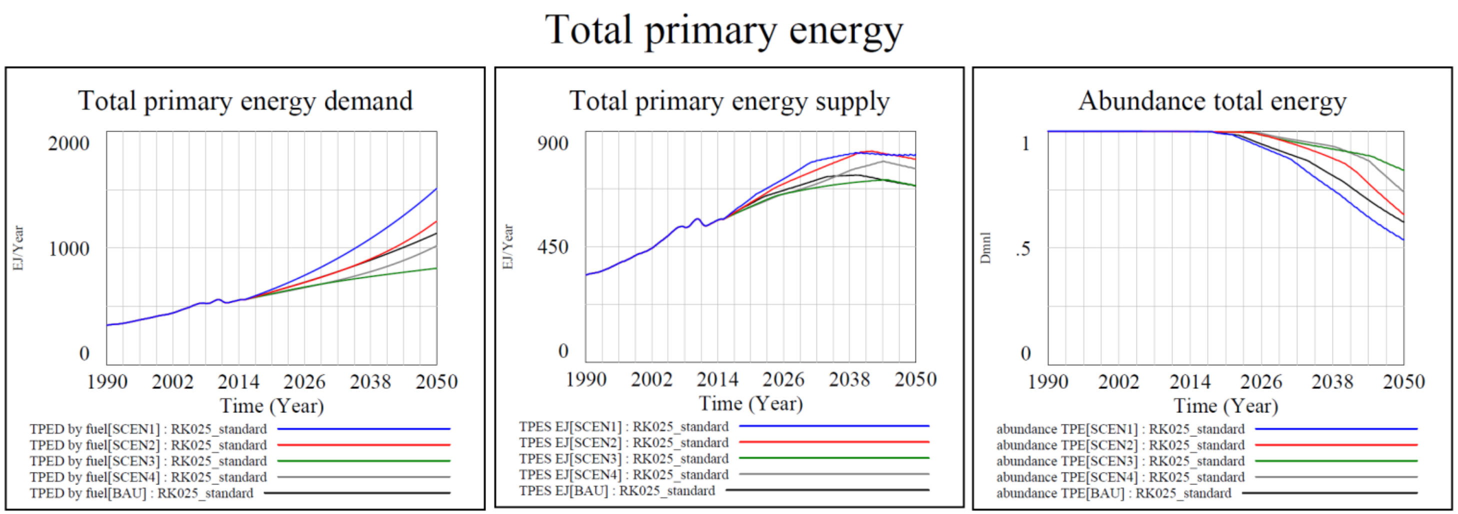


Figure 40: WoLiM 1.5 results: total primary energy demand and supply.

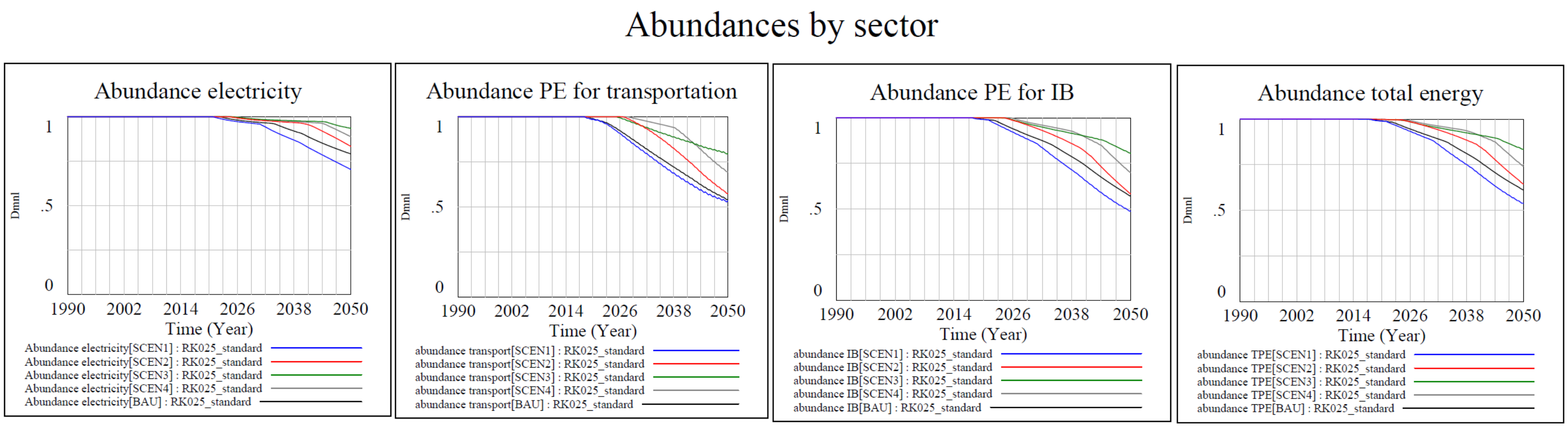


Figure 41: WoLiM 1.5 results: Abundances by sector.

Emissions and Climate Change

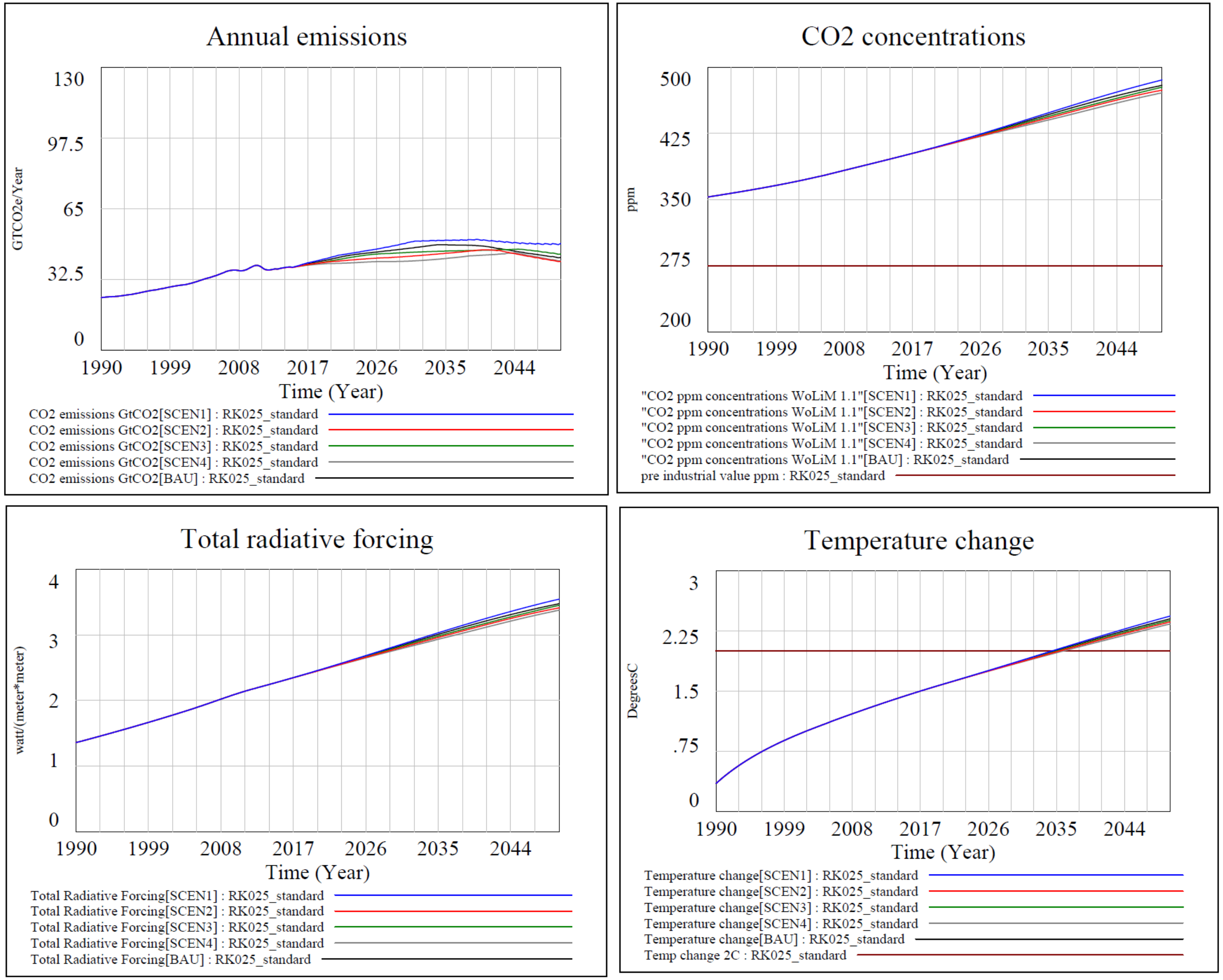


Figure 42: WoLiM 1.5 results: emissions and climate change.

5.2. Discussion and comparison with the previous version of WoLiM

Table 15 compares the supply-demand divergences (at 5%) for non-renewable energy resources and sectors, as well as the potential reached (95) of renewable energy sources between beoth versions. Although the obtained results are qualitatively similar to the previous version of WoLiM 1.0 (Capellán-Pérez et al., 2014b, 2014a), the energy scarcities have tended to decrease in importance (delays in the supply-demand divergence of between 5-10 years). This may be due to the fact to a combination of factors: the update of GDP historical values to 2015 translates into a lower energy demand than the projected by WoLiM 1.0 due to the global finantial crisis or the curve used for unconventional oil that assumes that this resource is extracted in all the world when real developments show that its development at large scale at outside North-America is very unlikely (Murray, 2016). Also, updated policies such as the high assumed penetration level of electric vehicles in some scenarios allows to delay the scarcity points in Liquids and Transportation in relation to the previous version.

Fuel / Sector	**Supply-demand divergence (5%)**	
	WoLiM 1.0 (Capellán-Pérez et al., 2014a)	**WoLiM 1.5** (this report)
Liquids	2015-2018	2024-2041
Gas	2022-2032	2023-2029
Coal	2024-2034	2032-2046
Uranium	2031-…	2034-…
TPE	2020-2027	2025-2035
Electricity	2025-2036	2032-2048
Transportation	2015-2018	2024-2037
IB	2017-2025	2024-2034
	Potential reached (95%)	
Wind	2032-2050	2042-…
Solar	2052-…	…
Hydroelectric	2033-…	…
Aggregated thermal RES	-	2031-…

Table 15: Comparison of the supply-demand divergence (5%) and potential reached (95%) range in the 5 modeled scenarios for all fuels and sectors with WoLiM 1.0 and 1.1.

Other policies might also prove too optimistic. For example, the level of growth of RES for electricity has reached a peak in most countries that hold the greates capacities. Another example is the effect of the economic crisis in the energy intensities, which has tended to increase its level (which has not been taken into account in this model version since the energy intensities have not been updated), contraty to the usual assumptions (also applied here) of exogenous reduction. In particular, electricity generation intensity has increases over 10% since the year 2009 reaching a historic maximum at 290 TWh/UST$, and a total primary energy intensity at levels of the 1990s (Figure 43).

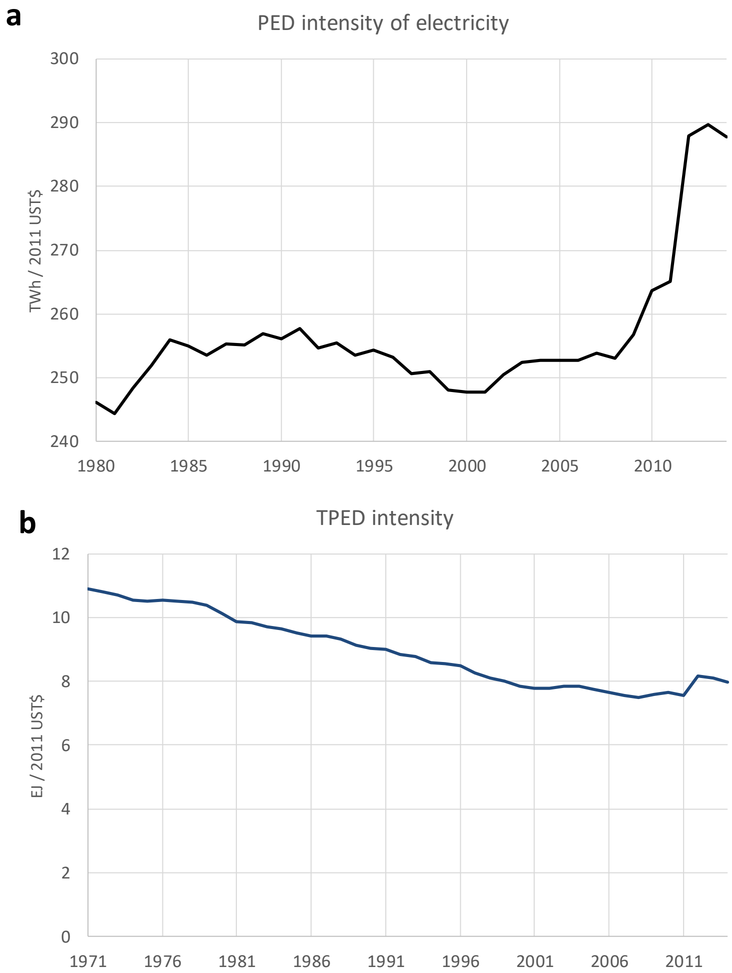


Figure 43: Historical evolution PED intensity of electricity and total energy supply.

WoLiM 1.5 also computes a number of energy indicators such as the number of people relying on traditional biomass, the average TPES per capita (without accounting for the people relying on traditional biomass) and the average electricity per capita. Figure 44 shows the average TPES per capita without accounting for the people relying on traditional biomass. The results range 110-130 GJ per capita for all scenarios by 2030, delclining thereafter to 85-115 GJ per capita by 2050. As a reference, we compare with the energy use threshold (in terms of total primary energy footprint) of 106 GJpc found by (Arto et al., 2016) to reach high development (HDI>0.8), and the approximative energy use value to fulfill the aceptable standard of living (in terms of total primary energy use) of 30-40 GJpc (Goldemberg, 2001; Rao et al., 2014; WBGU, 2003). These results indicate that, in the absence of a distribution of the energy supply at global level, most population will remain at low levels of development from the perspective of industrial-consumerist economies.

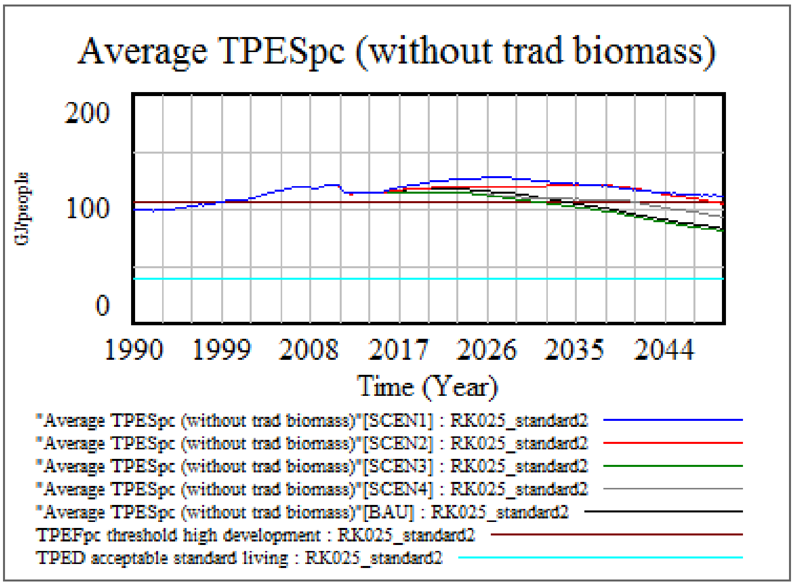


Figure 44: Average TPES per capita (without accounting for the people relying on traditional biomass) and comparison with threshold values to reach (1) high development and (2) cover acceptable standard of living.

6. Limitations and future developments of the model

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:

- In this model version there are not mechanisms for assigning different fuels/technologies to cover different needs, the allocation is made through priorities and constant shares. Future developments should be able to tepresent the competition between different techonlogies and fuels to deliver the same final energy.
- Not integration of energy supply and demand interactions for each sector (static maximum supply curves), especially relevant in situations of energy scarcity.
- The estimation of primary energy demands for the industry and buildings sectors is based on an indirect method with fixed shares. The use of historical data to fit each sector would improve the estimation of the energy demand of this sector.
- The transition to alternatives energies in the IB sector is made through primary energy demands, however the replacement should be done at final-energy level.
- In terms of alternative policies, the introduction of the option of public transportation seems critical given the degree of energy scarcity in this sector. Also, an explicit representation of the technological alternatives in these sectors would allow to model more precisely transition policies.
- A regional disaggregation would allow to capture regional particularities. In fact, it is unlikely that the world responds as a whole to the energy scarcities foreseen by the simulated scenarios (the most feasible scenarios are those that follow regionalization storylines, i.e. Scenarios 3 and 4). In this sense, a specific methodology should be developed to consistently integrate regional frameworks within the global model.
- The current representation of carbon cycle based on DICE is simplistic. The DICE carbon cycle is a first-order linear structure where the uptake of emissions is more rapid in the short run and morecomplete in the long run (Fiddaman, 1997). Moreover, the model only captures CO_2 emissions from fossil fuel combustion, which represent around 65% of the annual GHG (IPCC, 2014b).
- Not integration of the energy investments required to extract/make available the energy resources. (i.e. EROI). 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 energy return on energy investment (EROI) of the non-renewable resources diminishes due to the smaller EROI of unconventional resources (Murphy and Hall, 2010). Some modern renewable energies also perform low EROI ratios (e.g. solar (Prieto and Hall, 2013)). Thus, we do not consider here the so called "energy trap" (Murphy, 2011; Zenzey, 2013). If we would take 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 fuels.[30]
- Not 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 feedbacks are 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, Rockstöm et al., (2009) identify 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 model version.

[30] 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 EROI pegged at 10:1) will require giving up 8 percent of the net energy available for the economy".

- Others: non-consideration of phenomenons such as the rebound effect (e.g. (Freire-González, 2017)), conflicts and inequalities (within and between countries, e.g. corruption, wars) (e.g. (Motesharrei et al., 2014)), unexpected events (e.g. natural disasters), etc.

Although in previous work the feedback energy-economy has been implemented (Capellán-Pérez et al., 2015; de Castro, 2009; de Castro et al., 2009), the reason for this simplification in this model version is the lack of consensus on the literature about the influence of energy scarcity on the economic growth. Although some authors (e.g. (Hirsch, 2008)) quantify this relationship, there is not enough historical data at a global level to identify a tendency. On the other hand, in previous studies, this feedback tends to drive the system into collapse (e.g. (de Castro, 2009; de Castro et al., 2009; Nel and Cooper, 2009)). The omission of restrictions and feedbacks 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 scarcity points for both fuels and sectors would tend to converge in time, thus, not affecting the main conclusions of the modeling exercise. However, from a societal point of view, the transition might be less challenging if the “scarcity points” are more spread in time.

Current developments of WoLiM address some of these limitations in the frame of the development of the MEDEAS project “Modeling the renewable energy transition in Europe” (http://www.medeas.eu/) with the aim to build a energy-economy-environment global and European model in which WoLiM 1.5 constitues the basis for the Energy Module (GEEDS, 2016).

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Appendixes

A. Econometric estimations of sectoral energy demands

Total PE demand:

```
Modelo 2: MCO, usando las observaciones 1972-2010 (T = 39)
Variable dependiente: Itot

             Coeficiente   Desv. Típica   Estadístico t   Valor p
  ---------------------------------------------------------------
  Itot_1     0,988582      0,00202720         487,7       9,45e-074 ***

Media de la vble. dep.  11,61510   D.T. de la vble. dep.   1,611948
Suma de cuad. residuos  0,856381   D.T. de la regresión    0,150121
R-cuadrado              0,999840   R-cuadrado corregido    0,999840
F(1, 38)                237811,3   Valor p (de F)          9,45e-74
Log-verosimilitud       19,12412   Criterio de Akaike     -36,24825
Criterio de Schwarz    -34,58468   Crit. de Hannan-Quinn  -35,65137
rho                     0,011045   h de Durbin             0,068093
```

Transport PE demand:

```
Modelo 1: MCO, usando las observaciones 1972-2005 (T = 34)
Variable dependiente: Itransp

              Coeficiente  Desv. Típica  Estadístico t   Valor p
  -------------------------------------------------------------
  Itransp_1   0,992764     0,00217595        456,2      2,76e-064 ***

Media de la vble. dep.  2,207511   D.T. de la vble. dep.    0,161665
Suma de cuad. residuos  0,026399   D.T. de la regresión     0,028284
R-cuadrado              0,999841   R-cuadrado corregido     0,999841
F(1, 33)                208158,6   Valor p (de F)           2,76e-64
Log-verosimilitud       73,48942   Criterio de Akaike     -144,9788
Criterio de Schwarz    -143,4525   Crit. de Hannan-Quinn  -144,4583
rho                     0,053937   h de Durbin              0,309870
```

Electricity consumption (model is non-stationary and cannot thus be applied):

```
Model 4: OLS, using observations 1981-2011 (T = 31)
Dependent variable: Ielec

             coefficient   std. error   t-ratio    p-value
  ---------------------------------------------------------
  Ielec_1     1.00375      0.00178238    563.2    6.27e-062 ***

Mean dependent var   255.2808   S.D. dependent var   6.281690
Sum squared resid    191.1971   S.E. of regression   2.524527
R-squared            0.999905   Adjusted R-squared   0.999905
F(1, 30)             317140.2   P-value(F)           6.27e-62
Log-likelihood      -72.18652   Akaike criterion     146.3730
Schwarz criterion    147.8070   Hannan-Quinn         146.8405
rho                  0.284479   Durbin's h           1.558229
```

Table B1: Econometric estimations of sectoral energy demands

B. Adaptation of WoLiM model to coal unlimited extraction scenarios

In the standard version WoLiM version, fuel substitution mechanisms between fossil fuels where 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 (gas and coal). Thus, the essential conclusions would remain unchanged. However, when assuming scenarios with unconstrained coal resources (as in (Capellán-Pérez et al., 2015)), these mechanisms are essential in order to allow for a transition to a coal-based economy. We assume that when gas and coal scarcity approaches to a critical level, there would be a switch to coal in the IB end-use sectors (1% annual each from gas and liquids to coal).

C. A rough estimation of the global solar thermal potential

We will start by estimating the energy density of the solar thermal (ST):

- Capacity (C_{instal}) is around 700 W/m^2 of installed power per unit of horizontal surface (SHC, 2011),

- Global efficiency in the collector ($X_{collector}$) reported by the industry for 2009 was 9.5% ($W_{th\text{-}colector}/W_{instal}$) (SHC, 2011), including shadow losses, orientation, distance between the collectors, failures, snow, maintenance, etc.

- Losses in the pipes and in the heat exchanger as estimated by the industry amount around 15%;[31] the rest of the losses will be located in the water storage deposits. We will refer to them as P. These losses are strongly dependant on the typology of the installation (single circuit, a primary and a secondary circuit), the frequence of use, type of use (climatization, industrial, SWH, etc.), the type of storage deposit, the external temperature (especially in winter when the solar potential will be the most reduced), etc. However, at global level domestic hot water systems for single-family houses are predominant (80% in 2009), and we consider this application. Following (Faiman et al., 2001):

"In order to help quantify the problem, consider a cylindrical storage tank of nominal volume 100 l. Typical internal dimensions might be 0.44 m diameter and 0.66 m length. Let us suppose that the tank is enveloped in a 0.05-m thickness layer of glass wool insulation, k=0.037 W/(m.K). The total surface area for heat loss is 1.22 m^2, hence the total heat loss coefficient of the insulated tank will be UA=0.90 W/K. If the water in such a tank had reached, say, 60°C by sunset on a given day, and the mean ambient overnight temperature was 10°C, then it is a simple calculation to determine that by sunrise the next morning (typically 12 h later) the temperature of the water in the tank would still be above 55°C."

Calculations:

- The heat loss during the night (12h) is the heat lost by the storage deposit:

$$Q = m * cp * \Delta Tdeposit = UA * \Delta Tint\text{-}ext * t$$

$$1e5 * 4{,}18 * (60-T) = 0{,}9 * (60 - 10) * 12 * 3600$$

$$T = 55\ ºC$$

- Then, the losses in the deposit would amount to:

$$[1e5 * 4{,}18 * (60 - 55)\ ] / [1e5 * 4{,}18 * (60)] = 8{,}3\ \%$$

If we do the same calculations for a total heat loss coefficient of 5 W/K, we would obtain a tempertaure below 40 grados after the night which would translate into losses over 40%.

Following the manufacters[32], currently the UA of the deposit ranges between 1-5 W/K, with the majority around 2,5 W/K (22% losses). Thus, taking this number and the 15% of losses in the pipes and in the heat exchanger, the total average factor losses would amount to 37% and the average energy density of a typical solar thermal installation (ρ_e^{st}) would be:

[31] Jan Erik Nielsen: "Simple Method for converting Installed Collector Area to Annual Collector Output" - ESTIF technical consultant. <http://www.estif.org/fileadmin/estif/content/press/downloads/3-Nielsen-m2-kwh-webinar.pdf >

[32] http://www.ecoinnova.com/fileadmin/user_upload/content/downloads/pdf/ECO_FICHAS_SOLVIS_MAX_FUTURA.pdf, http://www.ecoinnova.com/fileadmin/user_upload/content/downloads/pdf/ES_SolvisIntegral_TechnischeInformation.pdf >

$$\rho_e{}^{st} = C_{instal} \cdot \chi_{collector} \cdot (1 - P) = 700 \cdot 0.095 \cdot (1 - 0.37) \cong 42\ \frac{W_{th}}{m^2} \qquad \textit{eq. 17}$$

We obtain 42 W_{th}/m^2, which is in the range of 30-100 W_{th}/m^2 given by (Smil, 2015).

It is important to realize that this number is a yearly average: while during summer, the captured energy will be much greater with lower losses, in winter both factors change their sign (and coinciding with the period of higher demand of the resource). For example, (Trainer, 2010) found a wide range highly dependant on the latitude between 18-25 Wth/m2 for solar termal in winter.

If we perform an aproximative calculation about the losses in the deposit in “summer” and “winter”:

- «summer » (Tnight=10 ºC) : 1e5 * 4,18 * (60-T) = 2,5 * (60 - 10) * 10 * 3600 → T = 49 ºC. **Losses = 18%.**
- « winter » (Tnight=-10 ºC) : 1e5 * 4,18 * (60-T) = 2,5 * (60 + 10) * 14 * 3600 → T = 39 ºC. **Losses = 36%**.

In order to estímate the techno-sustainable potential of the solar thermal we need to estimate the surface that might be covered by solar collectors. Due to the thermal losses, this power will be installed close to the consumption points, compiting in many cases with PV panels, mainly in rooftop locations. Due to its higher energy density and profitability, is probable that it will displace PV from the rooftop locations to on-land sites where larger power centrals are also economically more attractive. Estimations of current urbanized land range 200 – 400 Mha (de Castro et al., 2013b).

Most of the literature focuses on the potential share of rooftop available to install solar panels in relation to the built area ranging between 30-50%. However, when computing the area available in relation to the total urbanized area the share falls to below 2% (de Castro et al., 2013b; La Gennusa et al., 2011).[33] This potential might be higher if including other locations such as facades, along roads, etc. Moreover, current buildings are not designed to host solar panels, so in the future, the potential might increase although still subject to substantial inertias. We asume that due to the combined effects of the scarcity of appropiate rooftop locations and the better technical performance of termal solar collectors, the rooftop potential will be shared in a 75-25% ratio with the PV panels. Considering these factors, the solar thermal potential (year average) for 200 MHa would be around 1 TW_{th} see eq. (18):

$$P_{th}{}^{st} = 200\ \text{Mha} \cdot 1e10 \cdot \left(1.5\% \cdot \frac{3}{4}\right) \cdot 700 \cdot 9.5\% \cdot (1 - 0.37) = 0.95\ TW_{th} \qquad \textit{eq. 18}$$

The range of global urbanized area (200-400 Mha) would translate into a potential of ~1-2 TW_{th}.

Thus, the PV potential range in urban rooftops considering its likely future range (2.5-5 W_e/m2) would be almost negligible:

- Low bound: $P_e{}^{PV} = 200\ \text{Mha} \cdot 1e10 \cdot \left(1.5\% \cdot \frac{1}{4}\right) \cdot 2.5 = 0.02\ TW_e$ *eq. 19*
- High bound: $P_e{}^{PV} = 200\ \text{Mha} \cdot 1e10 \cdot \left(1.5\% \cdot \frac{1}{4}\right) \cdot 5 = 0.04\ TW_e$ *eq. 20*

Since this is a technical potential, socioeconomic factors will tend to reduce it. For example, it is very unlikely that the 2,500 million people currently using traditional biomass, often in poor and undeveloped conditions (WEO, 2010) begin to install these systems massively. Also, material constraints might be relevant at higher scales. For example, copper availability might limit future production since at a rate of around 2 kg/m^2, the achievement of the full technical potential may require around over 20% of the current copper reserves (950 million tonnes). Future great efficiency improvements are not expected since current collectors are very optimized; their low efficiency value (9.5%) is more related to factors dependent on the use of the installation. So, as a first approximation we will consider that a realistic, feasible potential in the next decades could be around half of the middle of the estimated technical potential range by half, thus around 0.7 W_{th}.

33 (La Gennusa et al., 2011) finds a 14% potential in relation to the built area.

D. Feedback energy scarcity-GDP: Socio-economy adaptation to supply constraints in scenarios C and D

The modeling of the socio-economy adaptation to the supply constraints follows the approach applied in (Capellán-Pérez et al., 2015) (scenarios C and D), which does not intend to be a general representation of the role of energy in the economy, and it is closely related to the specific storyline of the each scenario. 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:

$$I^{t}{}_{transp} = a_{transp} \cdot I^{t-1}{}_{transp} \qquad \textit{eq. 21}$$

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

$$\Delta GDP^{t}{}_{pc} = \frac{GDP^{t}{}_{pc}}{GDP^{t-1}{}_{pc}} = \frac{1}{a_{transp}} \cdot \frac{Pop^{t-1}}{Pop^{t}} \cdot \frac{E_{transp}{}^{t}}{E_{transp}{}^{t-1}} \cdot \frac{1}{K} \qquad \textit{eq. 22}$$

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

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