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Universidad del País Vasco
Euskal Herriko Unibertsitatea

Facultad de Economía y Empresa

Departamento de Fundamentos del Análisis Económico I

DEVELOPMENT AND APPLICATION OF ENVIRONMENTAL INTEGRATED ASSESSMENT MODELLING TOWARDS SUSTAINABILITY

A thesis submitted by IÑIGO CAPELLÁN PÉREZ

for the degree of Doctor of Philosophy in Economics in

the University of the Basque Country (Spain)

Bilbao, June 2016

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Publications based on this PhD thesis

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Abstract

The scale of human activities has reached globally such a size that is increasingly affecting the regular functioning of the Biosphere and critically threatening its equilibrium: during the last few decades, human actions have become the main driver of global environmental change. The design of effective policies to rectify current trends critically depends on our ability to understand the complex interactions between the environment and the society. In this context, Environmental Integrated Assessment Models (IAMs) constitute a powerful tool integrating multiple disciplines and dimensions to shed light on potential sustainability pathways. In particular, IAMs of Climate Change are considered one of the best tools for the implicit evaluation of the planetary and social boundaries. This PhD thesis aims at developing and applying these tools to investigate the risks and opportunities of potential sustainable pathways, and to gain a better understanding of how a transition to a low carbon economy can be achieved.

The field of IA Modelling of Climate Change is reviewed, assessing its past evolution and providing a thorough classification of the existing IAMs along seven axes that illustrates the diversity of modelling approaches and assumptions: policy-evaluation vs. policy-optimization; top-down vs. bottom-up; highly-aggregated vs. higher-resolution; regarding the level of integration among subsystems; deterministic vs. stochastic, equilibrium vs. disequilibrium and standard vs. biophysical economics models. Recent developments of the field are being directed towards increasing the interactions within the represented subsystems, as well as expanding the models to represent other Biosphere processes. Yet, many uncertainties and some controversy about the usefulness of these models exist in the scientific discussion.

Two modelling frameworks have been applied in this thesis: a state–of-the-art model (GCAM) and a new biophysical model (WoLiM). On the one hand, GCAM is a high resolution bottom-up IAM model that has been applied to produce emissions scenarios in all the Intergovernmental Panel on Climate Change (IPCC) reports to date. On the other hand, WoLiM takes a biophysical approach focusing on basic thermodynamic principles to analyze the economic process, inheriting from the Complex Systems that concentrate on the dynamic interrelation between its elements. Both models have not only different structures, but also different aims. This diversity has allowed us approaching a variety of issues, as well as exploring the same issue from different perspectives.

Both models have been applied to shed light on two current debates in the literature: (1) the implications of the uncertainty of fossil fuel resources availability and geological constraints for climate, energy and socioeconomic pathways, and (2) the implications of different post-Paris (December 2015) international climate policy regimes in terms of climate change and terrestrial and industrial carbon leakage.

In relation to the availability of fossil fuel resources, the obtained results considering the range of remaining ultimately recoverable resources (RURRs) for fossil fuels in the literature show that potential future constraints to their extraction would not solve the climate change challenge. In terms of temperature increase the probability of surpassing the 2°C from pre-industrial levels by 2100 reaches almost 90% for baseline scenarios (i.e. scenarios with no additional climate policy). However, the likely depletion of fossil fuels during the 21st century drives the transition to renewable energy sources faster than expected by current models. As a consequence, the cost of the future energy systems increases substantially, which in turn translates into lower mitigation efforts to stabilise the climate by 2100.

The integration of flow limitations from geological constraints with the RURR estimates for fossil fuels in combination with the simulation of the common socioeconomic scenarios considered in Global Environmental Assessments (GEAs) to 2050, allows to explore the challenges and opportunities of global energy transition pathways. According to our results, the future extraction of fossil resources reaches a plateau at around 500-525 EJ/year of maximum extraction in 2020-2035 and declines thereafter. The total primary energy supply can be stabilized or even grow in some scenarios to 2050, but the growth trends shown in the past cannot be maintained. This is due to the fact that fossil fuels depletion can only be partially compensated by unconventional fuels extraction, alternative technologies and efficiency improvements. Transport is the most critical sector due to its current dependency on liquid fuels. The obtained results indicate that a significant systemic energy-scarcity risk exists: global demand-driven evolution of fuel extraction seen in the past might be unfeasible in the future. Overcoming the potential fall in fossil energy availability would thus require structural changes in the economy combined with social and behavioural changes. Hence, anticipatory strategies should be urgently implemented.

In relation to the implications of different international climate policy fragmentation scenarios in terms of climate change and terrestrial and industrial carbon leakage, the results show that, even in the more optimistic scenarios where only Russia, the Middle East and Africa do not participate in the international climate regime, coordinated climate action of most of the countries would only have the capability of limiting the temperature rise to around 2.5 ºC by the end of the century. Moreover, the results show that terrestrial carbon leakage may be the dominant type of leakage by 2050. In fact, afforestation in participating regions occurs at the expense of massive deforestation in non-participating regions, where substantial amounts of food and bioenergy production are shifted. The results show that, the higher the mitigation target, the greater the increase in the global price of food due to the intensification of land competition driven by the substantial deployment of land-based climate mitigation options such as afforestation or bioenergy crops. In the scenarios considered, food prices increase between 3 and 7 times by 2100 in relation to the baseline. Under these circumstances, food security and biodiversity conservation might be at risk in some countries. These results are essential to the design of effective climate policies under climate fragmentation scenarios such as the Intended National Determined Contributions after the Paris Agreement.

Finally, since there is a large discrepancy between natural scientists' understanding of ecological feedbacks and the representation of environmental damages in IAMs, the thesis concludes with some final remarks and suggestions to advance in modelling towards sustainability. In particular, four key features are proposed: (i) adoption of a precautionary principle approach, (ii) emphasis on feedbacks between the processes and subsystems, (iii) consideration of the relevant planetary and social boundaries, (iv) enhancement of the credibility and legitimacy of the models by improving the documentation and transparency of the tools. In fact, to properly assess the risks of environmental unsustainability, IAMs should be able to simulate potential collapse pathways of human societies, especially in baseline scenarios. Thus, the main objective of sustainability analyses should be directed to detect the conditions to reach the equilibrium.

Resumen de la tesis:

Desarrollo y Aplicación de Modelos Ambientales de Evaluación Integrada para la Sostenibilidad

Las actividades humanas han alcanzado tal magnitud que están afectando cada vez más al funcionamiento natural de la Biosfera y amenazando su equilibrio: en las últimas décadas, los humanos nos hemos convertido en los causantes del cambio ambiental global. El diseño de políticas efectivas para rectificar las tendencias actuales depende de nuestra habilidad para entender las complejas relaciones entre el medio ambiente y la sociedad. En este contexto, los Modelos (Ambientales) de Evaluación Integrada (MEIs) constituyen una potente herramienta que integra diferentes disciplinas y dimensiones para informar en la toma de decisiones hacia la sostenibilidad.

Esta tesis examina el campo de los MEIs de cambio climático, repasando su evolución y proponiendo una clasificación de los modelos existentes en torno a siete ejes que muestra la diversidad de los enfoques de modelado en la literatura: de evaluación de políticas vs. de optimización de políticas; *bottom-up* vs. *top-down*; gran agregación vs. alta resolución; en relación al nivel de integración entre subsistemas; determinísticos vs. estocásticos; de equilibrio vs. de desequilibrio y de economía estándar vs. economía biofísica. Los desarrollos actuales están enfocados a incrementar las interacciones entre los subsistemas de los modelos, así como a expandir los modelos para integrar otros procesos de la Biosfera. A pesar de los progresos realizados durante las últimas tres décadas, importante incertidumbres permanecen, y existe debate en la comunidad científica en relación a la utilidad de los modelos actuales.

En esta tesis se han aplicado dos MEIs: el GCAM y el WoLiM. Por un lado, el GCAM es un modelo *bottom-up* de alta resolución que ha sido desarrollado durante los últimos treinta años y ha sido utilizado en todos los informes del Panel Intergubernamental del Cambio Climático (IPCC) hasta la fecha. Por otro lado, el WoLiM es un modelo de tipo biofísico desarrollado en el marco de esta tesis en dinámica de sistemas, un método para modelar Sistemas Complejos que presta particular atención a las interacciones entre los subsistemas. Ambos modelos tienen no solo diferente estructura, sino diferentes objetivos. Así, esta diversidad ha permitido analizar diversos temas, así como estudiar el mismo tema desde perspectivas diferentes.

Ambos modelos han sido aplicados a dos debates científicos candentes: (1) las implicaciones de la incertidumbre en la disponibilidad futura de los recursos energéticos fósiles para la futura evolución de los sistemas energéticos, el clima y la sociedad, y (2) las implicaciones de diferentes coaliciones climáticas en el contexto de los acuerdos de París (Diciembre de 2015) para el clima y la fuga de carbono de origen industrial y terrestre.

En relación a la disponibilidad de los recursos energéticos fósiles, los resultados obtenidos considerando el rango de recursos recuperables restantes (*remaining ultimately recoverable resources*, RURRs) en la literatura muestran que potenciales límites a su extracción futura no resolverían por sí solos el problema del cambio climático. Así, la probabilidad de que el incremento de temperatura a final de siglo supere la barrera de los 2ºC en relación a los niveles pre-industriales alcanzaría prácticamente el 90% en los escenarios de referencia (i.e. aquellos en los que no se implementan políticas climáticas adicionales a las existentes actualmente). Por otro lado, los resultados sugieran el probable agotamiento de estos recursos fósiles durante este siglo, induciéndose la transición a las energías renovables mucho antes que lo estimado por la mayoría de modelos. Esta transición implicaría mayores costes del sistema energético debido a las características biofísicas de las energías renovables, lo que se traduciría en una reducción de los costes de mitigación.

La integración de las restricciones geológicas a los flujos de extracción junto con las limitaciones a los stocks (i.e. RURRs) de los recursos fósiles en el contexto de los escenarios socioeconómicos considerados usualmente en los informes de Evaluaciones Ambientales Globales (GEAs), permite explorar los riesgos y oportunidades de la transición energética en el futuro. De acuerdo con nuestros resultados, la extracción de recursos fósiles alcanzará entre 2020 y 2035 una meseta de producción de entorno a 500-525 EJ al año, declinando a partir de entonces. La extracción de energía primaria total puede estabilizarse o incluso crecer en algunos escenarios hasta 2050, pero el nivel de crecimiento del pasado no puede mantenerse. Esto se debe al hecho de que la reducción en la extracción de recursos fósiles provocada por su agotamiento sólo puede ser compensada parcialmente por la contribución de los recursos no convencionales, el uso de nuevas tecnologías y las mejoras en eficiencia. El sector del transporte es el más afectado debido a su casi total dependencia actual de los combustibles líquidos. Los resultados obtenidos sugieren que existe el riesgo de escasez energética en las próximas décadas, y la importancia de incluir las limitaciones en la extracción de los recursos en el diseño de la transición energética. Superar el progresivo declive de los recursos fósiles requeriría profundos cambios estructurales en la economía combinado con importantes cambios sociales y de comportamiento. Así, es urgente la implementación de estrategias de anticipación.

En relación a las implicaciones de diferentes coaliciones climáticas para el clima y la fuga de carbono de origen industrial y terrestre, los resultados muestran que, incluso en el más optimista de los escenarios en el que tan sólo Rusia, Medio Oriente y África no participan en la coalición climática, la temperatura todavía aumentaría hasta alcanzar los 2.5ºC al final del siglo. Por otro lado, el análisis realizado en la tesis muestra que la fuga de carbono de origen terrestre podría ser el tipo dominante de fuga de carbono hacia 2050, debido a la deforestación masiva inducida en los países no participantes. Así, la reforestación producida en los países participantes provoca el desplazamiento de grandes superficies de cultivos agrícolas y de biomasa hacia los países no participantes. De hecho, cuanto más ambicioso es el objetivo de mitigación, más se incrementa el precio de la comida a nivel global debido a la competición en los usos de la tierra causado por el gran despliegue de opciones de mitigación de emisiones como la reforestación y biomasa. En los escenarios considerados, el precio de los alimentos se incrementa entre 3 y 7 veces hacia el final del siglo en relación al escenario de referencia. En estas circunstancias, la seguridad alimentaria y la conservación de la biodiversidad estaría amenazadas en muchos países. Los resultados obtenidos en este análisis son fundamentales para el diseño de políticas climáticas como las contribuciones previstas y determinadas a nivel nacional (INDCs) tras el Acuerdo de París.

Finalmente, puesto que actualmente existe una gran discrepancia entre la importancia de la degradación de los procesos ecológicos y del medio ambiente, y su representación limitada en los MEIs, esta tesis concluye con algunos comentarios y sugerencias para avanzar en el modelado hacia la sostenibilidad. En particular, se proponen cuatro condiciones fundamentales: (i) adopción del principio de precaución; (ii) énfasis en la representación de realimentaciones entre los subsistemas; (iii) consideración de las limitaciones planetarias y sociales relevantes; (iv) incremento de la credibilidad y la legitimidad de los modelos mediante la mejora de su documentación y transparencia. De hecho, para evaluar adecuadamente los riesgos relacionados con la insostenibilidad, los MEIs deberían de ser capaces de reproducir potenciales escenarios de colapso de las sociedades humanas, especialmente en los escenarios de referencia. Así, el estudio de las condiciones para alcanzar el equilibrio deberían de situarse en el centro de los análisis de sostenibilidad.

Abbreviations and acronyms

- ABM: Agent-based modelling
- AEI: Annual efficiency improvements
- AOGCM: Atmosphere-Ocean General Circulation Model
- ASPO: Association for the Study of Peak-Oil
- BAU: Business-as-usual
- BGR: German Federal Institute for Geosciences and Natural Resources
- BRICS: Brazil, Russia, India, China, South Africa
- BU: Bottom-up
- CCS: Carbon capture and storage
- CSP: Concentrating solar power
- CTL: Coal-to-liquids
- E^3: Energy-Economy-Environment
- ECDF: Empirical cumulative distribution function
- ECS: Equilibrium climate sensitivity
- EEA: European Energy Agency
- EROEI: Energy return on energy invested
- ESM: Earth System Model
- EU: European Union
- EV: Electric vehicle
- FFICT: Fowwil fuel and indutry carbon tax
- GCAM: Global Change Assessment Model
- GCM: Global Circulation Model
- GDP: Gross domestic product
- GEA: Global Environmental Assessment
- GEA: Global Energy Assessment (2012)
- GHG: Greenhouse gases
- GTL: Gas-to-liquids
- HEV: Hybrid electric vehicle
- IA: Integrated Assessment
- IAM: Integrated Assessment Model
- IAV: Impacts, Adaptation and Vulnerability
- IB: Industry and Buildings
- ICE: Internal combustion engines
- ICL: Industrial carbon leakage
- IEA: International Energy Agency
- ILUC: Indirect land use changes
- IMF: International Monetary Fund
- INDC: Intended Nationally Determined Contribution
- IPCC: Intergovernmental Panel on Climate Change
- IPCC SRES: Special Report on Emissions Scenarios (2000)
- IPCC-AR4: IPCC Fourth Assessment Report (2007)
- IPCC-AR5: IPCC Fifth Assessment Report (2014)
- IPCC-FAR: IPCC First Assessment Report (1990)

- IPCC-SAR: IPCC Second Assessment Report (1992)
- IPCC-TAR: IPCC Third Assessment Report (2001)
- LtG: "Limits to Growth" report
- MEA: Millenium Ecosystem Assessment (2005)
- MSW: Municipal solid waste
- NGV: Natural gas vehicle
- PE: Primary energy
- PP: Precautionary Principle
- ppm: parts per million
- PV: Photovoltaic
- R&D: Research and development
- RCP: Radiative concentration Pathway
- RURR: Remaining ultimately recoverable resources
- SD: System Dynamics
- SRC: Standardized regression coefficient
- TCL: Terrestrial carbon leakage
- TD: Top-down
- TPES: Total primary energy supply
- TRF: Total radiative forcing
- UCT: Universal carbon tax
- UN: United Nations
- UNFCCC: United Nations Framework Convention on Climate Change
- URR: Ultimatey recoverable resources
- US EIA: US Energy Information Administration
- USGS: US Geological Survey
- WEC: Worle Energy Council
- WoLiM: World Limits Model

Units

- EJ: Exajoule (10^{18} joules)
- Gb or Gboe: Gigabarrel of oil equivalent (10^{9} barrels)
- Gt: Gigatonnes
- GtC: Gigatonnes of carbon
- Mha: Megahectare (10^{6} hectares, 10 thous. km^{2})
- Mtoe: Megatonnes of oil equivalent (10^{6} toe)
- ppm: Parts per million
- TCF: Trillon cubic feet
- TW_e : Electric terawatt (10^{12} W_e)
- ZJ: Zetajoule (10^{21} joules)

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“Mais la science et la technologie ont fini par faire cette découverte capitale: toute activité productive vit des emprunts qu’elle fait aux ressources limitées de la planète et des échanges qu’elle organise à l’intérieur d’un système fragile d’équilibres multiples.”

André Gorz, 1977

“Aunque la energía y la relación con el entorno han sido fundamentales en la historia de la humanidad, […] no determinan el futuro. El entorno físico y biológico y la energía disponible marcan los contextos de la acción humana, pero no la gobiernan. En ocasiones, las sociedades han sido capaces de romper los límites mediante desarrollos tecnológicos u organizativos, mientras que en otros han sido los límites quienes han forzado el devenir humano, bien generando crisis o bien por el acoplamiento social a ellos. En definitiva, son los seres humanos, a través de su organización, quienes definen el curso de la historia dentro de los márgenes de lo posible. Aunque esta definición también es en muchos casos estocástica: ni mucho menos todos los cambios son dirigidos ni conscientes.”

Glz Reyes y Fernández Durán, 2014

“Every person approaches his problems, wherever they occur on the space-time graph, with the help of models. A model is simply an ordered set of assumptions about a complex system.”

Limits to Growth, 1972

“…there is a limit to what we can do with numbers, as there is to what we can do without them.”

Georgescu-Roegen, 1958

PART I: INTRODUCTION AND LITERATURE REVIEW

CHAPTER I

1. Introduction

1.1. Context and motivation

1.1.1. A human-driven global scale environmental crisis

The scale of human activities has reached globally such a size that is increasingly affecting the regular functioning of the Biosphere and critically threatening its equilibrium. During the last few decades, human actions have become the main driver of global environmental change. Almost 25 years ago, some 1,700 of the world's leading scientists, including the majority of Nobel laureates in the sciences, issued the appeal "World Scientists' Warning to Humanity" that stated that:

> *Human beings and the natural world are on a collision course. Human activities inflict harsh and often irreversible damage on the environment and on critical resources. If not checked, many of our current practices put at serious risk the future that we wish for human society and the plant and animal kingdoms, and may so alter the living world that it will be unable to sustain life in the manner that we know. Fundamental changes are urgent if we are to avoid the collision our present course will bring about. […] No more than one or a few decades remain before the chance to avert the threats we now confront will be lost and the prospects for humanity immeasurably diminished*. (UCS, 1992)

During the 1990s, robust scientific evidence corroborated these trends, confirming that the "human alteration of Earth is substantial and growing [...] it is clear that we live on a human dominated planet" (Vitousek et al., 1997). Since then, the main trends have endured in the absence of effective policies and the collision course continues its progress (Rockström et al., 2009; Steffen et al., 2015a, 2015b). The overwhelming evidence of the human alteration of the Biosphere cycles has even lead to the definition of the "Anthropocene" as a distinct geologic era from the Holocene critically determined by human activities (Crutzen, 2002; Steffen et al., 2015a; Third Nobel Laureate Symposium on Global Sustainability, 2011; Waters et al., 2016; Zalasiewicz et al., 2011). In fact, its upgrade to an official geological epoch is currently under scientific discussion. References to non-linearities, thresholds and tipping-points of the Biosphere have become common in the literature (Barnosky et al., 2012; Lenton et al., 2008). As humans, we critically depend on the natural life-support systems and processes to sustain our own existence. By substantially altering and degrading them, we are risking the continuity of our societies as we know them nowadays (Daily, 1997; Levin et al., 2009; Schneider and Morton, 1981). In fact, the statement from the UCS (1992) that "*no more than one or a few decades remain ...*" brings into question to what extent the carrying capacity of the Earth is nowadays exceeded and if the recoverability of many degradated processes and components along the Earth is still possible.

How have we arrived to such a situation?

Since the Industrial Revolution, the exponential growth of both population and economic output have driven a dramatic increase in the use of renewable and non-renewable materials and energy resources, resulting in the disposal of great amounts of waste and pollution. From 1900 to 2010, population has increased from 1.6 to near 7 billion people, economic activity (real Gross Domestic Product, GDP) has risen almost 30-fold in the same period in parallel to the transition from agrarian to industrial regimes in many territories of the globe.[1] The share of population living in urban areas has increased from 25% to more than 50%. This transition has implied also an immense surge in primary energy use (x10-fold in that period), switching from a biomass-dominated economy to the fossil fuel age: nowadays fossil fuels account for around 85% of the global primary energy consumption (Krausmann et al., 2008; Smil, 2008). Renewable energy sources have decreased in share but not in absolute terms. Global biomass extraction has grown from 5Gt to near 20 Gt from 1900 to 2005 (Krausmann et al., 2009) and nowadays there are almost 32,000 large damns around the globe (from below 1,000 in 1900). In the last century, fertilizer consumption has increased 200-fold and water use almost 6 times. Moreover, the phenomenon of globalization has increased international trade flows, thus increasing the requirements of transportation and communications dramatically. Thus, today there are around 1,300 million motor vehicles on the roads and 6.5 billion landlines& subscriptions, compared to below 200 thousand vehicles and no telecommunication landlines at the beginning of the century (Steffen et al., 2015a).

The massive use of materials and non-renewable energies in combination with a very low degree of circularity (i.e. recyclability) of the global economy has translated into two main negative effects: (1) substantial amounts of waste and emission outflows disposed to the environment and (2) an increased degradation, appropriation and

[1] Sociometabolic regimes represent dynamic equilibrium of society–nature interactions and are characterized by typical patterns of material and energy flows (metabolic profiles). This framework complements the economic and technical analysis by focusing on the qualitative and systemic differences between the different metabolic profiles (Krausmann et al., 2008).

destruction of natural stocks and ecosystems. The saturation of the natural capacity of the Biosphere to absorb substances such as carbon dioxide, nitrogen or heavy metals implies their widespread diffusion to the ecosystems (i.e. pollution), potentially altering their functioning and affecting other Biosphere processes. Although technological progress has played an important role in reducing both the resource and pollution intensity of production, it has only allowed, in general, to achieve relative rather than absolute decoupling[2] of production and environmental degradation (Arrow et al., 1995; Stern, 2004). As a consequence, the concentration of many of these pollutants has rocketed. Human activities create almost 4 times more reactive nitrogen than natural processes on continents (Lassaletta et al., 2014). Anthropogenic greenhouse gas (GHG) emissions have enormously increased since the pre-industrial era leading to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last 800,000 years. Carbon dioxide has recently reached a concentration of 400 ppm when levels before the industrial age where around 275 ppm, affecting other ecosystems and processes (e.g. ocean acidification). In fact, changes in many extreme weather and climate events have been observed since about 1950 (IPCC, 2014a). With regard to the destruction, degradation and appropriation of natural stocks and ecosystems, the domesticated land has doubled in the last century reaching 40% of the global emerged land, the tropical forest loss reached almost 30% by 2010 (Steffen et al., 2015a), more than half of all accessible surface fresh water is put to use by humanity (Postel et al., 1996) and the human appropriation of net primary production[3] is around 25% of the global potential (Haberl et al., 2007). The resilience of the ecosystems, i.e. their capacity to respond to a perturbation or disturbance by resisting damage and recovering quickly, is deeply being reduced (Folke et al., 2004). The Millennium Ecosystem Assessment (MEA) found that “to meet rapidly growing demands for food, fresh water, timber, fiber and fuel […] approximately 60% of the ecosystem services examined […] are being degraded or used unsustainably, including fresh water, capture fisheries, air and water purification, and the regulation of regional and local climate, natural hazards, and pests“ and that “human activities have taken the planet to the edge of a massive wave of species extinctions, further threatening our own well-being”. In fact, biologists are suggesting that a sixth mass extinction may be under way (Barnosky et al., 2011). The expression “the Great Acceleration” has become popular to refer to the accelerated trends in both the socioeconomic drivers and the environmental impacts during the last 50 years (MEA, 2005; Steffen et al., 2015a).

Due to the novelty of the research focusing on the Earth processes and characteristics, most of the impacts (natural cycles alteration –carbon, nitrogen, phosphorus, etc.-, biodiversity loss, deforestation, etc.) have been to date studied separately due to the need to develop distinct new methodologies for each. Although the inventory of impacts

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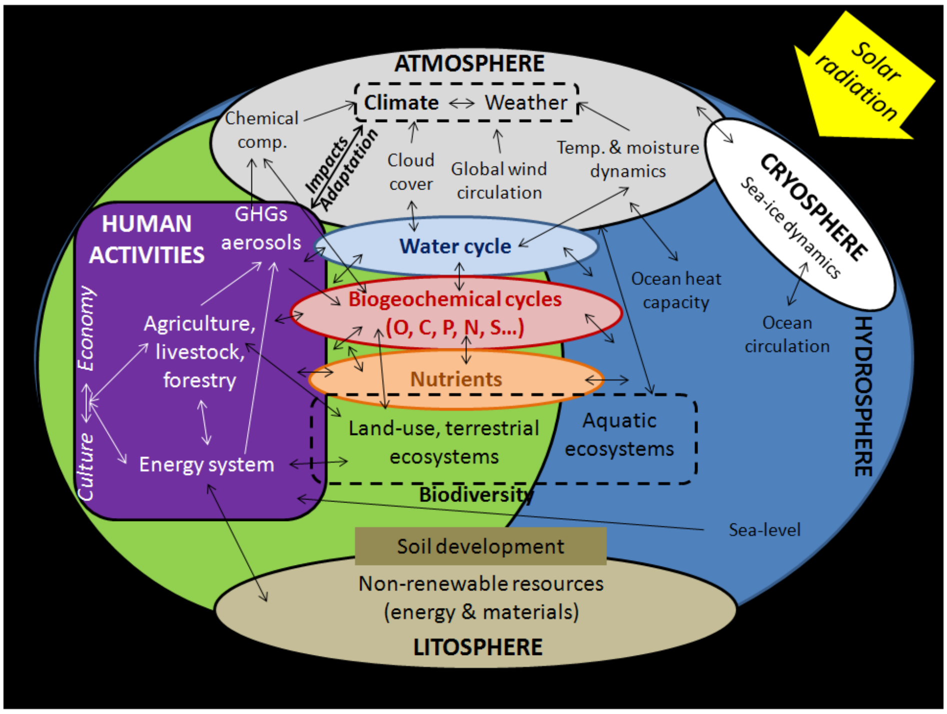
[2] Decoupling means reducing the amount of natural resources such as water or fossil fuels used to produce economic growth and delinking economic development from environmental deterioration. Relative decoupling refers to using less resources per unit of economic output, while absolute decoupling refers to reducing the amount of resources used (UNEP, 2011a).

[3] The human appropriation of net primary production refers to the human alterations of photosynthetic production in ecosystems and the harvest of products of photosynthesis (Haberl et al., 2007).

is useful to apprehend the influence of human actions in the planet, a step further is required to interrelate these independently studied processes with the dynamics taking action in the Biosphere system and to assess their full implications. The Biosphere can be understood as a Complex System. These systems are composed of many elements that have diversity, individuality and individual interrelations with each other, but are also influenced by the system itself. In fact, a system is a functional aggregate with properties that cannot be deduced from the independent analysis of its elements (Auyang, 1999). The Biosphere can be defined as the global ecological system integrating all living beings and their relationships, including their interaction with the elements of the lithosphere, geosphere, hydrosphere and atmosphere (see Figure 1.1). A tightly-coupled system, largely self-regulating, emerges with many interdependent cycles: water, biogeochemical (oxygen, carbon, phosphorus, nitrogen, sulphur, etc.), nutrients, etc. in a multi-scale environment (from microscopic to ecosystem, from regional to global) that ultimately determines biodiversity, soil development, precipitations, climate, etc. (Bolin et al., 1983; Levin et al., 2009):

> *Climate and life are linked by a complex web of interconnected cycles. Life on earth depends on the cycling of nutrients through air, water, soil, and living things. The climate mediates the flow of materials through these global cycles. Solar energy degrades to heat at each stage of the cycling process and is eventually returned to space as infrared radiation. The composition of the earth's atmosphere regulates the radiative balance on earth between absorbed solar energy and emitted infrared energy, which, in turn, controls the climate.* (Alexander et al., 1997)

Figure 1.1: Schematic representation of the interrelated Biosphere processes



Source: own work.

The design of effective policies critically depends on the ability to disentangle these relationships. Thus, taking a holistic approach allows tackling the crucial questions for effectively addressing sustainability since global environmental change occurs as a number of interacting components alter the structure and function of Earth as a system. What is the scale of human pressures in relation to the Biosphere? What is the disruption potential of human activities? Are there any key cycles? Are some of them more resilient to external impacts?; in other words, is the Biosphere's stability more dependent on some cycles over others? Are there any safe boundaries that should not be trespassed? What would be, in turn, the implications for the societies along the planet of a potential imbalance of the Biosphere?

Fortunately, there is currently a notable interdisciplinary research effort to shed light on these directions by combining the observable impacts of the rapid increase in human pressures on the planet with the emergence of global environmental change and Earth System-thinking (Rockström et al., 2009).

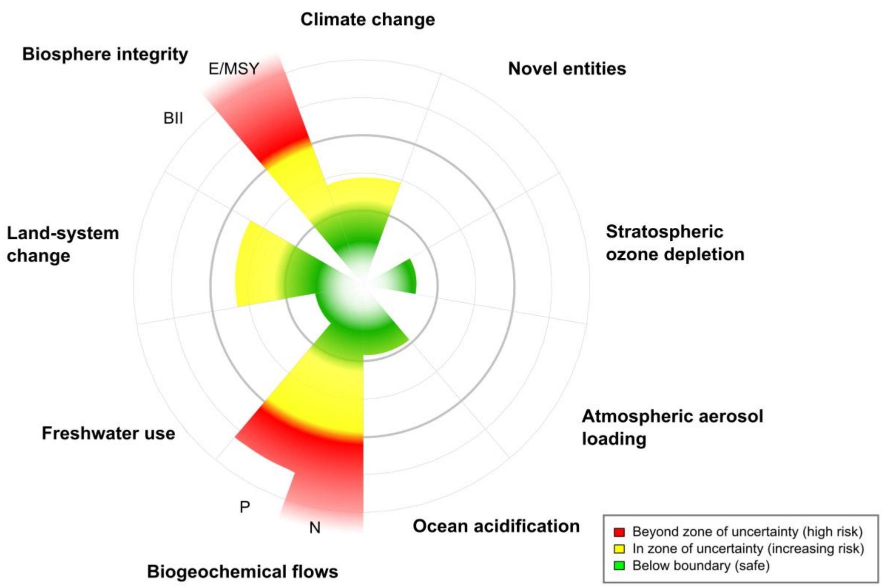
An approach to assess the scale of human pressures is to build aggregate indicators that try to capture the idea that the Biosphere is ultimately one macro-ecosystem. One popular example is the Ecological Footprint, defined as "the area of productive land and water ecosystems required to produce the resources that the population consumes and assimilate the wastes that the population produces, wherever on Earth the land and water is located" (Wackernagel et al., 2002; Wackernagel and Rees, 1996). Despite its limitations, it is a concept that can qualitatively illustrate the human pressure on nature over time. For example, it has been assessed that the global ecological footprint surpassed the global biocapacity ratio[4] in the 1970s, which since then is being depleted (the global ecological footprint is assessed to be over 150%) (GFN, 2015).

But the aggregated approach does not properly allow confronting most of the critical questions raised, and alternative approaches that recognize the incommensurability of Earth processes are required. Additionally, the components of ecosystems may vary considerably in their resilience (Cumming et al., 2005). The Planetary Boundaries framework, for example, is a prominent research initiative aiming at defining a safe operating space for humanity based on the major intrinsic biophysical processes that regulate the stability of the Earth System. A planetary boundary refers to a specific point related to a global-scale environmental process beyond which humanity should not go in order to prevent disastrous consequences. The concept of planetary boundary should not be confounded with that of a tipping point, which commonly refers to critical thresholds at which a tiny perturbation can qualitatively alter the state or development of a system (Folke et al., 2004; Lenton et al., 2008). This buffer between the boundary (the end of the safe operating space—the green zone in Figure 1.2) and the threshold (i.e. the estimated tipping point) accounts not only for uncertainty in the precise position of the threshold with respect to the control variable, but also allows

[4] The biocapacity is an indicator of the available biological resource measuring the biological production in an area. It is an aggregate of the production of various ecosystems within the area, e.g. arable, pasture, forest, productive, etc. (Wackernagel and Rees, 1996).

society time to react to early warning signs that it may be approaching a threshold and consequent abrupt or risky change (both must be dynamically assessed since prolonged environmental degradation will likely translate into resilience reduction). Respecting these boundaries would greatly reduce the risk that anthropogenic activities could inadvertently drive the Earth System to a much less hospitable state. This holistic framework consistently selects and integrates those processes that are critical from the point of view of the Earth System (Rockström et al., 2009). Environmental footprints measure how much of the available capacity within the planetary boundaries is already consumed (Hoekstra and Wiedmann, 2014). The revised and updated analysis has come up with nine planetary boundaries: biosphere integrity (considering both genetic and functional diversity), climate change, novel entities, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biogeochemical flows (phosphorus and nitrogen), freshwater use and land-system change (Steffen et al., 2015b). As it can be seen in Figure 1.2, two of them could not be evaluated (novel entities and atmospheric aerosol loading) due to current knowledge gaps. From the remaining, it is estimated that two processes have already surpassed their planetary boundary (genetic diversity and biogeochemical flows), whereas two have been identified as currently lying in the uncertainty zone (climate change and land-use system change). This assessment is far from reassuring: although these planetary boundaries are described in terms of individual quantities and separate processes, they are in fact tightly coupled in the Biosphere non-linear system through multiple regional processes (Hibbard and Janetos, 2013; Rockström et al., 2009).

Figure 1.2: The current status of the control variables for seven of the nine planetary boundaries



Notes: Green zone is the safe operating space (below the boundary), yellow represents the zone of uncertainty (increasing risk), and red is the high-risk zone. The planetary boundary itself lies at the inner heavy circle. E/MSY: extinctions per million species-years; BII: Biodiversity Intactness Index.

Source: (Steffen et al., 2015b). Reprinted with permission from AAAS.

Recent findings are suggesting the existence of a two-level hierarchy in Biosphere processes. Hence, climate change and biosphere integrity have been identified as core planetary boundaries through which the other boundaries operate.[5] Both function at the level of the whole Earth System and have co-evolved for nearly 4 billion years and they are regulated by the other boundaries, simultaneously providing the planetary-level overarching systems within which the other boundary processes operate. In fact, transitions between time periods in Earth history have often been delineated by significant shifts in climate, the biosphere, or both. Both "core boundaries" have each the potential on their own to drive the Earth System into a new state should they be substantially and persistently transgressed. The crossing of one or more of all of the other boundaries may seriously affect human wellbeing, and may predispose the transgression of a core boundary(ies), but does not by itself lead to a new state of the Earth System. In their update of the Intergovernmental Panel on Climate Change (IPCC) "reasons for concern", Smith et al., (2009) conclude that the risks of large-scale discontinuities (i.e. tipping points) become significant for even modest levels of global warming (~2.5 °C).[6] In fact, continued emissions of GHGs are expected to cause further warming (+3.7°C to 4.8°C above the average for 1850–1900 for a median climate response in considering no additional policies) and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts to the rest of the Biosphere (heat waves, extreme precipitation events, ocean acidification, sea level rise, etc) (IPCC, 2014a).

1.1.2. In the quest of sustainable pathways: integrating planetary and social boundaries

In the light of the information presented in the previous section, a radical transformation of human activities during the next century is required to avoid dangerous disruptions of the Biosphere. The objective would be to trigger a dynamic process that would lead societies to reach a *sustainable* state in the future. However, a great diversity of definitions for *sustainability* can be found in the literature,[7] which critically affects the operationalization of the concept.

Since we are ultimately concerned with the sustainability of the human societies within the Biosphere, most definitions of the sustainability concept have to do with: (i) living within the limits, (ii) understanding the economy-society-environment interconnections

---

[5] However, scientific debate is ongoing. For example, the MEA stated that "land use changes are perhaps the most critical aspect of anthropogenic global change in influencing the future of ecosystems and their services", while recognizing that other global changes such as climate change and biodiversity loss may produce indirect effects on future ecosystem services with superimposed effects on land use changes (MEA, 2005). See for example Jones et al., (2013a, 2013b) for an analysis of the interactions between global climate change and land-use shifts.

[6] Nine potential 'tipping elements' in the climate system have been identified that could pass a tipping point this century (Lenton et al., 2008). See also Barnosky et al., (2012) for a discussion on planetary-scale tipping points.

[7] Already Pezzey (1992) mentions "dozens of definitions of sustainable development" and the EEA (1997) identified 300 interpretations.

and (iii) and an equitable distribution of resources and opportunities (both spatially and intergenerationally). For example, the Third Nobel Laureate Symposium on Global Sustainability (2011) concluded that "environmental sustainability is a precondition for poverty eradication, economic development, and social justice". Moreover, the study of past civilizations has shown that equality is a central element of a stable and sustainable future (Diamond, 2005; Motesharrei et al., 2014). Unfortunately, most economies around the globe are currently characterised by enduring poverty and socioeconomic inequality. Thus, almost 900 million people (12.5% the global population) were estimated to be chronically undernourished in 2010-12 (FAO, 2012) and the proportion of people living on extreme poverty in 2008 was 24% (around 1.5 billions) according to World's Bank estimates (WB, 2012).

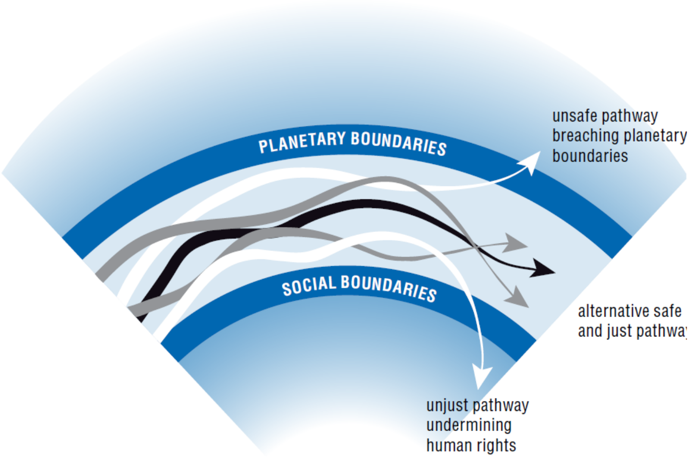
The most popular and influential definition of sustainability was included in the Brundtland report (1987) of the United Nations (UN):

> *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:*
>
> - *the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and*
> - *the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs."* (Brundtland et al., 1987, p. 36)

The original definition was deliberately general to be as much inclusive as possible. However, as a trade-off, the sustainable concept is subject to multiple interpretations (and even distortions). Pearce et al., (1989) analysed the differences in the development of the concept, noting that in some cases the ideas developed had nothing to do with sustainability. A report by the European Environmental Agency concluded that these definitions are in fact "the products of conflicting worldviews, differing ideologies, varied disciplinary backgrounds, opposing knowledge traditions, value systems and vested interests" (EEA, 1997).

Translating the planetary boundaries framework to social systems, it could be argued that "human well-being also depends upon each person having access to the resources needed to meet their human rights, such as food, water, health and energy. Just as there are planetary boundaries beyond which lies environmental degradation that is dangerous for humanity, so too there are social boundaries below which lie resource deprivations that endanger human well-being" (Leach et al., 2013). The combination of the inner limits of social boundaries and the outer limits of planetary boundaries creates a sustainable space within which all humanity can prosper by pursuing a range of possible sustainable pathways (see Figure 1.3).

Figure 1.3: Possibilities within the safe and just space



Source: (Leach et al., 2013).

Research with Complex Systems proved that the achievement of sustainable pathways in the presence of erodible limits (e.g. carrying capacity, planetary boundaries, etc.) critically depends on the delays in society's responses to eventually approaching these limits (which are in turn dependent on the correct and timely flow of information to the potential policy-changers). Different modes of approaching to the limits can then emerge: smooth approach to equilibrium; overshoot and oscillation; and overshoot and collapse. The last mode represents an unsustainable pathway that may occur when society does not prepare sufficiently well for the future and the erodible resource base gets destroyed during overshoot (e.g. (Meadows et al., 2004)).

1.1.3. Modelling sustainability

The required changes to achieve sustainable pathways face multiple technological, economical, historical and cultural barriers and inertias. Moreover, there is a substantial heterogeneity among socioeconomic systems. We can broadly distinguish three groups of territories: the advanced industrial economies that fully participate in the globally integrated markets of goods, services, finances and labour (i.e. North-America, Europe and Japan), territories of the world that are still mostly isolated from other economies and maintain an agrarian economy; and territories that are in an intermediate position (e.g. BRICS countries[8]). In this sense, the Rio Declaration stated that "in view of the different contributions to global environmental degradation, States have common but differentiated responsibilities" (UN, 1992). The notion of responsibility is being increasingly shaded nowadays by means of the intensification of international trade that expands the differences between territorial and consumption-based responsibilities (e.g. carbon, energy, land, water, nitrogen, etc. footprints (Arto et al., 2016; Hoekstra and Mekonnen, 2012; Hoekstra and Wiedmann, 2014; Lassaletta et al., 2014; Peters et

[8] BRICS is the acronym for an association of five major emerging national economies: Brazil, Russia, India, China and South Africa. They are developing or newly industrialised countries characterized by their large, fast-growing economies and significant geopolitical influence.

al., 2011)). Due to the fact that, although the safe boundaries are planetary the implementation of policies is done within political jurisdictions, and given that there is no global government a certain level of international coordination must be guaranteed to ensure effective policies at a global level. Regional processes and phenomena should be an integral part of the global change research agenda (Hibbard and Janetos, 2013). In this sense, Global Environmental Assessments (GEAs) have become a key instrument to inform policy-makers on global environmental and sustainability problems, both with respect to their importance and possible response options (van Vuuren et al., 2012b). In the case of climate change, for example, there has been a shift in the international climate negotiations from the initial top-down strategy from the Kyoto Protocol (cap&trade with emission reductions only for developed countries) to a more bottom-up process where each country makes its emission reduction proposal (i.e. Intended Nationally Determined Contributions at Paris Agreement) (Fawcett et al., 2015).

Thus, compounded approaches combining both social and physical sciences are extremely necessary and urgent. However, the integration of disciplines of these two families is specially challenging given that there has been a historical gap between them in relation to environmental modelling (e.g. (Bardi, 2011; Cumming et al., 2005; Lenton and Ciscar, 2013)). Scientific research is just one aspect of the challenge, which must be complemented by an effective communication of the results to the concerned stakeholders.[9].

Models are a simplified representation of reality. A perfect replica of reality would be of no-practical-use anyway, since the goal of creating a model is to focus on a manageable set of aspects of reality that are key to answer some specific questions. Thus, one must always keep in mind the limitations of the model and be aware of all the questions it does not answer (Sterman, 1991). When properly explained and documented, formal models allow the justification of transparent recommendations, avoiding the use of mental models which can be biased by many non-explicit factors such as ignorance, prejudices and captured-interests. Formal models allow also to productively engage in a dialogue with other approaches to improve the understanding of the studied topic:

> *Mental models are the abstractions carried in minds. They are not directly accessible by others; they are informal. Formal models exist in a form that can be directly viewed, and sometimes manipulated, by others. The two should ideally interact. Using formal models, we can learn more about reality and about others' mental models. And that enriches our own mental models. As we learn, we are able to create more useful formal models*. (Meadows et al., 2004)

[9] Additionally, the effective communication also depends on governance structures, processes, culture, history, scale, etc. and other factors such as that in the policy realm public opinion matters and that the scientific evidence is often not the only factor to take into account. In fact, insofar as the viability of industrial society is at stake, sustainability research is not a normal scientific issue (Friedrichs, 2011)

Environmental Integrated Assessment modelling refers, in general, to any type of analysis that aims at integrating multiple disciplines (economy, natural sciences, engineering, etc.) and dimensions (short vs. long-term, regional vs. global, economic vs. biophysical, etc.) trying to capture interactions between human and natural systems and with the objective of providing useful information for policy making. These relationships tend to be complex, dynamic and highly non-linear. A great diversity of environmental integrated assessment models (IAMs) exists due to the different approaches used by modellers striving to capture the complex interactions and high uncertainties involved in the environment/economy/society interface. IAMs differ in the available policy options, the level of geographic, economic and technological disaggregation, the sophistication of the representation of the Biosphere processes, the economic assumptions and generic approach (e.g. equilibrium models, biophysical models), the consideration of equity across time and space, the degree of foresight, the treatment of uncertainty, the responsiveness of agents within the model to environmental policies, etc.

Climate Change is the most researched process among the core Earth-system processes identified in the literature. In fact, climate change control would have many co-benefits, even able to put other planetary boundaries under control (e.g. ocean acidification) (Steffen et al., 2015b). This fact is also pointed out by the IPCC: "adaptation, mitigation and sustainable development are closely related, with potential for synergies and trade-offs",[10] and recognizing "sustainable development as the overarching context for climate policy" (IPCC, 2014b). As a consequence, the Integrated Assessment Modelling of Climate Change is currently one of the most performing and widely used frameworks to assess the interaction between the human activities and the environmental processes. Although these models are subject to a set of critical uncertainties and shortcomings, they represent a continuous multidisciplinary effort of almost three decades, widening the framework and further integrating more elements and processes. Climate IAMs are in fact being used as a starting platform to integrate further processes (e.g. biodiversity (Harfoot et al., 2014)) or to link them with models that include rich couplings among the natural subsystems as Earth System Models (ESMs) (e.g. (Collins et al., 2015; Tol, 2006).

Modelling for shedding light on future sustainable pathways requires frameworks capable to deal with complexity, limited knowledge of natural and social sciences and a substantial level of uncertainty. In this sense, scenario methodology constitutes an internally consistent framework considering these limitations and has become very popular in recent GEAs, e.g. IPCC's Assessment reports (IPCC, 2014b, 2007a, 2001a; IPCC SRES, 2000a), UNEP's Global Environmental Outlook (UNEP, 2012, 2007, 2004) or the MEA (2005)). Future will depend on alternative assumptions about the technological, economic, demographic, geopolitical, and social aspects of development

[10] "Mitigation can positively or negatively influence the achievement of other societal goals, such as those related to human health, food security, biodiversity, local environmental quality, energy access, livelihoods and equitable sustainable development. These influences can be substantial, although sometimes difficult to quantify, especially in welfare terms" (IPCC, 2014b).

and the ways in which institutions, personal and public values, and natural systems may be expected to respond to historically novel stressors.

An additional complication, critical for effective policy making, arises from the uncertainties associated to some planetary boundaries. The difficulties start with the selection of the representative control variables; also, a static threshold might be equivocal due to the intrinsic dynamic nature of the processes. Let us take the case of climate change. Although adaptation can reduce the risks of climate change impacts, there are limits to its effectiveness. For this reason the solution to climate change requires substantial reductions of emissions along the 21st Century (IPCC, 2014b). The planetary boundaries framework proposes two control variables with an uncertainty range: CO_2 concentration (350-450 ppm) and energy imbalance (+1.0-1.5 W/m^2) (Rockström et al., 2009; Steffen et al., 2015b) (see Figure 1.2). Hansen et al., (2008), taking into account slow climate feedback processes not included in most climate models, such as ice sheet disintegration or vegetation migration, argue for considering a target below 350 ppm. The IPCC estimates that a level of about 450 ppm CO2-eq in 2100 is consistent with a likely chance to keep warming below 2°C relative to pre-industrial level (IPCC, 2014b, 2007a).[11] Policy-makers have followed IPCC recommendations, endorsed by the agreements reached at the United Nations Framework Convention on Climate Change (UNFCCC) conference in Cancun (UNFCCC, 2011) and Paris (UNFCCC, 2015). In the latter, a special mention to "pursue efforts to limit the temperature increase to +1.5ºC" was included. On the other hand, the climate change community has recently taken a dynamic approach and has built one of the four reference Radiative Concentration Pathways (RCPs), the RCP2.6 that reaches a radiative forcing of around +2.6 W/m^2 by 2100, considering "a relatively high probability to limit global mean temperature increase to 2°C" (van Vuuren et al., 2011d).

1.1.4. The debates on sustainability and the scarcity of natural resources

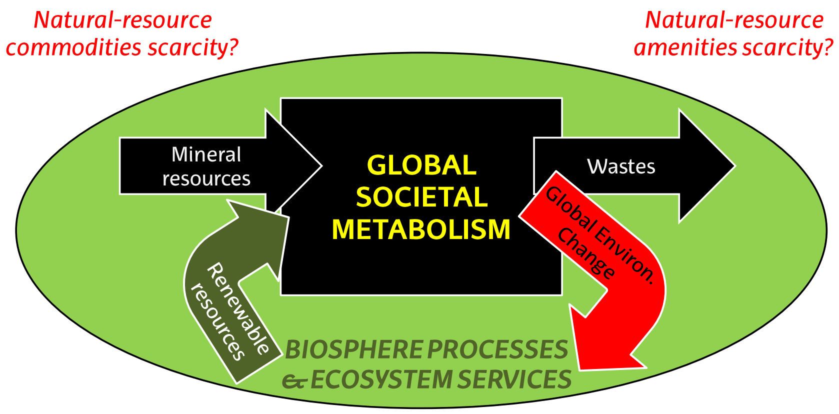
Whether economic growth[12] can be indefinitely sustained in a finite natural world is one of the earliest and most enduring questions in the economic literature. The relationship between economic growth and the environment is approached from very different perspectives. Van den Bergh and de Mooij (1999) identified five perspectives: "immaterialist" (growth is undesirable), "pessimist" (growth is impossible in the long run), "technocrat" (growth and environmental quality are compatible), "opportunist" (growth and environmental degradation are inevitable) and "optimist" (growth is necessary for environmental conservation). The issue is to what extent technological progress and capital accumulation can overcome diminishing marginal returns to finite

[11] Ultimately, cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond (Allen et al., 2009). In this sense, the amount of carbon dioxide emissions we can emit while still having a likely chance of preventing dangerous climate change (i.e. the carbon budget) has been estimated to be in the range of 260-410 GtC (IPCC, 2014b).

[12] Economic growth is generally defined as the increase in the total value-added of marketable, man-made goods and services in the economy (Jeroen van den Bergh and de Mooij, 1999). Economic growth is usually measured as GDP increase.

natural resources. In essence, the different perspectives differ in basic claims about future possibilities for substitution and technical progress (Neumayer, 2003). Very different natural resources exist, although from the human perspective they can be classified in two broad categories. On the one hand, natural resource commodities are renewable and non-renewable (mineral) raw materials such as food, timber, coal, iron, copper, oil, etc. On the other hand, natural resource amenities[13] include services provided by the natural world such as the Biosphere cycles (e.g. water quality, climate, nutrients, etc), biodiversity, ecosystem services or the sinks where we deposit the waste products (Krautkraemer, 2005). While human action uses (and eventually depletes) the stocks of natural-resource commodities, natural-resource amenities are being degradated by pollution and global environmental change (see Figure 1.4).

Figure 1.4: Natural-resource commodities and amenities scarcity



Source: own work.

Public and scientific debates on the limits to economic growth due to the scarcity of natural resources have being ongoing at least since the time of Malthus (1798). From the second half of the 21st Century, these debates have been framed from two different perspectives. In the 1970s and 80s, the convulsion provoked by the oils shocks drove the focus of the debate to the limits due to the constraints in the sources, i.e. non-renewable energy resources availability. These events coincided with the publication of the "*Limits to Growth*" (LtG) report (Meadows et al., 1972), whose baseline scenario projected a material resource crisis driving the global system into overshoot and collapse during the first half of the 21st Century.[14] Later on, the focus turned to the limits in the sinks, i.e. the degradation of natural resources amenities by pollution and global environmental change, and the challenge to conceal the growth promoting trade

[13] The term "amenities" is preferred than the more conventional of "sinks" due to its broader scope.

[14] The "*Limits to Growth*" analysis (Meadows et al., 1972), as well as its follow-ups (Meadows et al., 2004, 1992) included an integrated representation of the human activities interacting within the Biosphere. Among the unsustainable scenarios analyzed, there is a non-renewable resource crisis (scen. 1 baseline), global pollution crisis (scen. 2&7), renewable resources crisis (scen. 3&4), a cost crisis (scen. 6) as well as a crisis combination of many (scen. 5&8). The identification of the leverage points of the system allows to design scenarios achieving an equilibrium (i.e. sustainability) in the global system (scen. 9&10). The name of the scenarios refers to the last update of the report from Meadows et al. (2004).

liberalization (General Agreement on Tariffs and Trade, GATT in 1994) with global environmental protection (Rio Summit (UN, 1992)) (Krautkraemer, 2005).

Different reasons stand for this shift. Firstly, the economic context led to a decrease in public concern about non-renewable energy resources availability, since real prices of commodities and notably of fossil fuels declined from peaks in the early 1980s. This also gave support to the critics of the LtG report from the mainstream economics point of view since a price reduction is interpreted as a decrease in their scarcity (Krautkraemer, 2005). In fact, although the LtG report initially received many favourable comments from different fields, it was heavily criticised in the following years due to the absence of a price mechanism that would respond to natural resource scarcity and the non-consideration of substitution processes between factors of production (Neumayer, 2003). Ultimately, the debate on the LtG report was closed at the time by a broad rejection of its scientific validity (Bardi, 2011).[15] In parallel, in the 1980s, some new global challenges such as the ozone layer depletion, global warming, ocean contamination and biodiversity loss began to refocus the debate around the impacts of environmental degradation on economic growth. The interest was shifting away from natural resource availability towards the environment as a medium for assimilating wastes (i.e. from "commodities" to "amenities") (Krautkraemer, 2005). In this context, climate change was identified as the most worrisome environmental global challenge by international institutions. Thus, in 1988 the IPCC was created as a scientific intergovernmental body under the auspices of the UN. Since then, the main role of the IPCC is producing reports that support the UNFCCC, which is the main international treaty on climate change.

This shift from "commodities" to "amenities" scarcity occurred simultaneously with the reversal of the broader international sustainability discourse, shifting from a notion of growth vs. the environment to a notion of growth *for* the environment (Bermejo, 2014; Eastin et al., 2011; Gómez-Baggethun and Naredo, 2015). Recently, the UNEP issued its report "*Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication*" where a Green Economy was defined "as one that results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities". The Green Economy scheme can be thought of as one which is low carbon, resource efficient and socially inclusive; growth in income and employment should be driven by public and private investments that reduce carbon emissions and pollution, enhance energy and resource efficiency, and prevent the loss of biodiversity and ecosystem services (OECD, 2012a; UNEP, 2011b). The aim is to achieve absolute decoupling in both resource use (i.e. dematerialization) and environmental impacts (UNEP, 2011a). After the Brundtland Report, the Green

[15] Bardi (2011) reviewed the historical debate, reaching the conclusion that although there were some legitimate critics, the scientific discrepancies were mainly determined by a lack of understanding of the novel applied methodology. As a consequence, the scientific debate was closed without having been completed, in parallel with a discredit campaign (see Chapters 7 "The Scientific Debate" and 10 "The Political Debate" from Bardi (2011) for details). In fact, a certain reappraisal of the study has emerged in the last years (Bardi, 2011, chap. 11; Pasqualino et al., 2015; Turner, 2008).

Economy is the new institutional consensus for operationalising the concept of sustainable development.[16]

However, the five perspectives identified by Van den Bergh and de Mooij (1999) continue to coexist, and alternative understandings in relation to the link between economic growth, natural resources scarcity and sustainability that question the feasibility of achieving absolute decoupling are gaining momentum (e.g. the Steady-State Economy or Sustainable Degrowth (Kerschner, 2010; Schneider et al., 2010)). In the words of Daly "the main idea behind sustainability is to shift the path of progress from growth, which is not sustainable, toward development, which presumably is"; proposing three broad criteria for sustainability: renewable resources should provide a sustainable yield (the rate of harvest should not exceed the rate of regeneration); for non-renewable resources there should be equivalent development of renewable substitutes; waste generation should not exceed the assimilative capacity of the environment (Daly, 2007, 1990).

Similarly, different views about the scarcity of non-renewable energy resources exist in the scientific discussion. On the one hand, resource "optimists" claim that market mechanisms and human ingenuity will be able to both transform resources into reserves and find alternative energy sources to replace the scarce ones at a sufficient pace to avoid supply restrictions provided adequate investments are forthcoming (Adelman, 1990; Maugeri, 2012; Odell, 2004; Simon, 1996; Thielemann, 2012). Prices are considered to be the driving mechanism following Hotelling's rule (Hotelling, 1931); i.e. if resources are scarce, resource prices and costs will rise (Krautkraemer, 2005; Rogner et al., 2012; Thielemann, 2012). So, since the first studies on *Scarcity and Growth* in the early 60s (Barnett and Morse, 1963), mainstream economists have concluded that resources are becoming less scarce because prices or costs are falling.

On the other hand, the ecological/biophysical economics stresses the weaknesses of prices as an adequate scarcity indicator due to the impossibility to assure perfect market conditions (e.g. (Hall et al., 2001; Kaufmann and Cleveland, 2001; Meadows et al., 1992; Norgaard, 2002, 1990; Reynolds, 1999; Reynolds and Baek, 2012)), and thus recommends to focus on the biophysical components of the natural resources to assess their scarcity (e.g. ultimately recoverable resources (URR), resource discoveries, field size and depletion rates, energy return on energy invested (EROEI), etc.).[17] With the 21st century, interest in the future or mineral resources was spurred by renewed concerns about crude oil depletion. The reappraisal started with Campbell and Laherrère's (1998) milestone paper where the authors applied the geological model proposed by Hubbert (1956) to describe the maximum world's crude oil

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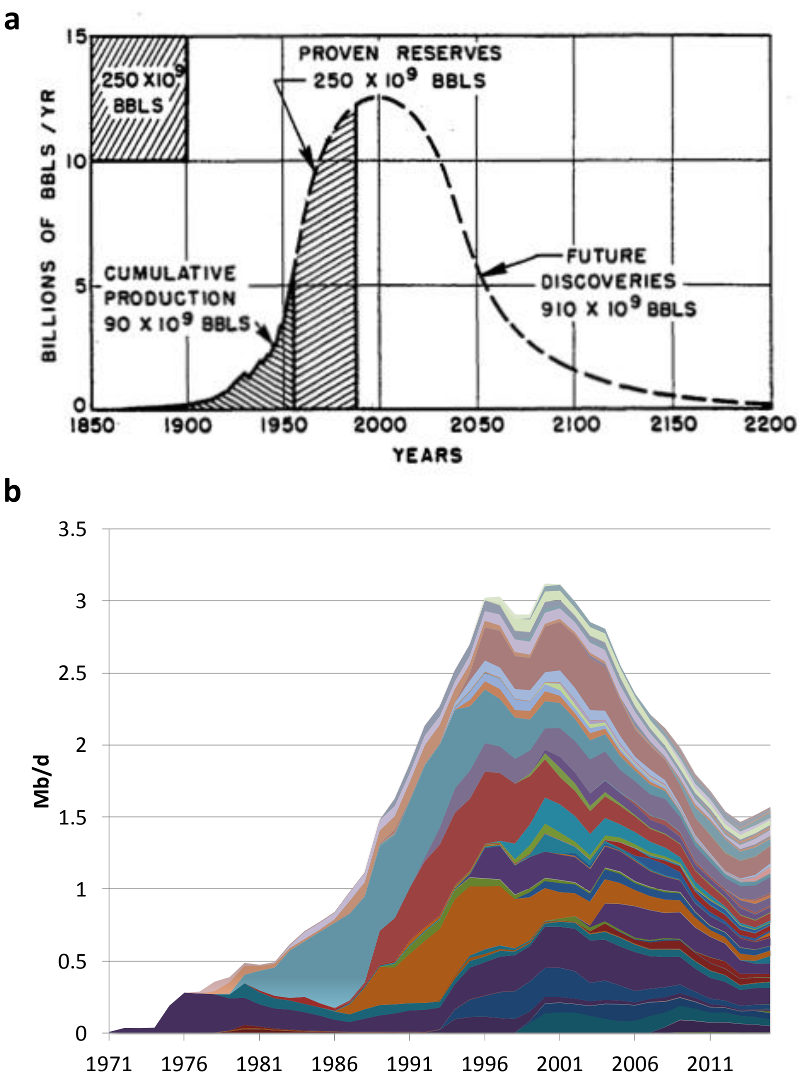
[16] The "Rio+20" agenda has adopted "green economy" to address the goals of sustainable development and poverty eradication (UNEP, 2011b).

[17] In fact, this was the approach taken by the first formal school of economics, the French Physiocrats, looking especially at land as the basis for generating wealth. Standard economics considers energy as a commodity rather than a critical factor of production (i.e. cost share theorem) (Giraud and Kahraman, 2014).

extraction. Hubbert empirically discovered that the maximum production rate of crude oil from all wells of a region follows the same logistic growth function (graphically, a bell shaped curve called Hubbert curve today) as the rate of discoveries in that region. His application of this empirical model successfully predicted the maximum of crude oil extraction for the US in the early 70s. Rather than predictions, these figures are geological maximum extraction profiles that might be affected by geopolitical context (e.g. OPEC curtailment of production in the 70s delayed by 10 years the global projection from Hubbert (1956), see Figure 1.5a). Indeed, Campbell and Laherrère (1998) found that, ceteris paribus, the worldwide peak of conventional oil production would occur at some moment during the first decade of the 21st century, most likely around 2005. The peak in world conventional oil production in the mid-2000s was indeed confirmed by the International Energy Agency (IEA) some years later (WEO, 2010). Peak oil research prospered in these years (e.g. (Aleklett et al., 2010; ASPO, 2008; Brecha, 2012; EWG, 2008; Maggio and Cacciola, 2012; Mohr and Evans, 2010; Sorrell et al., 2010)), and the geological grounds of the theory allowed for the extension of the concept to other non-renewable fuels such as gas, coal and unconventional fossil fuels[18] (e.g. (Aleklett et al., 2010; de Castro et al., 2009; EWG, 2007; Höök and Tang, 2013; Laherrère, 2010a; Maggio and Cacciola, 2012; Mohr, 2010; Mohr et al., 2015; Rutledge, 2011)). At the same time, many countries such as the UK (2002) and Norway (1999) (Figure 1.5b), stable advanced industrialized countries with the best available technology, have reached their peak in oil extraction. Thus, it is argued that geological factors determine a peak in the extraction of each resource that technology can only slightly modify, pointing out that these restrictions might have strong adverse economic consequences (Brown et al., 2011; Hamilton, 2009; Hirsch, 2008; Kumhof and Muir, 2012; Murphy and Hall, 2011; Tverberg, 2012). In this sense, even research from international institutions such as the IMF has shown some interest in these models acknowledging the need to reconcile the geological and economic/technological views concerning the future of world oil production and prices (Benes et al., 2015; Kumhof and Muir, 2014). Still, the fact that conventional crude oil may have peaked is not easing the climate problem, since it may direct the industry to extracting liquid fuels from “dirty” sources, such as tar sands and coal, which emit more CO_2 per unit energy produced (Bardi, 2011).

[18] Fossil fuels are usually classified in two broad categories: conventional and unconventional fuels. In general, conventional fuels are those that have been extracted historically, characterized by relatively low (monetary and energetic) extraction costs. Unconventional fuels, instead, refer to relatively high extraction cost fuels that require extraction methods and processing more challenging technologically and environmentally (see (Rogner et al., 2012)).

Figure 1.5: Oil depletion curves: (a) Hubbert (1956)'s theoretical projection for global conventional oil; (b) historical oil extraction in Norway by field (1971-2015)



Source: (a) from Hubbert (1956) and (b) own work from NPD (2016) data.

1.2. Objectives

In the light of the context and motivations presented in the previous section, in this doctoral thesis I focus on the development and application of Environmental IAMs to shed light on potential sustainable pathways. More specifically, IAMs of Climate Change are currently considered as the best tool for the implicit evaluation of the planetary and social boundaries. However, there is a diversity of climate IAMs due to the different approaches used by modellers striving to capture the complex interactions and high uncertainties involved in the climate/economy/society interface. In order to grasp the implications of this diversity this thesis applies two modelling frameworks that differ in their scientific approaches:

- GCAM:[19] a standard economic state-of-the-art IAM of climate change,
- WoLiM: a biophysical model built for this thesis.

Objective A: Implications of the uncertainty of fossil energy resources availability and geological constraints for climate change pathways and the feasibility of socioeconomic scenarios

The first objective (A) consists in shedding light on the implications for sustainable pathways of applying alternative assumptions in relation to the future availability of non-renewable energy resources to those currently considered in IAMs based on standard economics. Both models GCAM and WoLiM are used to answer the following questions:

- *Which implications does the integration of revised estimates of non-renewable energy resources have for future sustainable pathways in terms of energy mix (transition to low carbon energies), GHG emissions, energy system cost, climate policies, etc.?*
- *Would the consideration of revised estimates of non-renewable energy resources "solve" the climate change issue?*
- *Which are the consequences for socioeconomic pathways of considering geological constraints to the extraction rate of non-renewable fuels?*
- *Could unconventional fossil fuels compensate for the depletion of conventional fossil fuels?*
- *What are the implications of integrating inertias and delays?*
- *What is the substitution potential of alternatives to oil such as biofuels and electric vehicles in an eventual peak oil scenario?*
- *Are the scenarios usually considered in GEAs compatible with the carbon endowment from the revised estimates?*

Objective B: Implications of fragmented policy scenarios for carbon leakage

Secondly (B), we focus on the implications of different post-Paris (December 2015) international climate policy regimes in a world with a great level of integration between many regions in terms of climate change and terrestrial and industrial carbon leakage. Since models often deliver optimum solutions, this assessment is fundamental to assess the potential of unintended effects and provide adequate policy-advice. This means introducing governance and geopolitical issues in the framework. We analyze the scale of potential carbon leakage in fragmented scenarios with the GCAM model since this analysis is not possible with WoLiM. In this sense, we try to provide an answer to the following questions:

[19] The GCAM Model (formerly MiniCAM) is an IAM available under the terms of the ECL open source license version 2.0: www.globalchange.umd.edu/models/gcam/download/. It is developed at the Joint Global Change Research Institute and has been selected by the IPCC to represent the 4.5 RCP (Calvin et al., 2011; Thomson et al., 2011).

- *To what extent climate policy fragmentation has the potential to increase the carbon emissions of non-participatory countries in an international climate regime?*
- *What is the relationship between the carbon leakage and the size of the international climate coalition?*
- *How do the different types of leakage (industrial and terrestrial) evolve under different fragmentation scenarios?*
- *Which international climate coalitions are unlikely to be sufficient to drive global emission stabilization by the end of the century?*

Objective C: Analyze the different modelling frameworks of IAMs for climate change to identify key elements to advance towards IAMs to assess Sustainability

Many models, frameworks and approaches currently exist in the field of IAMs of climate change. Thus, my third objective is to answer to the following two questions:

- *Are they any key modelling elements and/or approaches to assess Sustainability?*
- *Are new models required, or instead enhancing/improvement of the existing ones might suffice?*

1.3. Methodology

For the fulfilment of the aforementioned objectives, the following methodology was implemented:

1. Getting expertise in the field of IA modelling of climate change

1.1. Overview of the state-of-the-art of IA modelling of climate change,

1.2. Learning and application of a state-of-the-art economic IAM of climate change (GCAM), including Integration of the community of users and developers and gaining expertise to follow future evolutions of the GCAM framework,

1.3. Development of a new biophysical IAM of climate change (WoLiM)

3. **Dual approach**: Application of two distinct frameworks:

GCAM	WoLiM
Standard economics	Biophysical economics
Policy-optimization	Policy-simulation
Partial equilibrium	Disequilibrium dynamics
Higher-resolution	Highly aggregated

4. Review of fossil fuel resources availability uncertainty (stock and flow)

5. Combination of probabilistic (Montecarlo simulation) and deterministic (scenario methodology) analysis

6. Review of potential climate coalitions

The first step was getting expertise in the field of IA modelling of climate change (1) by reviewing the literature (1.1), learning to use the state-of-the-art GCAM model as an advanced user (1.2) and developing the new model framework WoLiM in a system dynamics (SD) framework in two steps (1.3). The learning process of the GCAM model includes the communication with the developers and community-users community. In relation to WoLiM development, rather than building a “closed” model, the aim is to develop a framework able to be completed and expanded in the future.

Since there is a diversity of climate IAMs due to the different approaches used by modellers striving to capture the complex interactions and high uncertainties involved in the climate/economy/society interface, I apply two models that differ in their scientific approaches. On the one hand, GCAM represents a IAM of climate change with a framework based on conventional economics (partial equilibrium and policy-optimization) with a high regional and technological resolution. On the other hand, WoLiM is a SD highly aggregated model (one global region with a limited set of alternative technologies) based on biophysical economics, disequilibrium dynamics and focusing on policy-simulation scenarios.

In relation to the objective A, I start by a literature review on the uncertainty of fossil fuel resources estimates in order to perform two distinct analyses. Firstly, I perform a global sensitivity analysis of the climate pathways to the stocks with GCAM (Monte Carlo simulation) during the 21st century. Secondly, since GCAM model does not integrate flow constraints to the extraction of fossil fuels, it is not an appropriate framework to study supply-driven scenarios. In this case, the WoLiM framework is applied considering fossil fuel depletion profiles from the literature that approximately correspond with the medians from the probabilistic analysis performed with GCAM. Scenario methodology to the year 2050 is applied in WoLiM for the objective A.

GCAM is applied for the objective B since its regional disaggregation allows exploring the implications for carbon leakage of climate fragmented coalitions to 2100 (scenario methodology).

Finally, the literature review of environmental IA modelling provides the grounds for identifying the key modelling elements to assess sustainability (objective C).

The Figure 1.6 represents the chapter structure of the thesis in relation to the pursued objectives.

1.4. Thesis organization

The PhD is divided in three main parts: Part I consists of the Introduction to the PhD dissertation (Chapter 1) and an Overview of the IA Modelling of climate change field (Chapter 2). Part II constitutes the main corpus of the PhD and contains four papers published or submitted for publication at the time of writing this text. Part III coincides with Chapter 7 and concludes. Despite the obligated sequential presentation of information in this written dissertation, most of the performed work has in fact done simultaneously and in a coordinate way with many interactions between each chapter scope and objectives (see Sections 1.2 and 1.3).

Part I includes the introduction (Chapter 1) that presents and justifies the motivation, objectives and methodology applied in this work, and Chapter 2[20] where an overview of the Integrated Assessment Modelling of Climate Change field is performed from an historical and methodological point of view. I include a review of the current robust outcomes found across the field, as well as a discussion on the state of the art and future developments.

Part II is divided in two main sections, each responding to an objective of the PhD:

- Part II.A consists of three chapters (Chapters 3, 4 and 5) that that seek shed light on the Implications of the uncertainty of fossil energy resources availability and geological constraints for climate change pathways and the feasibility of

[20] This chapter is based on a previous working paper (Capellán-Pérez et al., 2014a) and the deliverables "D5.1 - State of the art review of climate-energy-economic modelling approaches" and "D5.2 - Review of existing literature on methodologies to model nonlinearity, thresholds and irreversibility in high-impact climate change events in the presence of environmental tipping points" of the FP7 European Project COMPLEX.

socioeconomic scenarios (objective A). Chapter 3[21] analyzes the likelihood of climate change pathways under uncertainty on fossil fuel resources availability. Chapters 4 and 5 document and apply WoLiM framework. Chapter 4[22] focus on the physical limits and temporal conditions of the transition towards renewable energies with a preliminary version of the WoLiM model. Chapter 5[23] includes the full version of the WoLiM (i.e. including all economic sectors and fuels) and is applied to analyze the implications of fossil fuel depletion in the context of different socio-economic scenarios.

- Part II.B consists on one chapter (Chapter 6[24]) that analyzes the implications of fragmented climate policy scenarios for carbon leakage (objective B) applying the model GCAM.

Finally, Part III (Chapter 7) concludes presenting the main results, highlighting the identified limitations and avenues for further work from the PhD dissertation. Final remarks address the objective C to identify key modelling elements and approaches to advance towards assessing Sustainability with Environmental IA. The Figure 1.6 represents the chapter structure of the thesis in relation to the pursued objectives:

[21] This chapter has been submitted for publication as: Capellán-Pérez, Iñigo, Iñaki Arto, Josué M. Polanco-Martínez, Mikel González-Eguino, and Marc B. Neumann. "Likelihood of Climate Change Pathways under Uncertainty on Fossil Fuel Resources Availability." *Submitted*, 2016.

[22] This chapter has been published as: Mediavilla, Margarita, Carlos de Castro, Iñigo Capellán, Luis Javier Miguel, Iñaki Arto, and Fernando Frechoso. "The Transition towards Renewable Energies: Physical Limits and Temporal Conditions." *Energy Policy* 52 (January 2013): 297–311. doi:10.1016/j.enpol.2012.09.033.

[23] This chapter has been published as: Capellán-Pérez, Iñigo, Margarita Mediavilla, Carlos de Castro, Óscar Carpintero, and Luis Javier Miguel. "Fossil Fuel Depletion and Socio-Economic Scenarios: An Integrated Approach." *Energy* 77 (Diciembre 2014): 641–66. doi:10.1016/j.energy.2014.09.063.

[24] This chapter has been submitted for publication as: González-Eguino, Mikel, Iñigo Capellán-Pérez, Iñaki Arto, Alberto Ansuategi, and Anil Markandya. "Industrial and Terrestrial Carbon Leakage under Climate Policy Fragmentation." *Submitted*, 2016.

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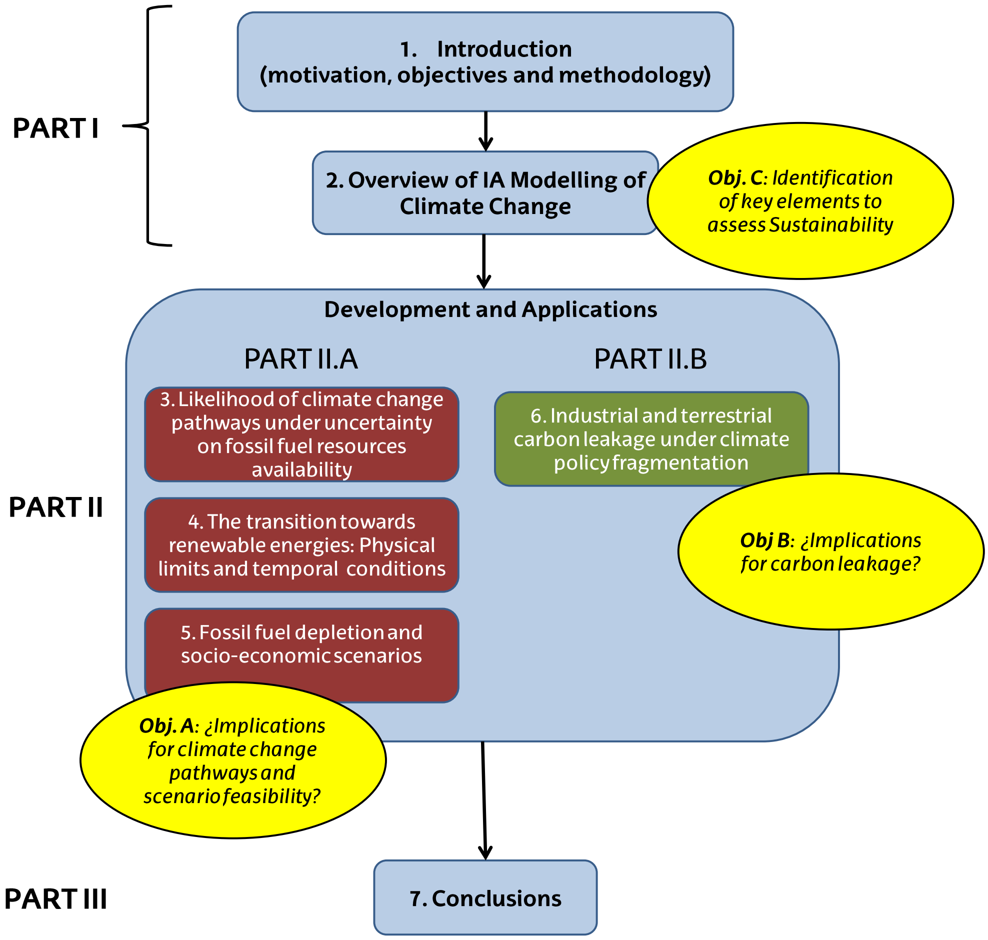
Figure 1.6: Scheme of the organization of the thesis linking the main objectives with the structure by chapters



Source: own work.

CHAPTER II

2. Overview of Integrated Assessment Modelling of Climate Change

In this chapter we give an overview of the field of Integrated Assessment (IA) modelling of climate change (or integrated energy-economy-climate modelling), which has been extensively reviewed in the last two decades (Arigoni and Markandya, 2009; Dowlatabadi, 1995; Farmer et al., 2015; Hedenus et al., 2013, 2013; IPCC, 1995a; Janetos et al., 2009; Kelly and Kolstad, 1998; Norgaard and Baer, 2005; Parson et al., 1997; Pindyck, 2013; Pollitt et al., 2010; Rotmans and Asselt, 1999; Sarofim and Reilly, 2011; Schneider, 1997; Schneider and Lane, 2005; Scrieciu et al., 2013; Stanton et al., 2009; Tol, 2006).[25]

Environmental IA modelling refers to any type of analysis that aims to integrate multiple disciplines (economy, natural sciences, engineering, etc.), in order to capture interactions between human and natural systems and with the objective of providing useful information for policy making. These relationships tend to be complex, dynamic and highly non-linear. The central element in IA modelling of climate change is the climate focused energy-economy-environment (E^3) IA model (IAM). IAMs are computer programs that link an array of component models based on mathematical representations of information from the various contributing disciplines, thus ensuring consistency among the input assumptions with the various components of the model. IA modelling also includes the definition of the problem, the formulation of policy questions and the interpretation and communication of results (IPCC, 1995a; IPCC SRES, 2000a; Kriegler et al., 2012; MEA, 2005; Schwartz, 2003; Tol, 2006). Even though most IAMs have focused on climate change and air pollution (Parson et al., 1997; Tol, 2006), recently, these models have also been expanded to assess other environmental problems such as water scarcity, depletion of non-renewable resources and overexploitation of renewable resources (Stehfest et al., 2014).

The field started to be developed in the early 1970s with the pioneers World2 and World3 models, the first global computer simulation models, applied for the "Limits to Growth" report (Forrester, 1971; Meadows et al., 1972). The study analysed the sustainability of societal pathways focusing on the dynamic interactions between socioeconomic drivers, resource availability and biosphere limits. A new discipline was

[25] This chapter is based on a previous working paper Capellán-Pérez et al., (2014a) and the deliverables "D5.1 - State of the art review of climate-energy-economic modelling approaches" and "D5.2 - Review of existing literature on methodologies to model nonlinearity, thresholds and irreversibility in high-impact climate change events in the presence of environmental tipping points" of the FP7 European Project COMPLEX.

born and before the end of that decade the first IA model linking energy conversion, emissions and atmospheric CO_2 concentration appeared (Nordhaus,1979). Increasing concern regarding transboundary environmental problems led to the development of a set of models explicitly addressed environmental issues, such as the RAINS model focusing on acid rain for Europe (Alcamo et al., 1990). The DICE model (Nordhaus, 1990) and the IMAGE1.0 model (Rotmans, 1990) marked the first attempts at fully integrated representations of climate-economy systems. In the years that followed, the number of climatic IAMs grew very rapidly. In fact, since many energy-economy models were developed in the 70s and 80s to analyze energy security issues in the context of the oil/energy shocks, the climate dimension was straightforward to include by estimating the GHG emissions of the considered sectors (Hedenus et al., 2013; Janetos et al., 2009). Actually, the first purpose of IA modelling of climate change was to produce plausible emissions scenarios to be run in the Global Circulation Models (GCMs) in order to compute the climate consequences of increasing GHG emissions (Edmonds and Reilly, 1983). Dozens of climatic IAMs currently exist: a review in 1995 already identified more than 30 models (IPCC, 1995a); nowadays most of them continue to be developed and many more have been created (Stanton et al., 2009; Tol, 2006).

The results of IAMs, as those of any other model, depend on the assumptions and methods considered for their construction, and are subject to high uncertainties due to the complex interactions involved in the climate/economy/society interface, including unknowns such as future human behaviour. One approach for dealing with uncertainty is through developing scenarios that provide plausible descriptions of how the future might unfold in different socioeconomic, technological and environmental conditions.

IA applied to climate change typically uses standard economics as the basis for decision making, and is oriented to inform policy-makers on the feasibility and cost of meeting alternative climate stabilization targets under a range of salient long-term uncertainties. This is implemented in a variety of ways, but it fundamentally implies that the models tend toward the goal of minimizing the aggregate economic costs of achieving mitigation outcomes (IPCC, 2014a). IAMs generally focus on “insights about the nature and structure of the climate problem, about what matters, and about what we still need to learn” (Morgan and Dowlatabadi, 1996); IA modelling is a continuous learning process (Rotmans and Asselt, 1999). In general terms, IA can help to:

- Put a complex problem in the broader context of other problems, by exploring the interrelations of the specific problem with other issues;
- Assess potential response options to complex problems (e.g. cost-benefit & cost-effectiveness analysis, etc.);
- Identify, illuminate and clarify the different types and sources of uncertainties in the cause-effect chain(s) of a complex problem;
- Translate the concept of uncertainty into the concept of risk analysis, to assist in decision-making under uncertainty;
- Set priorities for research topics, also by identifying and prioritising decision-relevant gaps in knowledge.

Ideally, climate IAMs should try to reproduce the complex, full-scale integrated Biosphere as shown in Figure 1.1 to analyze the climate change problem in its full context. This would allow capturing the interactions between human activities, the atmospheric composition, the climate and the rest of Earth subsystems. For example, climatic change has an impact on ecosystems, biodiversity, etc. and also on human activities, which in turn are capable of adapting to these environmental changes. However, until now a sequential[26] approach (Figure 2.1) has been extensively used instead of the full-scale integration with a limited representation Biosphere processes (e.g. (Collins et al., 2015; Janetos et al., 2009)) and environmental impacts (e.g. (Pollitt et al., 2010)). Different reasons for this simplification are given in the relevant literature: scientific knowledge gaps, technical and methodological difficulties in practical integration, uncertainties and different representations of environmental impacts, delays between the IA model calculations and the impact and adaptation assessments, idealized assumptions about the (high) resilience of ecosystems, etc. (Arigoni and Markandya, 2009; Cumming et al., 2005; Hibbard et al., 2010; Janetos et al., 2009; Lenton and Ciscar, 2013; Moss et al., 2010; Schneider and Lane, 2005; Stanton et al., 2009; Tol, 2006). In practice, IA models usually focus on the interactions between processes and systems within the "Human Activities" box of Figure 1.1, such as the energy, agriculture, livestock and forestry systems. Then, the effects of human activities on the composition of the atmosphere are analyzed, as are the subsequent effects on climate and sea levels. A simple climate model version emulating GCMs outputs is usually applied to minimize time-resolution (Sarofim and Reilly, 2011).[27] Most of the existing models adopt a sequential approach, where these climate impacts are not feedbacked to the other subsystems (e.g. models considered by the Working Group III from the IPCC).

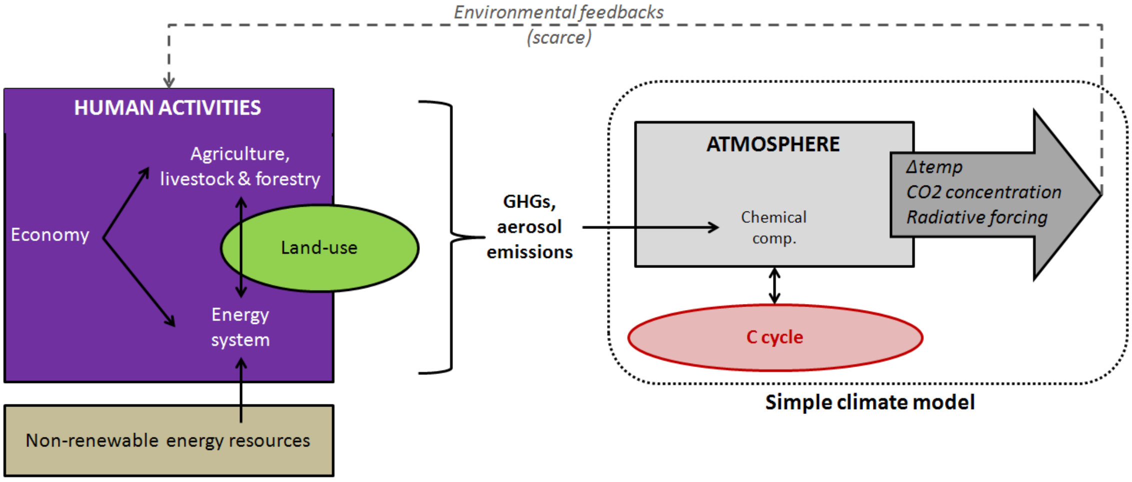
In fact, two modelling paradigms of climate change have been historically developed largely independently of each other, and their interactions have historically been relatively simplistic (Collins et al., 2015; Hilderink et al., 2008; IPCC, 2014c).[28] On the one hand, climate models have focused on the representation of the climate system based on the physical, chemical and biological properties of its components and their interactions and feedback processes such as the Atmosphere-Ocean General Circulation Models (AOGCMs) or the Earth System Models (ESM). These models are the primary tools for examining the climatic, biogeophysical, and biogeochemical impacts of changes to the radiative properties of the Earth's atmosphere. On the other hand, the IAMs has focused on describing the human components of the Earth system, the sources of GHG and short-lived species emissions, and drivers of land use change (see also Figure 2.4).

[26] The terminology "vertical" vs. "horizontal" integration is also sometimes used (e.g. (Davies and Simonovic, 2010)) instead of "sequential" vs. "full-scale" integration.

[27] MAGICC model is a classic example (Meinshausen et al., 2011a, 2011b), and has even been used to standardize outputs from IAMs in the last IPCC report (IPCC, 2014a).

[28] Typically, projections of GHGs emissions have been produced by the human system components of IAMs, archived in databases, and used by ESMs to produce projections of climate and altered biogeophysical processes (e.g. SRES, RCPs).

Figure 2.1: Typical sequential characterization of climate IAMs



Notes: In practice, IAMs usually focus on the interactions between processes and systems within the "Human Activities" box of Figure 1.1, including the energy system, the agriculture, livestock and forestry system and the other human systems. Some also include Land-use, while environmental feedbacks are scarce in the literature.

Source: own work.

Most of the climate IA models have long and very long temporal scales because climate change is by nature a long-term issue due to the huge inertia of global climate (Hansen et al., 2008). The time scale for climate policy analysis is usually 100 years (IPCC, 2007a, 1990), although models can even go further in order to reach climate stabilization conditions.

The chapter is organized as follows: section 2.1 reviews the different classifications of IAMs proposed in the literature following different axes. Results and implications typically obtained by current IAMs of climate change are reviewed in section 2.2. Finally, the state of the art of the field and future developments are discussed in section 2.3.

2.1. Classification of IAMs

The diversity of climate IAMs is due to the different approaches used by modellers striving to capture the complex interactions and high uncertainties involved in the climate/economy/society interface. IAMs differ in the available policy options, the level of geographic, economic and technological disaggregation, the sophistication of the climate sector and the GHGs considered, the economic assumptions and approach, the consideration of equity across time and space, the degree of foresight, the treatment of uncertainty, the responsiveness of agents within the model to climate change policies, etc.

Different classifications have been proposed in the literature:

- Policy-evaluation vs. policy-optimization models,
- Top-down vs. bottom-up models,
- Highly-aggregated vs. higher-resolution models,
- Level of integration among subsystems,
- Deterministic vs. stochastic models,
- Equilibrium vs. disequilibrium models,
- Standard vs. biophysical economic models.

Since different models are applied with different objectives and by people with different backgrounds, each proposed or highlighted classification is directly related with the main approach (or field) of the author(s) of the assessment. For example, assessments designed for providing policy-advice usually apply the first and second categorizations (e.g. IPCC, assessments for official institutions), while those scientists focusing on Biology and Ecology tend to give priority to the level of integration among subsystems.

2.1.1. Policy-evaluation vs. policy-optimization models

The III Working Group of the IPCC (1995a) applied a two-dimensional classification for Economy-Climate IAMs between policy-evaluation and policy-optimization models that has been extensively used ever since in the relevant literature (Kelly and Kolstad, 1998; Tol, 2006; Toth, 2005).[29] Policy-evaluation models take a small set of policies and assess the consequences of these policies in a "what-if" exercise. They describe a number of interconnected relationships between economic and environmental variables that allow both to explore the propagation of disturbances into the system and to evaluate the effect of certain policy instruments in the economy, without the maximisation of a particular objective function. There are many different simulation techniques, including stochastic modelling, SD, discrete simulation, and role-playing games. Classical representatives of this family are World3 (Meadows et al., 2004, 1972), ICAM (Dowlatabadi, 1998), GTEM (Kemfert, 2005), AIM (Kainuma, 2003; Masui et al., 2006; Morita et al., 2003) and IMAGE (Alcamo et al., 1998; Bouwman et al., 2006; Stehfest et al., 2014) (also econometric models such E3MG (Barker et al., 2006) or POLES (JCR EC, 2010)). Policy-optimization models, on the other hand, optimize key policy control variables such as carbon emission control rates or carbon taxes, given formulated policy goals such as maximizing welfare or minimizing the cost of meeting carbon emission/concentration targets. Different approaches are used, such as cost-benefit analysis and cost-efficiency analysis. Examples of this category are: the DICE family (RICE, SLICE, etc.) (Nordhaus, 2010, 2008; Popp, 2006), MiniCAM/GCAM (Clarke et al., 2007; Edmonds et al., 1994), MERGE (Manne and Richels, 2004), MIT-EPPA (Chen et al., 2015; Paltsev et al., 2005), GEM-E3 (Capros et al., 2010), Phoenix (Fisher-Vanden et al., 2012) or WIAGEM (Kemfert, 2005).

[29] In fact, this is a standard classification in policy-oriented modelling (see for example (Sterman, 1991)).

2.1.2. Top-down vs. bottom-up models

Another useful categorization, traditionally used to classify energy-economy models, distinguishes between top-down (TD) and bottom-up (BU) models depending on the level of complexity of the economy and the energy systems, respectively. TD models evaluate the system from a macroeconomic perspective, addressing the consequences of policies in terms of public finances, trade, economic competitiveness, and employment (e.g. Computable General Equilibrium models, Ramsey growth models). Classic examples are the DICE-family, GTAP-E (Burniaux and Truong, 2002), ENV-Linkages (Chateau et al., 2011), SGM (Edmonds et al., 2004). On the other hand, BU models are partial equilibrium representations of the energy sector. They describe in detail the current and prospective competition of technological options and project-specific climate change mitigation policies. These models are typically cast as optimization problems which compute the least-cost combination of energy activities to meet a given demand for final energy or energy services subject to some technical restrictions and policy constraints. Some examples of BU models are MiniCAM/GCAM, POLES, MARKAL/TIMES (Loulou et al., 2005; Seebregts et al., 2002) or the World Energy Model (WEM) (IEA, 2015). In general, TD models are found to be more expensive than BU, due to greater feedback of the energy sector to the economy, and a coarser representation of the mitigation options (Böhringer and Rutherford, 2008; Hourcade et al., 2006; IPCC, 2001b, 1995a). Although conventional bottom-up models are very helpful in illustrating the possibility of radically different technology futures with significant different environmental impacts, they typically incorporate relatively little detail on non-energy consumer behaviour and interactions with other sectors of the economy, neglecting the macroeconomic impacts of energy policies. On the other hand, conventional top-down models lack technological flexibility though they represent macroeconomic effects better. For critical reviews see (Hourcade et al., 2006; Latif, 2011; Stanton et al., 2009; Toth, 2005). Closely connected with this classification is the issue of innovation and technical progress, i.e. the consideration of endogenous vs. exogenous technological change (Scrieciu et al., 2013; van der Zwaan et al., 2002).

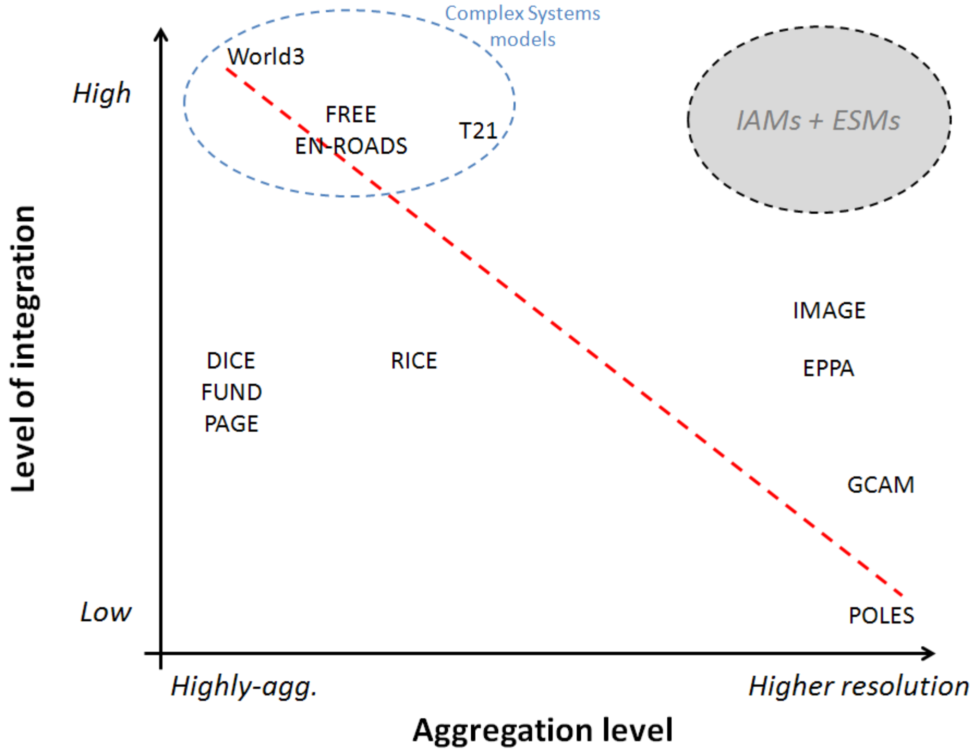
2.1.3. Highly-aggregated vs. higher-resolution models

A third frequent classification distinguishes between highly-aggregated and higher-resolution IAMs (Calvin et al., 2013). Research using highly-aggregated models largely focuses on cost-benefit analysis; that is, identification of the GHG and carbon price trajectories that balance the costs of mitigation with the associated benefits from reduced climate change (e.g. welfare optimization models). These climate impacts are modelled through damages functions that relate temperature increase with utility or GDP loss. In this framework, the long-term climate goal (e.g., global mean temperature rise) is an output of the model. These models typically discount future impacts from climate change at relatively high rates. Although this practice may be appropriate for short-term financial decisions, its extension to intergenerational environmental issues rests on several empirically and philosophically controversial hypotheses (Fiddaman, 2002; Stanton et al., 2009; Stern, 2006). Some examples of highly-aggregated models include the DICE-family, PAGE (Hope, 2011) and FUND (Anthoff and Tol, 2012). In contrast, the main goal of higher-resolution models is to understand the interactions between processes and systems that would not have been available through a purely disciplinary approach, including the energy system, the agriculture, livestock and forestry system and the other human systems. Few include also a full representation of terrestrial land-use (Otto et al., 2015). Some examples of these models are those that were used to generate the IPCC-SRES (2000a) scenarios in the IPCC framework (AIM (Morita et al., 1994), ASF (Lashof et al., 1989), IMAGE, MARIA (Mori et al., 2013; Mori and Takahashi, 1998), MESSAGE (Messner and Strubegger, 1995; Riahi et al., 2007) and MiniCAM/GCAM) and the more recent RCP scenarios (MESSAGE, AIM, GCAM, IMAGE) (van Vuuren et al., 2011b).

2.1.4. Level of integration among subsystems

Schneider (1997) proposed another classification focusing on the level of integration among sub-systems (i.e. feedbacks), roughly paralleling the development of IAMs as they incorporated more components of the coupled physical, biological and social scientific disciplines needed to address a "real world" problem like climatic change impacts and policy responses (Schneider, 1997; Schneider and Lane, 2005). They distinguish a hierarchy of five generations of IAMs from "premethodological" (essentially unintegrated) assessments to a "fifth generation" with largely integrated climate impact and policy assessments. By 2005, the authors assessed that the bulk of contemporary IAMs resided somewhere in the second and third generation categorizations, i.e. between "some integration" and "partly integrated" climate impact and policy assessments, i.e. as depicted in *Figure 2.1*. In fact, the environmental feedbacks on the economy are scarce in the literature, since most IAMs, although assuring economic consistency, tend to treat the material flows, biochemical, physical and ecological processes in a stylised way, which limits their capacity to capture feedback mechanisms of the natural system. In fact, the analysis of detailed climate impacts and feedbacks requires location-specific temperature and precipitation changes (Stehfest et al., 2014). Some exceptions from the higher-resolution models are the EPPA, AIM and IMAGE models which include environmental feedbacks through human health, agricultural productivity, water availability, etc. IMAGE also includes the Nitrogen cycle and a Biodiversity module (AIM and IMAGE have been for example applied in both IPCC assessments and in the Millennium Ecosystem Assessment (MEA, 2005)). Models from the Complex Systems approach focus by definition on these feedbacks since they tend to endogenise most of the structure of the model (fully closed system), although at much more geographical and sectoral aggregated level (e.g. World3, FREE or Threshold21). Therefore, these models tend to be global or with a low number of regions, with a reduced number of economic sectors and considering a relatively reduced set of alternative technologies. In fact, there is a trade-off between the level of integration and the aggregation level (see Figure 2.2). Also, highly-aggregated models such as DICE, FUND, PAGE and MERGE often include a damage function that directly translates temperature increases into GDP losses. However, the uncertainty on the damage functions currently used in IAMs is extremely high (Arigoni and Markandya, 2009) and subject to concerns such as the degree of arbitrariness in the choice of parameters (Ackerman et al., 2009; Pindyck, 2013; Stanton et al., 2009; Stern, 2013).

Figure 2.2: Trade-offs between the level of integration and the aggregation level in IAMs



Source: own work.

2.1.5. Deterministic vs. stochastic models

IA models, for the most part adopt best guesses about likely outcomes (Ackerman et al., 2009; Kelly and Kolstad, 1998; Lomborg, 2010; Nordhaus, 2007; Tol, 2002; Webster et al., 2012). However, since the Earth's climate is a strongly nonlinear system that may be characterized by tipping points and chaotic dynamics (Barnosky et al., 2012), forecasts are necessarily indeterminate. Although an uncertainty and sensitivity analysis can be performed with any model providing deterministic outcomes, stochastic simulation models generalize the sensitivity analysis idea by including probability distributions for all major inputs and model parameters (IPCC, 1995a; Sterman, 1991). The PAGE and ICAM models are prominent examples of integrated assessment models that take this approach. A Monte Carlo simulation applied to the MIT-IGSM model illustrated three insights not obtainable from deterministic analyses: *i)* that the reduction of extreme temperature changes under emissions constraints is greater than the median reduction; *ii)* that the incremental gain from tighter constraints is not linear and depends on the target to be avoided; *iii)* comparing median results across models can greatly understate the uncertainty in any single model (Webster et al., 2012).

2.1.6. Standard vs. biophysical economics models

Biophysical economics has been defined as “a system of economic analysis that is based on the biological and physical properties, structures and processes of real economic systems as its conceptual base and fundamental model” (Odum, 1971). In comparison with standard economics, the biophysical approach highlights the role and importance of natural resources in the economic processes, stressing the weaknesses of price signals as an adequate scarce indicator. Consequently, prices are often not modelled. Standard economics considers energy as a commodity rather than a critical factor of production. The biophysical approach argues that this assumption has been valid due to its abundance during the last century, but pointing to the fact that this might change in the future (Dale et al., 2012a; Hall and Klitgaard, 2012). In this sense, optimization and equilibrium models such as DICE, MESSAGE, MARKAL or WEM are standard economics models, while the biophysical approach has been rarely applied to climate change (World3 could be considered an exception due to its focus on persistent pollution). Instead, researchers have focused rather on energy-economy models, developing tools to analyze the implications for the energy transition and in terms of future emissions of alternative assumptions in relation to energy availability (e.g. (Brecha, 2008; Chiari and Zecca, 2011; Dale et al., 2012b; Doose, 2004; Mohr et al., 2015; Nel and Cooper, 2009; Ward et al., 2012)), few of them can be considered as IAMs of climate change due to the lack of complexity in the representation of other sectors than the energy system (an exception is the model from (de Castro, 2009)). (Dale et al., 2012a) performed a review of both approaches and existing models.

2.1.7. Equilibrium vs. disequilibrium models

As pointed out before, most of the IAMs of climate change draw on the energy-economy models of the 70s and 80s. While these models can be quite varied in scope, most share a common core of economic optimization and (general or partial) equilibrium assumptions (Fiddaman, 2002; Scrieciu et al., 2013).[30] However, optimization techniques show difficulties when the system to be optimized is relatively static and free of feedback, conditions that are rarely true for the social, economic, and ecological systems. Hence, this approach is not compatible with all the principles for dynamic modelling, especially in relation to the difference between desired states and actual states and the balance between short and long-term run that arise in a context of non-perfect markets (Sterman, 1982). Thus, alternatives focusing instead on disequilibrium are proposed. In this sense, two main approaches exist in the literature: on the one hand, disequilibrium economics that consider that markets do not necessarily clear, neither in the short run nor in the long run and that economic systems evolve and are under continuous perturbations (Scrieciu et al., 2013) (e.g. the

[30] In the words of Scrieciu et al., (2013): “This is demonstrated, for instance, by undertaking a quick survey of relatively recent and widely cited model comparison exercises in the area of economics and climate change mitigation. Out of 30 climate–economy models spanning seven model comparison studies, only one model coming from the nonoptimization, nonequilibrium simulation approach was included in the analysis—the hybrid macroeconometric E3MG model drawing on demand-driven growth and post-Keynesian economics”.

post-keynesian macroeconomic nonequilibrium E3MG model (Barker and Scrieciu, 2010)[31]). On the other hand, an approach coming from the physical sciences studying Complex Systems is proposed that, instead of imposing equilibrium, analyzes the conditions to reach such equilibrium (Fiddaman, 2002; Meadows et al., 1972). World3 developed in the 70s represents a good example of the latter, and this radical difference in the approach may explain to a large extent the misunderstandings in the scientific debate.

2.1.8. The Complex Systems approach

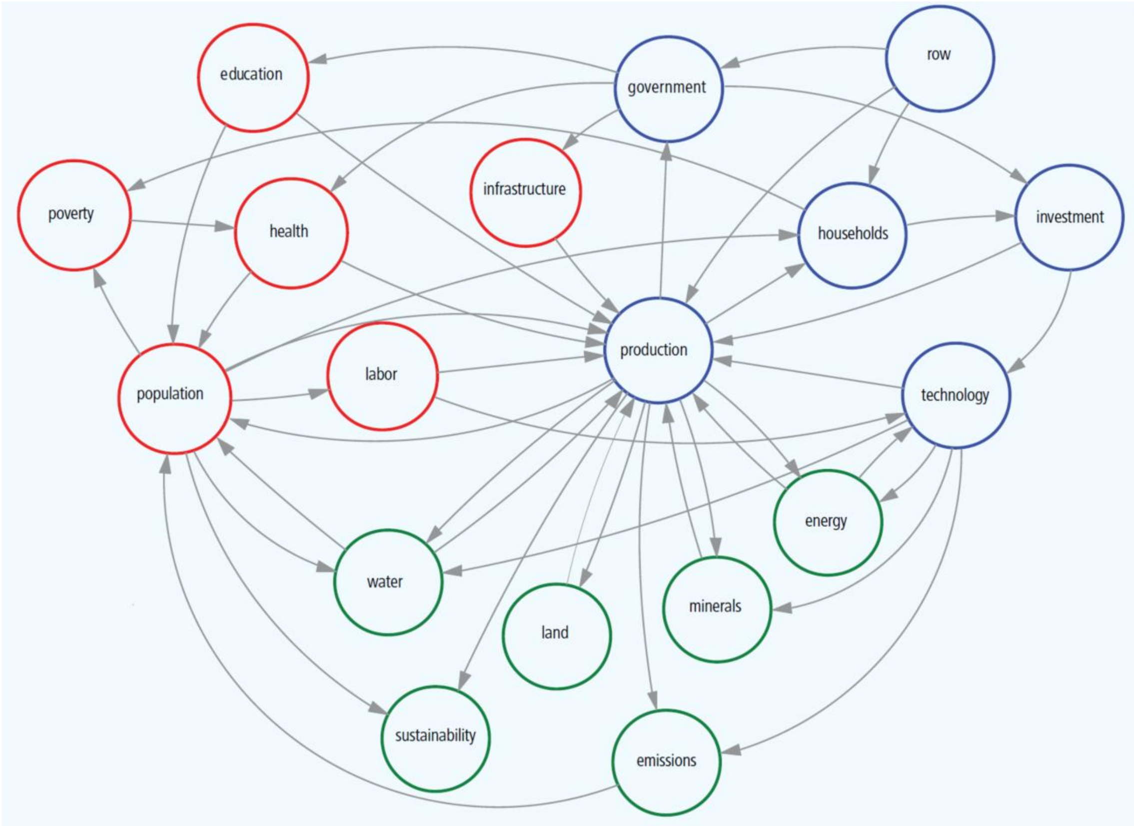
Among IAMs, those following Complex Systems (or Systems Theory) constitute an exception to the dominant approach characterized by a low integration level and following the equilibrium paradigm. Complex Systems focus on the modelling of systems characterized by dynamic complexity where “everything is connected to everything else”, i.e. most of the structure is endogenous (see Figure 2.3 for an example). Essentially, causes lead to effects, which then become causes in turn: the world system is thus modelled as a full-closed system characterized by abundant feedback-loops. This perspective entails a profound shift in the modelling paradigm from a one-way to a circular causality: “In effect, it is a shift from viewing the world as a set of static, stimulus-response relations to viewing it as an ongoing, interdependent, self-sustaining, dynamic process” (Richmond, 1993). Thus, *it is the interaction* between human activities and natural feedbacks which causes environmental changes. The ultimate objective of Complex Systems is to understand how the structure of the system analyzed creates its behaviour (Davies and Simonovic, 2010; Meadows et al., 2004, 1972; Sterman, 2000).

SD is a popular method to study complex systems due to its ability to explicitly represent rich feedbacks, delays and non-linearities between subsystems since they are not rigidly determined in their structure by mathematical limitations as optimization models often are (Sterman, 1991). On the other hand, SD models show complications in the description of the decision rules, the quantification of soft variables and the choice of the model boundary (Sterman, 1991).

Despite great spread after the development of the World2 and World 3 models (Forrester, 1971; Meadows et al., 1972) and the publication of the LtG report (e.g. WIM from Mesarović and Pestel (1974), the [US] Government’s Global Model (Barney, 1980), etc.), the application of the Complex Systems approach to global change and sustainability declined considerably. However, this approach has somewhat reemerged in the last years. The following models represent modern examples: FREE (Fiddaman, 2002), ANEMI (Akhtar et al., 2013; Davies and Simonovic, 2010), Threshold-21 (Bassi et al., 2011, 2010) and EN-Roads (Siegel et al., 2015; Sterman et al., 2012).

[31] Other disequilibrium frameworks such as stock-flow consistent models (e.g. FALSTAFF (Jackson et al., 2015)) could be applied as IAMs in the future.

Figure 2.3: Subsystem diagram of the Threshold 21 model



Source: UNEP (2014).

Another alternative approach, often applied in a SD framework, is agent-based modelling that focus on the different behaviours among different actors. Thus, agent-based models (ABMs) simulate the behaviour of social and economic systems by differentiating between different rationally bounded controlling agents largely drawing on the cultural theory of risk. In this way, they manage to provide more realistic microeconomic theoretical foundations for the driving forces of economic processes (Farmer et al., 2015; Janssen and de Vries, 1998; Scrieciu et al., 2013). Two ABMs in particular, ENGAGE (Gerst et al., 2013) and Lagom RegiO (Wolf et al., 2013), represent progress towards the successful development of agent-based integrated assessment models (ABIAMs). ENGAGE is a flexible multi-module modelling framework designed to simulate the interaction among international climate treaty negotiation, national policy formation, and the dynamics of domestic economic and technological systems. Lagom RegiO is a multi-agent model of several growing economic areas in interaction.

2.1.9. Towards model hybridization

In principle, a model could be characterized by indicating its approach in relation to the seven highlighted classifications. For example, a model can be for policy-optimization, top-down, highly-aggregated, with an intermediate level of integration among subsystems, deterministic and following a standard economics equilibrium dynamic approach: an example of the former would be the DICE-family. However, in practice, not all integrated models fit perfectly the typologies presented above. In fact, after more than two decades of development, most research groups have directed efforts at model hybridization, thus allowing for some overlap between sub-groups of IAMs (Arigoni and Markandya, 2009; Edenhofer et al., 2010; Fiddaman, 2002; Hourcade et al., 2006; IPCC, 2007b; Scrieciu et al., 2013; Stanton et al., 2009). One option is the coupling of existing bottom-up and top-down models (e.g. MARKAL-MACRO (Loulou et al., 2004) and MESSAGE-MACRO (Rao et al., 2006)) so as to use the advantages of both approaches.[32] Another increasing field of hybridization is the development of simulation based optimization models. This means embedding optimization procedures in the policy-evaluation models, which has been specially popular in SD-based models (e.g. FREE, T21-World, ANEMI); although not limited to it (other examples are MERGE, REMIND and MiniCAM/GCAM) (Akhtar et al., 2013). ABM and SD are also being increasingly combined, such as in the MADIAMS family (Hasselmann and Kovalevsky, 2013) or the GRO-SD development from World3 (Pasqualino et al., 2015). Other options are to directly build hybrid models (e.g. E3MG, IMACLIM models (Sassi et al., 2010), WITCH (Bosetti et al., 2006), MIND (Edenhofer et al., 2005) and REMIND-R (Leimbach et al., 2010)). In the case of AIM, a whole family of models covering most categories has been developed (Kainuma, 2003; Masui et al., 2006; Morita et al., 2003). A different approach is the design of a flexible tool that can be used as a basis to create models of different energy systems (where each requires its own unique data structures) rather than the development of a model of a particular energy system. LEAP is an example supporting a wide range of modelling methodologies (Heaps, 2012).

In Table 2.1 around 40 representative IAMs are classified following the axe policy-evaluation vs. policy-optimization. Models are also categorized following the traditional TD/BU taxonomy for energy-economy models, Complex Systems and ABM approaches. In fact, each category represents a modelling approach with a different focus: energy-economy modelling tend to focus on scenario planning, Complex Systems the on interactions among subsystems and system behaviour, and ABM on the system response when accounting for heterogeneous actors.

Given the characteristics of the problem and the diversity of associated policy dilemmas, it is difficult to conceive an integrated model capable of providing the best answers to all questions. The different model structures provide results that inform climate and development policy in very different ways. In short, two things should be noted: firstly, that each of these modelling approaches has its own strengths and weaknesses, and secondly that different policy questions require different perspectives and, therefore, different modelling approaches. In the words of Sterman:

The inherent strengths and weaknesses of computer models have crucial implications for their application in foresight and policy analysis. Intelligent

[32] However, there are many theoretical and computational difficulties associated with such coupling (see for example (Burniaux and Truong, 2002).

decision making requires the appropriate use of many different models designed for specific purposes—not reliance on a single, comprehensive model of the world (Sterman, 1991)*.*

Table 2.1: Representative global IAMs of climate change

		Policy-evaluation	Policy-optimization
Energy-Economy	**Top-Down**	AIM/Dynamic global GTEM *PAGE*[b] *ICAM*[b]	DICE-family FEEM-RICE FUND GEM-E3 GTAP-E SGM Phoenix WIAGEM ENV-Linkages
Energy-Economy	(Macroeconomic model coupled with an energy model)		MERGE MIT-EPPA MARIA
Energy-Economy	*Hybrid*	AIM/Emission-Linkage E3MG	REMIND IMACLIM-R MIND MARKAL-MACRO MESSAGE-MACRO WITCH
Energy-Economy	(Energy model coupled with a partial depiction of the economy)	POLES	GCAM/MiniCAM
Energy-Economy	**Bottom-Up**	AIM/Enduse IMAGE	MARKAL/TIMES MESSAGE WEM
Complex Systems		World2 & World3 WIM [US] Government's Global Model T21-World ANEMI	
Complex Systems		FREE EN-ROADS	
Agent-Based-Modelling		MADIAMS-family ENGAGE Lagom RegiO GRO-SD	

Notes: Classification following the axe policy-optimization vs. policy evaluation. [a]DICE family includes: DICE, RICE, ENTICE, AD-RICE among others. [b]Stochastic models.

Source: own work.

2.2. Mitigation pathways assessment

In this section the insights obtained by current climate IA modelling in relation to the future pathways for climate stabilization are overviewed based on the review from the last IPCC report (IPCC, 2014a) and from inter-model comparisons exercises (Leon Clarke et al., 2009; Edenhofer et al., 2010; Krey et al., 2013; Kriegler et al., 2014).

Firstly, it is important to recognize that the energy system, which accounts for the majority of GHG emissions, is slow to change even in the face of concerted policy efforts (Davis et al., 2010; Fouquet, 2010; GEA, 2012; IPCC, 2014a). The last IPCC report concluded that “there are multiple mitigation pathways that are likely to limit warming to below 2°C relative to pre-industrial levels. These pathways would require substantial emissions reductions over the next few decades [40 to 70% reduction in GHG emissions by 2050, relative to 2010 levels] and near zero emissions of CO2 and other long-lived GHGs by the end of the century. Implementing such reductions poses substantial technological, economic, social and institutional challenges, which increase with delays in additional mitigation and if key technologies are not available” (IPCC, 2014b). For example, in the last IPCC assessment 114 scenarios were classified in the RCP2.6 category (i.e. radiative forcing between 2.3 – 2.9 W/m^2).[33]

All mitigation strategies in climate IAMs require setting a price on carbon (explicitly through a carbon tax or implicitly through a carbon cap). Without it, the required structural shifts and technological developments of current R&D technologies would never happen at a significant level. Model scenarios are typically designed to find the least-cost pathway to meet a long term goal, in some cases under specific constraints, such as the availability of certain technologies or the timing and extent of international participation. Despite the diversity of IAMs of climate change, robust findings from the field are:

- Mitigation options are available in every major sector.
- Many adaptation and mitigation options can help address climate change, but no single option is sufficient by itself.
- Electricity is the easiest sector to decarbonise.[34]

Three interrelated factors are particularly important determinants of emissions profiles in the modelling literature:

[33] In the IPCC 4th Assessment Report (IPCC, 2007b), only three models containing 6 out of a total of the 177 mitigation scenarios presented results for the lowest category of a radiative forcing (2.5 – 3.0 W/m^2).

[34] In the majority of low concentration stabilization scenarios, the share of low carbon electricity supply (comprising renewable energy (RE), nuclear and CCS, including BECCS) increases from the current share of approximately 30% to more than 80% by 2050 and 90% by 2100, and fossil fuel power generation without CCS is phased out almost entirely by 2100 (IPCC, 2014a).

(1) The degree of overshooting: Overshoot scenarios entail less mitigation today in exchange for greater reductions later.

(2) Technology options and associated deployment decisions:

- Many models cannot reach 2100 concentration levels between 430 ppm and 480 ppm CO2eq if the full suite of low carbon technologies is not available.
- Advanced bioenergy and CCS (and their combination, i.e. advanced bioenergy coupled with CCS, BECCS) figure among the “key technologies” (especially in overshooting scenarios).
- Afforestation is a major mitigation option.

(3) Policy assumptions: climate stabilization feasibility depends critically on the early and full participation of all countries.

The set of technologies for carbon dioxide removal such as BECCS and afforestation has been assessed in the last IPCC report as the most critical in the context of the timing of emission reductions. This is due to the fact that, while GHGs continue to grow globally we approach the carbon-budget, the possibility to make the transition without removing emissions from the atmosphere fades. However, the feasibility of scaling-up these technologies to the required levels is still uncertain since they are still in a research and development stage (Sims et al., 2010; UKERC, 2012; van Renssen, 2011)

A wide range of models such as AIM, IMAGE, MESSAGE, GCAM, GET, MERGE, REMIND, POLES, TIMER (Azar et al., 2010; Calvin et al., 2009; Edenhofer et al., 2010; Luderer et al., 2012; Masui et al., 2011; Rao et al., 2008; Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011a; Vuuren et al., 2007) has shown that it is technically possible and economically viable to limit radiative forcing (RF) to 2.6 W/m^2 under very optimistic (very unlikely to hold) conditions: if all regions participate simultaneously in emission reduction with access to the full suite of technologies and effective and immediate long-term policy instruments are applied promptly (particularly carbon pricing, typically from 2020 (IPCC, 2014a; Iyer et al., 2015; Staub-Kaminski et al., 2014).

In relation to the aggregate economic implications of these transformation pathways, mitigation is expected to affect economic conditions through several avenues, only some of which are included in estimates from integrated models. Reductions in the consumption of energy services and the use of more expensive technologies are the predominant factors captured by the models and lead to aggregate economic losses in relation to counter-factual baseline scenarios without mitigation policies. Change in welfare, GDP losses, consumption losses and area under the marginal abatement cost function are more widely used ways of measuring these losses.

An useful benchmark for exploring aggregate economic mitigation costs is estimates based on the assumption of a stylized implementation approach considering efficient global markets in which there are no pre-existing distortions or interactions with other, non-climate market failures. An ubiquitous price on carbon and other GHGs is applied across the globe in every sector of every country and rises over time in a way that minimizes the discounted sum of costs over time. These “idealized implementation” scenarios are included in most studies as a benchmark against which to compare results based on less-idealized circumstances. According to the review of these scenarios in the last IPCC report, most of global consumption loss estimates for reaching levels of low climate stabilization by 2100 range at relatively low levels, between 1-4% in 2030, 2-6% in 2050, and 3-11% in 2100 relative to consumption in the baseline (IPCC, 2014a). This variability can be attributed to differences in model assumption (e.g. driving socio-economic forces, technological portfolio availability and different model structure and scope), although availability, cost, and performance of mitigation technologies dominates (CCS technologies having a critical importance due to their potential versatility and ability to produce negative emissions when coupled with bioenergy).

These ranges are extremely low when comparing with the projected 4-10 times increases in global GDP along the century (i.e. a mitigation cost of 10% by 2100 would mean that the global GDP in that year would be instead *only* 3.6 to 9 times higher than current levels). The fact that the action to prevent dangerous climate change incurs in relative low costs in relation to the baseline might seem counterintuitive due to the foreseen potential disruption potential of climate change without mitigation. This is due to at least three reasons: (i) the reviewed ranges are biased downwards by the fact that results from models not successfully solving (thus reporting scenario unfeasibility) are not included; (ii) climate IAMs generally do not include the benefits from reducing climate change, i.e. they do not include the damages of climate change in the baseline scenario (see section 2) (Rosen and Guenther, 2015);[35] (iii) climate IAMs, for the most part, adopt best guesses about likely outcomes (Ackerman et al., 2009; Kelly and Kolstad, 1998; Nordhaus, 2007; Tol, 2002; Webster et al., 2012) while probabilistic analysis have consistently showed that comparing median results across models can greatly understate the uncertainty in any single model (Webster et al., 2012).[36] Additionally, these “idealized implementation” scenarios do not consider a number of factors that are fundamental in actual world that tend to increase real mitigation costs, such as restrictions to technology combinations and availability (Iyer et al., 2015; Kriegler et al., 2014), fragmented action and delayed participation (Leon Clarke et al., 2009) and the assumption of idealized implementation environment with perfectly functioning economic markets without market failures, institutional constraints and pre-existing tax distortions (IPCC, 2014a).

[35] And when included, the damages functions are found to grossly underestimating risks (Pindyck, 2013; Rosen and Guenther, 2015; Stern, 2013).

[36] Exceptions exist that find negative losses, i.e. benefits to applying a carbon price, such as models that additionally consider recycling of revenues raised from the full auctioning of carbon permits to the energy sector and applying carbon taxes for non-energy activities (e.g. E3MG (Barker et al., 2006) (Edenhofer et al., 2010).

Finally, substantial regional variation in costs is estimated depending on the nature of international participation in mitigation, regional mitigation potentials, and transfer payments across regions. Under the assumption of efficient markets, effort-sharing schemes have the potential to yield a more equitable cost distribution between countries (Höhne et al., 2014).

2.3. Discussion on the state of the art of IA modelling and future developments

IA modelling activity for climate change experienced a rapid surge after the publication of the first IPCC report in 1990, increasing the number of projects from 3 to approximately 40 by the end of that decade (Parson et al., 1997). However, by then the field was assessed to be still at an early stage of development, with few and tentative significant insights, mainly due to the novelty of the integration approach and the extensive complexities involved. It was estimated a long way before IAMs would be fully accepted by the scientific modelling community on the one hand, and by the decision-making community on the other (Parson et al., 1997; Rotmans and Asselt, 1999; Schneider, 1997).

Since then, with increasing computational power and improvements in algorithm design, IAMs have been able to increase in complexity, particularly assisting the progress of the field by allowing increasing the integration of subsystems while keeping the resolution time workable (Sarofim and Reilly, 2011). Examples of features added to IA modelling were the incorporation of more regions and sectors, more detailed science components with higher resolution or inclusion of additional physical processes, etc. (see Table **2.2** and Figure 2.4). Notably, the agriculture land-use change was integrated in the field and many experiments explicitly addressed some of the previously highlighted limitations (e.g. uncertainty analysis (Mastrandrea and Schneider, 2001) or endogenous technological change (Kahouli-Brahmi, 2008)).

Table 2.2: Evolution of the IAM field and future developments to late 2010s

Time	Features added to IA modelling
Early 1980s	Energy-economy models
Early 1990s	+ Ocean carbon cycle + Climate model emulator + Atmosphere chemistry
Late 1990s	+ Energy technologies + Sulphur & Aerosol
Late 2000s	+ Non-sulphur aerosol + Agriculture land-use
In the decade ahead (to late 2010s)	+ Ecosystem impacts + Hydrology + Fresh water systems + Energy impacts + Local air quality + Ocean acidification + Sea level and ice + Coastal zones

Source: Edmonds and Smith (2008).

After the publication of the IPCC-TAR (IPCC, 2001a), the situation changed considerably for climate IAMs. Schneider and Lane (2005) referred to “a new phase in integrated assessment modelling”. Tol (2006) also affirmed that “the situation has changed considerably. Integrated assessment has become widely accepted [...] and IA modellers seem more concerned about the day to day business of applying and developing their models and databases than about the grand questions of the philosophy of science. Yet, a quiet revolution is taking place, as integrated assessment models are increasingly challenged by earth system models of intermediate complexity and, in the not too distant future, full complexity models”. In fact, important phenomena such as ecosystem impacts, hydrology, ocean acidification or many feedbacks are generally not implemented in the IAMs, although some of them are currently under research, e.g. water integration (Hejazi et al., 2014) or the investigation of full-scale integrated systems (Hilderink et al., 2008). Krey (2014) identifies two broader categories of current model developments: (1) the increase in the degree of integration and (2) the increase in the representation of heterogeneity (or level of detail) of various entities (e.g., spatial, sectoral and socioeconomic) to adequately address distributional effects. However, the progress is slow due to the complexity of the task. In fact, there is a continuous tension between the limitations of highly aggregated models on both spatial and temporal scales that do not provide sufficient detail of processes, and the more detailed models which cannot represent feedbacks and processes that only appear in models that represent the economy or the earth system at a high level (Sarofim and Reilly, 2011) (see also Figure 2.2).

On the other hand, IAMs often still adopt deterministic estimates or "best guesses" about a number of crucial unknowns. This procedure eliminates uncertainty from the model, at the cost of making the results dependent on the particular estimates that are employed. However, there has been an increasing interest on the exploration of technological, economic, political and climatic uncertainties in the last years (IPCC, 2014a; Knutti and Hegerl, 2008; Meinshausen et al., 2009; Rogelj et al., 2013; van Vuuren et al., 2008; Webster et al., 2012; Wigley and Raper, 2001). Still, these experiments are rather exceptions, and calls for systematic uncertainty analysis have been made to strengthen the deductions obtained from IAMs (Hedenus et al., 2013).

Critics to the IA process and models are intertwined with scientific debates that often transcend the field of climate change and sometimes go even beyond science, e.g. politics, due to their intention for being policy-relevant. In this sense, critics have highlighted different shortcomings that are related with the organization, approach, methodologies and hypothesis of the IPCC framework. In fact, climate science and therefore climate IAMs have evolved closely with the IPCC process in the last three decades due to the adoption of a "consensus approach" as the strategy to deal with scientific uncertainties in interfacing science and policy.[37] The following is a non-systematic list of some of the topics raised in the literature: a questioning of the utility of the IPCC's "consensus approach" (Oppenheimer et al., 2007; Tol, 2011; van der Sluijs et al., 2010) and the difficulties in introducing innovations in the intergovernmental body (InterAcademy Council, 2010; Tol, 2011); the design of scenarios (Raskin et al., 2002, 2010) including the failure to explore surprises and/or extremes which are poorly understood but have the potential to cause enormous damage (Lenton and Ciscar, 2013; Oppenheimer et al., 2007); the treatment of uncertainty (Oppenheimer et al., 2007; Webster et al., 2003; Weitzman, 2009); the lack of integration among subsystems (Bassi and Shilling, 2010; de Castro, 2009; Fiddaman, 2002); the assumption on future energy abundance and the neglection of the role of energy in economic growth (de Castro et al., 2013b; Höök and Tang, 2013; Trainer, 2010); optimistic assumptions on the energy transition and future technologies availability (Anderson, 2015; Arvesen et al., 2011; Pielke et al., 2008); the use of a conservative methodology that has systematically downplayed the impacts of climate change (Brysse et al., 2013), the lack of model transparency (NCC, 2015; Schneider, 1997; Stanton et al., 2009) and of research in inter-comparison exercises (Hedenus et al., 2013; O'Neill and Nakicenovic, 2008); the preponderance of natural sciences research over social sciences –excepting Economics- (Barnes et al., 2013; Garb et al., 2008); the lack of pluralism in the economic modelling (Scrieciu et al., 2013), the identification of progress following western values (Anderson and Bows, 2012), etc.

[37]Van der Sluijs et al. (2010) list three strategies to deal with scientific uncertainties in interfacing science and policy: 1) quantify uncertainty, 2) building scientific consensus, and 3) openness about ignorance.

The above list shows that current debates are rooted in a diversity of factors such as uncertainties due to incomplete knowledge of scientific processes, different scientific approaches and even diverging cultural values. In the light of these controversies, the relevant question is then: how useful is climate IA modelling nowadays? A recent editorial in *Nature Climate Change* raised a similar question: “IAM helpful or not?” (NCC, 2015). The dominant view in the political and scientific arena since about the publication of the 3rd IPCC assessment (IPCC, 2001a), is that climate IAMs, especially higher-resolution models, are an useful tool for policy-advice. The application of “different IA methods and models each have their own strengths and weaknesses. Understanding these strengths and weaknesses is useful in order to best match a method to a problem, and in order to assess the limits of the results produced at the end of the process” (Sarofim and Reilly, 2011). Main identified achievements include insights into mitigation options and climate change dynamics and impacts, analysis of optimal timing of emission reductions, weighting of different GHGs, or impacts of alternative energy promotion policies; additionally, IAs have contributed to identify and rank technological, economic, political and climatic uncertainties (IPCC, 2014a; Mastrandrea and Schneider, 2004; Rogelj et al., 2013; Schaeffer et al., 2008; van Vuuren et al., 2008; Webster et al., 2012). The limitations are usually discussed in a constructive way to stimulate progress in the field through the integration of new features (Janetos et al., 2009; Staub-Kaminski et al., 2014).

On the other hand, some authors call for addressing the existing uncertainties (both model-dependent and scientific) beyond its mere theoretical acknowledgment. Thus, the widespread use of uncertainty and sensitivity analyses in and between models, and a qualitative interpretation of the results are suggested. In the words of Hedenus et al., (2013): “Considering this level of complexity, one must interpret the results of models with care and be aware of the limitations of such models and their results. Rather than generating foresights the models should be seen as tools for generating insights and offering plausible pictures on how the future may develop in internally consistent way. These pictures of the future could be generated for different sets of assumptions on important driving factors such as climate policies, resources, technology progress, etc. In that way, qualitative insight may be generated on how these parameters and different policy alternatives interact”. Furthermore, the sequential structure of most IAMs prevents from having unstable properties or multiple solutions, thus favouring the obtainment of plausible outputs in the simulations. For this reason, IA modelling has been criticised as being practiced by “professional experts, rather than scientists as we have thought of scientists historically” (Norgaard and Baer, 2005). Highly-aggregated models focusing on cost-benefit are more controversial due to the low reliability of the applied damage functions and the differences on discount rates (Fiddaman, 2002; Stanton et al., 2009; Stern, 2006). For these reasons, the IPCC only considers outcomes from the higher-resolution IA models (IPCC, 2014a). Hence, the usual view is that, for informing policy advice is better to have an incomplete model than not having model at all.

In relation to the current usefulness of IAMs, it is important to note that it ultimately depends on the nature of the pursued objective. In fact, there is a great difference between applying climate IAMs to produce plausible emission scenarios for GCMs, and applying them to analyse specific and sectoral policies, i.e. analysing consequences or causes of climate change. In fact, current IAMs should be better understood as a scenario planning tool rather than a predictive instrument since they have not been tested against history (backcasting) due to the absence of the required data at global level, contrary to, for example, to GCMs. Thus, the key questions should rather be: what are climate IAMs useful for, and what improvements can be made to expand the scope of their usefulness? [38]

The increasing policy relevance of climate IAMs has a paradoxical effect on the resulting scientific assessments since there is a trade-off between policy impact and visibility of the publications and the prudence in communicating the results.[39] In fact, most of the teams developing climate IAMs are currently involved in projects aiming to integrate their models with ESMs in order to advance towards the further integration of human activities with the biosphere processes, overcoming the historical limited cooperation between these communities (Tol, 2006; van Vuuren et al., 2012a, 2011c). This coupling requires the collaboration with the third main community in the study of climate change: Impact Adaptation and Vulnerability (IAV) modellers that study the consequences of changes to Earth's climate for humans and Nature (Janetos et al., 2009). Figure 2.4 depicts the current scope of research and integration among these three fields; as main common areas of interest and interdependencies stand out land-use, ecosystems and sea level rise. For example, the iESM project that links GCAM with CESM (Collins et al., 2015) or the IGSM model from MIT that applies EPPA and a set of models to represent the Earth System (Sokolov et al., 2005). The GISMO project from PBL represents an alternative approach including the social dimension of sustainability to IMAGE and focusing on indicators such as Quality of Life and Millennium Development Goals (Hilderink et al., 2008). PRIMA is another example at regional level in USA (Kraucunas et al., 2014). The integration is already providing interesting outcomes that differ qualitatively from previous results: as expected, the integration of new processes causes the emergence of new properties (Janetos et al., 2009; Meadows et al., 1972). For example, Jones et al., (2013a) found that the current exclusion of climate forcing from land-use changes (e.g. albedo, changes in latent heat flux, etc.) in IAMs results in inconsistent scenarios with temperature change errors exceeding 3°C in some regions. These results have important implications since they demonstrate that the assumptions used to build the RCPs scenarios do not hold.[40]

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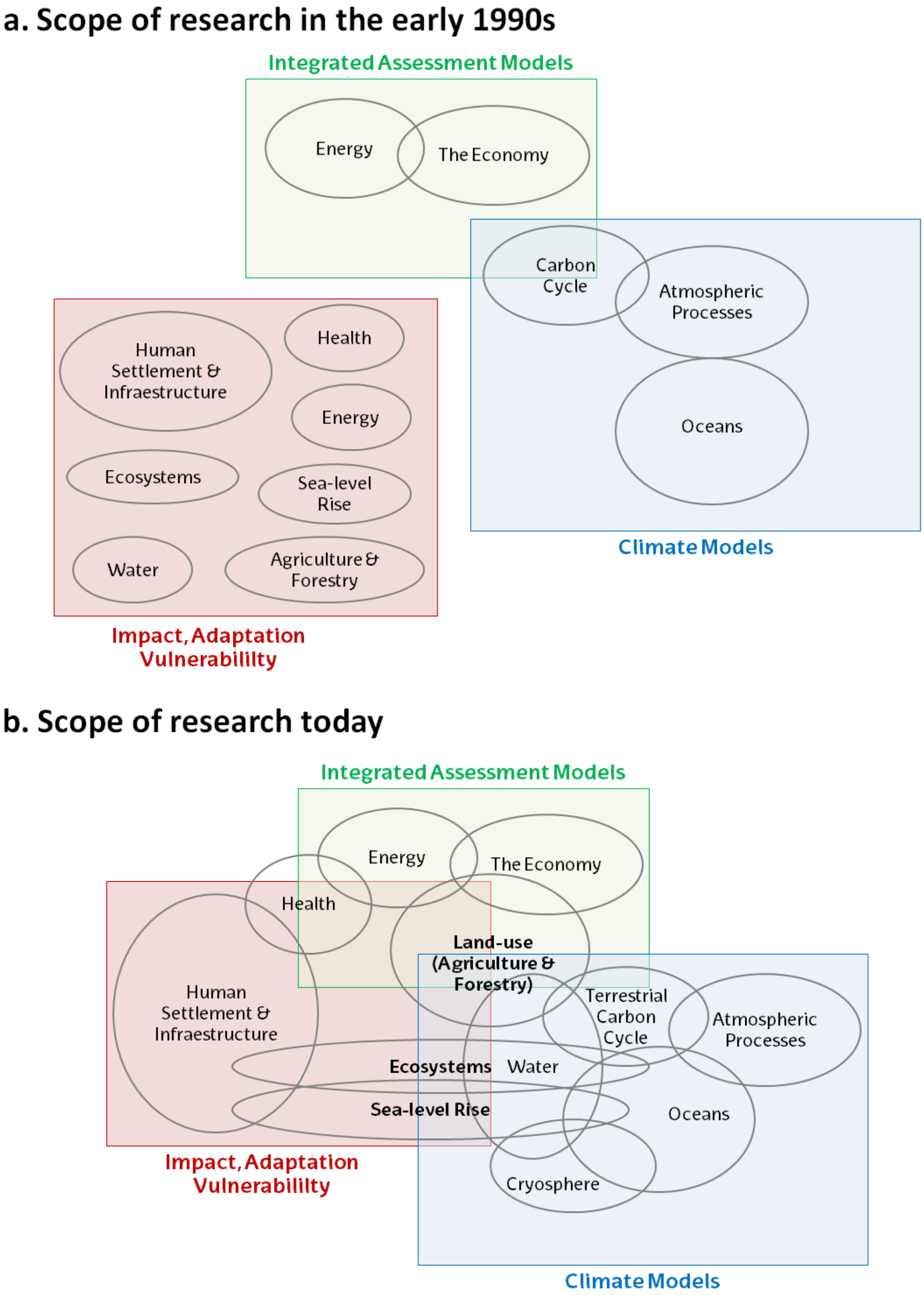
[38] This paragraph is a summary of the reflections from Robert Link, GCAM developer, in relation to the usefulness of IAMs of climate change (Personal Communication 1-3-2016).

[39] In the words of Krey (2014): "...with the increasing policy relevance [...] the interpretation of results deserves particular attention" including "interpreting the results of a particular study against the background of the original study design and objectives as well as taking into account the strengths and weaknesses of the applied models. For the scientific community this means adopting a careful communication strategy, pointing out the limitations of their analyses, and stating caveats explicitly which is not always easy given that policy impact and visibility are becoming increasingly important indicators for the evaluation of research groups."

[40] Additionally: "…equivalent LUC and CO_2 forcings can lead to substantially different climate change patterns, not just in temperature but also in atmospheric and hydrological responses. In

Figure 2.4: Scope of research in the three major climate science research communities (a) in the early 1990s; and (b) today



Source: adapted from Janetos et al., (2009).

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fact, the patterns of climate change from these forcing agents differ so much that when they are combined to yield nearly neutral forcing, a new, hybrid pattern of global temperature and precipitation change emerges" (Jones et al., 2013b).

Another direction towards improving the consistency of current IAMs is the integration of environmental impacts on the socioeconomic variables, which usually follow an exogenous evolution (Pollitt et al., 2010). Let us consider the case of human population: although in most scenarios demographic past trends by region are extrapolated, this hypothesis is incompatible with the expected regional impacts of climate change in baseline scenarios. For example, Hansen and Sato (2016) concluded that "the tropics and the Middle East in summer are in danger of becoming practically uninhabitable by the end of the century if business-as-usual fossil fuel emissions continue".

Some recent works are claiming that current climate IAMs are not an appropriate tool for policy-advice due their inability to take into account deep (inescapable) uncertainties related with scientific knowledge, human behaviour, future opportunities, etc. Among the most radical views, it is argued that elaborate IAMs will never be useful for policy-advice (e.g. (Pindyck, 2015, 2013; Rosen and Guenther, 2015)). Their attitude in fact emerges as a reaction to the perceived current misuse of IAMs, and those authors in fact propose the use of radically different models (e.g. very simplified models with a strong focus on the precautionary principle). On the other hand, other authors are arguing that these shortcomings might be addressed by the development of a new generation of IAMs based on novel approaches such as ABM or Dynamic Stochastic General Equilibrium models (Farmer et al., 2015; Scrieciu et al., 2013; Stern, 2016, 2013). The emphasis is put on simulation (vs. optimization) and heterogeneous rationally bounded agent (vs. representative agent) models due to their expected capacity to better capture socioeconomic realities and understand economic behaviour, in combination with an explicit incorporation of uncertainties about the future through the introduction of shocks to output, consumption or environmental damages (i.e. allowing to account for the possibility of catastrophic outcomes and irreversible damages). In fact, optimization models have been to date the most common in the literature (see *Table 2.1* and Scrieciu et al., (2013)), but alternative relevant frameworks are emerging in the last years such as the E3MG model (the only nonoptimization, nonequilibrium simulation model considered in the last seven model comparison studies from the Energy Modelling Forum up to 2013 (Scrieciu et al., 2013)) or the T21 (a SD model applied for the UNEP reports about *Green Growth* (UNEP, 2011b)).[41]

Finally, it has been suggested that, in addition to the traditional focus on product and credibility, the IA approach would benefit from more focus on process, relevance, legitimacy, and the multiple potential audiences. Also, increased openness and transparency can itself lead to increased legitimacy and salience, improving its ability to achieve the larger goals of reaching the public and policy makers (Sarofim and Reilly, 2011).

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[41] For an extensive review examining the links between macroeconomic perspectives and sustainable development in economy-environment models (including almost 20 IAMs) see Pollit et al., (2010).

PART II: DEVELOPMENT AND APPLICATIONS OF ENVIRONMENTAL IA MODELLING OF CLIMATE CHANGE

PART II.A: Future pathways and non-renewable energy resources availability

CHAPTER III

3. Likelihood of climate change pathways under uncertainty on fossil fuel resources availability[42]

Research to date on climate change related uncertainties has primarily focused on technological, economic, political and climatic factors (IPCC, 2014a; Knutti and Hegerl, 2008; Mastrandrea and Schneider, 2004; Meinshausen et al., 2009; Rogelj et al., 2013; Schaeffer et al., 2008; van Vuuren et al., 2008; Webster et al., 2012; Wigley and Raper, 2001). Although future emissions critically depend on the availability of fossil fuel resources (responsible for 65% of total GHGs in 2010 (IPCC, 2014a)), their global resource base is commonly considered to be large enough to cover the bulk of the energy demands through the 21st century in current baseline scenarios based on the high estimates assumed by the IPCC (Höök and Tang, 2013; IPCC, 2014a; IPCC SRES, 2000a; McCollum et al., 2014; Rogner et al., 2012; van Vuuren et al., 2011b). As the Special Report on Emissions Scenarios (SRES) report concluded, "It is evident that, in the absence of climate policies, none of the SRES scenarios [ending at 2100] depicts a premature end to the fossil fuel age" (IPCC SRES, 2000a). Accordingly, fossil fuel resource abundance, understood as vast geological availability accessible at an affordable price, is a default assumption in most of the prominent IAMs used for climate policy analysis, and future energy transitions are thus largely modelled as demand-driven transformations (Höök and Tang, 2013; McCollum et al., 2014; Rogner et al., 2012).

The consensus on the abundant availability of fossil energy was pointed out as a shortcoming in the IPCC-AR5 following the review of the full range of baseline scenarios in the literature (IPCC, 2014a). According to the report, although some assumptions vary considerably (e.g., future income, energy demand, and carbon

[42] This chapter is currently under submission as: Iñigo Capellán-Pérez, Iñaki Arto, Josué M. Polanco-Martínez, Mikel González-Eguino, and Marc B. Neumann. "Likelihood of Climate Change Pathways under Uncertainty on Fossil Fuel Resources Availability." *Submitted*, 2016.

intensity), there is less diversity in others: “the scenario literature does not systematically explore the full range of uncertainty surrounding development pathways and possible evolution of key drivers such as population, technology, and resources” (IPCC, 2014a). In fact, a fraction of unconventional fuels has only recently become economically profitable and the existing estimates for these are sparse and with a tendency to overestimation (Brecha, 2008; Höök and Tang, 2013; Hughes, 2013a; Inman, 2014; McGlade et al., 2013; McGlade and Ekins, 2015; Mohr et al., 2015). Although in-situ resources of unconventional hydrocarbons are vast, the proportion that can be recovered economically and at a net energy profit is much smaller (Hughes, 2013b; Rogner et al., 2012). For coal, usually seen as a vast abundant resource, there are large uncertainties related to the available resource base due to the lack of transparent, robust and up-to-date estimates at a global level. Recent studies are pointing to potentially large overestimates in coal resource assessments as geologists uncover restrictions on the coal that is extractable (Heinberg and Fridley, 2010; Höök et al., 2010; Mohr et al., 2015; Rutledge, 2011). This phenomenon is especially relevant in some regions that contain a substantial share of the global resource, such as the USA (30% of the world’s reported reserves) where the National Academy of Sciences recently concluded that existing coal reserve data are insufficient for long-term planning (National Academy of Sciences, 2007; USGS, 2009).

In the light of these facts, we have analysed the sensitivity of the climate response to the availability of fossil fuel energy resources considering the peer-reviewed estimates of the total amount of resources that could ever be recovered, i.e., the ultimately recoverable resources (URR). We apply the URR approach which aims to provide a “best estimate” using the most robust, transparent and up-to-date information available; the URR approach has been successfully applied to explore future fossil fuel extraction at regional and global levels (Campbell and Laherrère, 1998; Höök and Tang, 2013; Hughes, 2013a; Jones and Warner, 2016; McGlade and Ekins, 2015; Mohr et al., 2015). We focus our study on the implications for baseline scenarios (i.e. scenarios with no additional climate policy). Since the baseline scenarios are the counterfactuals against which policy scenarios are developed and tested, substantial changes in their energy system (e.g. in terms of the cost of technologies, energy mix, etc.) would entail profound implications for mitigation scenarios.

Although previous studies have estimated future emissions paths applying an URR approach, (Brecha, 2008; Chiari and Zecca, 2011; Doose, 2004; Höök and Tang, 2013; Jones and Warner, 2016; Kharecha and Hansen, 2008; Mohr et al., 2015; Nel and Cooper, 2009; Ward et al., 2012, 2011) in this chapter four main contributions to the literature are made by: (1) using a probabilistic approach to account for the uncertainty in up-to-date peer reviewed estimates on recoverable energy resources; (2) using an integrated assessment model of climate change (GCAM-MAGICC[43]), enabling us to capture the complexity of energy substitutions, technology improvements, economic interactions and trade-offs with land-use changes; (3) integrating the uncertainty in the response of global temperature to a doubling of atmospheric GHG concentrations

[43] See Appendix A or a full description of the GCAM model. In this chapter, the version 3.2 is applied.

(equilibrium climate sensitivity, ECS), allowing us to (4) analyse the relative importance of uncertainty in resources vs. uncertainty in the climate system with respect to total radiative forcing and global surface temperature change.[44]

Therefore, the proposed framework combines the uncertainties in future emission pathways and in ECS, which have been identified as the factors that contribute most to uncertainties in the projection of global temperature change (IPCC, 2014c; Knutti and Hegerl, 2008; Webster et al., 2012; Wigley and Raper, 2001). Although research to characterize climate sensitivity has now been going on for decades, little progress in narrowing the large uncertainty range has been achieved, with special difficulties in ruling out higher values. Current overall understanding of ECS indicates a range in the response of global temperature to a doubling of atmospheric GHG concentrations between 2–4.5 °C with more than 66% probability (Knutti and Hegerl, 2008).

In this chapter we integrate the approaches of two different research communities: geologists and geological engineers, who have focused on estimating recoverable energy resources robustly and transparently, and the climate integrated assessment community, which has centred its efforts on exploring the technological and socioeconomic dimensions assuming the energy-abundance paradigm. Finally, by applying an ECS consistent with IPCC-AR5 (IPCC, 2014c; Rogelj et al., 2014), and the GCAM-MAGICC integrated assessment model of climate change which has been used in all IPCC reports to date, we ensure a robust comparison with the reported IPCC-AR5 results.

The chapter is organized as follows: Section 3.1 reviews the methods and metrics to assess the availability of fossil fuel resources. Section 3.2 describes the materials and methods applied for the uncertainty and sensitivity analysis. Section 3.3 shows and discuss the results, while the related policy implications are outlined in Section 3.4. Section 3.5 points out some of the limitations of the analysis. Finally, conclusions are drawn in Section 3.6.

3.1. Assessment of the availability of fossil fuel resources

Non-renewable fuels are mostly underground resources. Thus, the methods to assess their availability such as sampling, simulation and extrapolation are inherently subject to uncertainty. Additionally, their future availability critically depends on factors such as technological advances, and economic and socio-political circumstances.

A variety of metrics is used to describe the future availability of fossil fuels. The most common type of classification distinguishes between different categories of "resources" and "reserves". Generally, the term "resources" is used to represent the amount of

[44] In fact, in Chapter 5 we precisely take a more conventional deterministic URR approach with a simple global aggregated model.

energy resources (proven or geologically possible) which cannot currently be exploited for technical and/or economic reasons but are estimated to be exploitable in the future. “Reserves” refer to the fraction of the resource base estimated to be economically extractable at the time of determination and are commonly quoted to three levels of confidence (1P, 2P and 3P).[45] A supplementary category named “additional occurrences” is also considered to include additional low-grade quantities with unknown degrees of assurance (Dale, 2012; McGlade and Ekins, 2015; Rogner, 1997; Rogner et al., 2012; USGS, 1980). These uncertainties can be represented in a McKelvey box (see Figure B.1 in Appendix B), which presents resource categories as a function of geological assurance and economic feasibility of extraction (Rogner et al., 2012; USGS, 1980).[46] These are the most widely used metrics by governments and international agencies such as the World Energy Council (WEC), IEA, IMF and IPCC.

Depending on the study, the term “resources” may refer to in place or recoverable amounts. Recoverability factors represent the fact that due to physical/chemical constraints, all the resource in place will never be recovered. Additionally, these factors try to capture the future evolution of two opposing forces: the diminishing returns of the resource-base (smaller deposits in harsher environments, increasing exploration and production costs, diminishing energy ratios, etc.) and the rate of technology improvement through innovation. For example, the average recovery from petroleum reservoirs around the world is estimated to be approximately 35%. Applying enhanced oil recovery techniques typically raises recovery factors by 5-15%; however the high costs and technological requirements reduce their large-scale deployment (Höök et al., 2014; Miller and Sorrell, 2014). Typical recovery rates are even lower for coal (~20% (Rogner et al., 2012; USGS, 2009, chap. D)), while for conventional natural gas they are in the range of 80-90% (Muggeridge et al., 2014a).

However, these resource and reserve estimates are subject to critical inconsistencies and uncertainties due to: (1) a lack of methodological standardisation (definitions, assessment of future recoverability from known fields or undiscovered volumes, probabilistic methods, etc.) at national and/or regional levels, which implies inconsistencies in the global aggregates;[47] (2) a lack of transparency in the reporting of reserve estimates in many countries with significant shares of world resources, such as Russia, Saudi Arabia and China (e.g., “political reserves”); (3) confusion in the use of terminology for classifying different types of resources (e.g., conventional and unconventional fuels); and (4) the scarcity of reports providing reliable estimates of

[45] 1P, 2P and 3P reserve estimates are commonly expressed as P90, P50 and P10 respectively (referring to the %percentiles): P1 thus refers to quantities recoverable with at least 90% probability (P90) under existing economic and political conditions and using existing technology (McGlade, 2012; Rogner et al., 2012).

[46] Moreover, as a result of advances in exploration and production technologies, the borders that distinguish reserves from resources and resources from occurrences are increasingly blurred (Rogner et al., 2012; USGS, 1980).

[47] For example, while reserves reporting in the United States require a 90% (1P) probability of recovery under existing economic, technological, and political conditions, other reporting bodies typically declare reserves at a median, 50% (2P), probability (Rogner et al., 2012).

unconventional resources due to their recent commercial exploitation (Campbell and Laherrère, 1998; EWG, 2007; Heinberg and Fridley, 2010; Höök et al., 2010; Höök and Tang, 2013; Laherrère, 2006; Malyshev, 2000; McGlade et al., 2013; McGlade, 2012; McGlade and Ekins, 2015; Miller and Sorrell, 2014; Mohr et al., 2015; Mohr and Evans, 2009; National Academy of Sciences, 2007; Rutledge, 2011; USGS, 2009; Wang et al., 2013a). The lack of updated, transparent and robust estimates at the global level is particularly problematic in the case of coal. In fact, coal assessments are relatively out of date, report rather in place than extractable estimates, and are characterised by a considerable heterogeneity in methods applied across different regions (EWG, 2007; Heinberg and Fridley, 2010; Höök et al., 2010; Mohr and Evans, 2009; Rutledge, 2011; Wang et al., 2013a).

The inadequate treatment of these ambiguities and uncertainties by most studies leads to wide ranges of uncertainty and large fluctuations over time, which is particularly problematic in long-term assessments such as those required for climate change research. In the case of the IPCC, currently applied estimates from Rogner et al., (2012) show notable differences in relation to the previous estimates by Rogner (1997). Whereas coal and unconventional oil reserve estimates approximately halved, the resource estimates substantially increased for unconventional gas (2- to 5-fold) and coal (3- to 4-fold) due to upgrading of large stocks previously identified with unknown degrees of geological assurance (see Table B.7). In fact, it is generally assumed that in the long-term, resource scarcity will drive up prices, spurring technical improvements and exploration activities. Provided adequate investments are forthcoming, these technical improvements are expected to continuously allow new discoveries and upgrading of abundant resources and occurrences to offset the cumulative extraction of reserves (Rogner et al., 2012; Thielemann, 2012).

To overcome these limitations, the URR approach has been proposed as an alternative explicitly addressing these uncertainties and aiming to provide robust estimates of the total amount of resources that can ever be recovered and produced from a region/country in the light of the best available transparent information (Dale, 2012; McGlade and Ekins, 2015; Mohr et al., 2015). Thus, it includes future reserve growth at known fields/mines as well as the fuel estimated to be economically recoverable from expected discoveries of new fields/mines. In this approach, resource prices are viewed as weak scarcity indicators since energy markets are far from functioning in perfect conditions (Norgaard, 2002; Reynolds, 1999). Instead, the focus is shifted to the physical components of energy resources (e.g. resource discoveries, field size, depletion rates, EROEI, etc.). Diverse methodological approaches are usually combined to estimate the URR of fossil fuels; they include: standardisation (McGlade et al., 2013; McGlade, 2012; McGlade and Ekins, 2015; Wang et al., 2013a); discarding of “political reserves” (Campbell and Laherrère, 1998); global bottom-up aggregation from a field-by-field analysis (EWG, 2013, 2008, 2007; Höök et al., 2010); and the generation of original, alternative URR estimates combining statistical methods with geological modelling (Campbell and Laherrère, 1998; Höök et al., 2010; Maggio and Cacciola, 2012; Rutledge, 2011).

The URR approach has been particularly successfully applied to forecast oil extraction. For example, global conventional oil production reached its peak in the mid-2000s and has already entered the phase of geologic decline (Murray and King, 2012; WEO, 2013); as forecasted by Campbell & Laherrère (1998) (and very well approximated in the original Hubbert (1956) projection). More recently, in 2011, the US EIA estimated California's Monterey Shale had 15.4 billion barrels recoverable tight oil, i.e. 64% of all reserves in the lower 48 United States at that time (EIA, 2011). However, in May 2014, the US EIA downgraded their previous estimates by 96%, a result anticipated by an URR-based analysis (Hughes, 2013a, 2013b).

The URR metric includes the sum of all historic and future production. The remaining URR (RURR) in a given time t is defined as the difference between the URR and cumulative extraction in time t (see *eq. 3-1*)).

$$RURR_t = URR - cumulative\_extraction_t \qquad \textit{eq. 3-1}$$

The RURR metric can be related to the conventional definitions of reserve and resource if: (1) official reserves and resources estimates are revised to take into account potential inconsistencies and reduce uncertainties (e.g. political reserves, erroneous aggregations, etc.); (2) resources refer to the recoverable portion of the amount in place; and (3) there is no double counting of reserves and resources. Under these conditions, the RURR can be estimated as the sum of reserves and recoverable resources at any given time (Dale, 2012; Rogner, 2012). The estimated ultimate recovery for oil and gas from the Federal Institute for Geosciences and Natural Resources (BGR) is a good example (BGR, 2013).

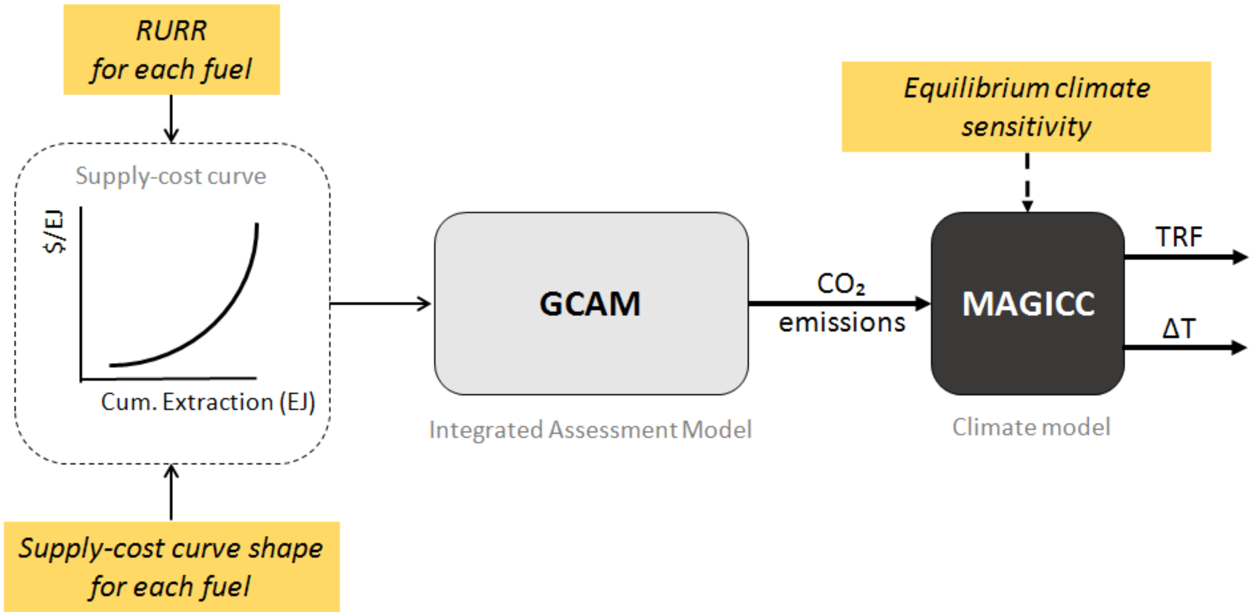
3.2. Materials and methods

In this section we describe the materials and methods applied to perform the uncertainty and sensitivity analysis in relation to the likelihood of climate change pathways under uncertainty on fossil fuel resources availability and equilibrium climate sensitivity.

All depletable resources are characterised in GCAM by cumulative supply curves, i.e., upward-sloping supply-cost curves representing the fact that the marginal monetary cost of resource extraction increases with cumulative extraction. This curve results from applying the law of diminishing returns to geology: the first deposits exploited are the most accessible and thus the most economically profitable. Thus, the availability of a non-renewable resource depends on the accessible amounts of resource and their corresponding extraction cost.

We designed a probabilistic analysis considering uncertainties in the following inputs: (a) the RURR estimates of non-renewable energy resources and associated supply-cost curve shape; and (b) the ECS. For each fuel type, a supply cost curve is constructed as input to the GCAM model which is run in baseline mode (i.e. scenarios with no additional climate policy). The CO_2 emissions arising from energy and land use changes are then computed in GCAM for the period 2005-2100. These emissions are then passed on to the climate model emulator MAGICC together with an input value for the ECS where the total radiative forcing (TRF) and global mean surface temperature change (ΔT) are computed. The entire process for a single simulation is illustrated in Figure 3.1.

Figure 3.1: Methodology of GCAM-MAGICC simulation



Notes: The yellow boxes (RURR, Supply-cost curves, ECS) refer to the uncertain inputs that need to be supplied for a simulation.

Source: own work.

The probabilistic analysis was performed in four steps, which are detailed in the following sections:

1. Literature review on uncertainty of inputs (section 3.2.1),
2. Propagation of uncertainty of inputs through the GCAM-MAGICC (section 3.2.2) for the period 2005-2100 using Monte Carlo simulation (n = 1,000),
3. Analysis of the uncertainty of outputs: total cumulative CO_2 emissions, total radiative forcing and global surface temperature change (section 3.2.3),
4. Identification of which inputs explain most of the uncertainty in the outputs (global sensitivity analysis, see section 3.2.3).

3.2.1. Literature review on uncertainty of inputs

In this section we document the literature review on uncertainty of inputs (RURR of non-renewable energy resources (section 3.2.1.1), the shape of the cumulative supply-cost curves (section 3.2.1.2) and the ECS (section 3.2.1.3)). The Figure B.2 shows the resulting empirical cumulative distribution functions (ECDF) of the input distributions.

3.2.1.1. Non-renewable energy resources RURRs

Non-renewable energy resources are divided in two broad groups: fossil fuels (section 3.2.1.1.1) and uranium (section 3.2.1.1.2). The section on fossil fuel resources uncertainty includes a comparison with the updated range given by the IPCC-AR5 (IPCC, 2014a). The considered estimates in the analysis are available as Electronic Supplementary Information.

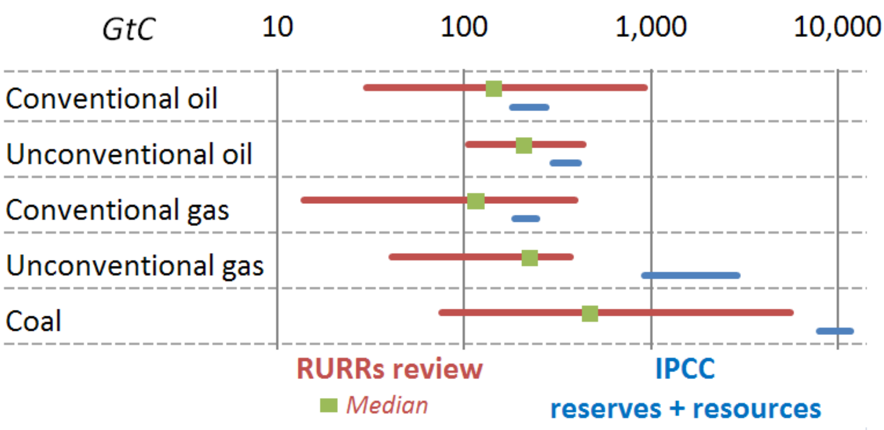
3.2.1.1.1. Fossil fuel RURRs

We performed a comprehensive literature review of the URR for all fossil fuels in order to identify the probability distributions for the inputs. RURRs for the year 2005, when the model starts to run, were computed applying *eq. 3-1*. For conventional fuels (coal – including bituminous, sub-bituminous and lignite-, conventional oil and conventional gas), we used Dale's (2012) dataset, resulting from a meta-analysis covering estimates made up to 2012. Due to the extensive exploitation of these resources over recent decades, large numbers of estimates have been published: coal (40), conventional oil (200) and conventional gas (70). We proceeded to filter the data to eliminate URR estimates less than current cumulative production; the number of estimates that needed to be removed was less than 5% for each of the fuels. These estimates are in agreement with a recent review of the RURR of fossil fuels performed by Mohr et al., (2015) (see).

The situation is very different for the unconventional oil and gas, with few published estimates and large associated uncertainties (Dale, 2012; Hughes, 2013a; McGlade et al., 2013; McGlade, 2012; Rogner et al., 2012). This implies that the existing sample of RURR estimates is too small and cannot be properly used for an uncertainty analysis (Dale, 2012). Thus, in this case, we considered the results of Mohr et al.(2015), who perform an exhaustive literature review of the estimates found in the literature, providing three estimates for each resource: "low case", "best guess" and "high case". We applied a discrete triangular distribution assigning the probabilities of 0.2, 0.6 and 0.2 to these three cases. Unconventional gas includes coal bed methane, hydrates, shale and tight gas, and unconventional oil includes extra-heavy, kerogen, natural bitumen and tight oil.

The carbon endowment associated with these RURR estimates is depicted in Figure 3.2 and compared to the updated range of reserves + resources given by the IPCC-AR5 (IPCC, 2014a), which stems from the *Global Energy Assessment* (GEA, Chaper 7, (Rogner et al., 2012)). As showed by model inter-comparison exercises, the addition of the reported reserves and resources represents the long-term future availability of fossil fuels resources considered by most IAMs of climate change (McCollum et al., 2014). An examination of these IPCC estimates reveals that the aforementioned abundance paradigm of fossil fuel resources stems mainly from coal (the most carbon intensive fossil fuel), and to a lesser extent, from unconventional gas. In both cases, these high estimates have wider ranges of uncertainty than oil or conventional gas. In the case of coal, which has been extensively extracted for decades and currently represents the second-largest primary energy source globally after oil, the IPCC lowest bound estimate is 45-fold its cumulated past extraction.

Figure 3.2: Ranges of remaining carbon content estimates (GtC) of fossil fuels in 2005 from the IPCC-AR5 (blue bars) and from our literature review of remaining ultimately recoverable resources (RURR) (red bars)



Notes: IPCC estimates include the carbon content of reserves and resources (for coal they are in place amounts); the values from the literature review of RURR are obtained by multiplying the energy content estimates by the carbon factors from the IPCC-AR5 (see Table 7.2 from IPCC (IPCC, 2014a) and Table B.2. For comparison, the total cumulative carbon emissions from fossil fuel combustion to date are around 350 GtC. Figure B.2 shows the empirical cumulative distribution function by fuel obtained in the RURR literature review.

Source: IPCC reserve + resources from (IPCC, 2014a; Rogner et al., 2012).

A comparison between the two sets of estimates shows that the energy resource base of the IPCC is in the top of the range (for oil and conventional gas) or above the range (for unconventional gas and coal) obtained with the URR methodology.[48] There are two main factors that explain the large differences for unconventional gas and coal in Figure 3.2. An analysis of the unconventional gas resources by type in the GEA reveals that this report assumes a very large resource potential for natural gas hydrates in the order of tens of thousands of EJ, which is well beyond other estimates provided in the

[48] Similar conclusions are extracted when comparing with the RURR data other references such as BGR or IEA (see Table B.2).

literature. For example, the BGR assessment reports an estimate below 7,000 EJ (BGR, 2013) and the World Energy Outlook 2014 from the IEA does not consider them since they "are not expected to play a major role during the projection period [to 2040]" (WEO, 2014). In fact, the GEA only includes 5,000 EJ of gas hydrates in the long-term supply cost-curve, which is also in the line with the best guess from the URR perspective (4,600 EJ).(Mohr et al., 2015) As a result, the BGR estimates total unconventional gas reserves and resources of 20,230 EJ (BGR, 2013) and the IEA reports 12,750 EJ as remaining recoverable resources (WEO, 2014) (Table **B**.2). This range is in accordance with the uncertainty considered by our RURR estimates of 14,600 ± 10,700 EJ (Mohr et al., 2015). In fact, as gas hydrate has not yet been commercially produced, estimates need to be treated with considerable caution, being uncertain when or even if, technological advances will make gas hydrates extraction technically and economically feasible in the future decades (Mohr et al., 2015).

On the other hand, for coal, the reported definition in the IPCC-AR5 is not accurate. In fact, the GEA actually reports in-place: "*resources are shown as in situ amounts,"* pointing out that *"the eventually extractable quantities will be significantly lower*" (Rogner et al., 2012). Since RURR estimates focus on the recoverable fraction, this difference explains most of the discrepancy with the estimates with the GEA and also with other sources such as BGR and IEA (Figure 3.2 and the Table **B**.2). However, the large variations in these estimates are also attributable to the lack of transparent, robust and independent estimates at the world level. Recent studies have pointed out that common coal reserve/resource estimates might be substantial overestimates, especially in some key regions. In fact, just six countries dominate coal globally: according to the BGR (2013) estimates, the combined reserves of the USA, China, India, Russia, Australia and South Africa represent almost 85% of the world's total. This overestimation originates from a combination of factors such as out-of-date data and methods in coal resource assessments and a considerable heterogeneity in methods applied across different regions hampering robust global aggregations (EWG, 2007; Heinberg and Fridley, 2010; Höök et al., 2010; Mohr and Evans, 2009; Rutledge, 2011; Wang et al., 2013a). In fact, only two original datasets exist at the global level: the BGR (2013) and the WEC (2013) assessments. However, the BGR assessment reports the total coal in place rather than an estimate of the resources that can be recovered, and the WEC estimates of resources and reserves are mainly data collected from its member countries, and hence do not address the limitations outlined above.

The widespread perception of coal abundance might be partly explained by these inconsistencies. For example, in the USA (holding 30% of reported world reserves and 40% of resources (BGR, 2013)), two recent assessments from the United States Geological Survey (USGS) and the National Academy of Sciences concluded that the reported coal reserve estimates for the country are out of date ("Present estimates of coal reserves […] are based upon methods that have not been updated since their inception in 1974, and much of the input data were compiled in the early 1970s" (National Academy of Sciences, 2007)) and of poor quality ("However, it is not possible to confirm the often quoted assertion that there is a sufficient supply of coal for the next

250 years" (USGS, 2009)). The implied downgrading may be significant, since the results of the USGS assessment indicate that, in most cases, less than 20% of the original coal is expected to be economically recoverable (USGS, 2009, chap. D). Moreover, the USA is no exception; many countries have not reassessed their coal reserves for a long time, and when they have, revisions have mostly been downwards, (EWG, 2007; Hartnady, 2010; Heinberg and Fridley, 2010; Malyshev, 2000; Rutledge, 2011) contrary to what would be expected from the energy abundance paradigm (Rogner et al., 2012; Thielemann, 2012).

Thus, in the light of the evident limitations of available data, the URR approach interprets the in-place estimates as an upper bound of the actually recoverable amounts. If we estimate the recoverable coal from the GEA values of reserve and in-situ resources by assuming a conventional recovery factor of 20% (Rogner et al., 2012; USGS, 2009, chap. D), we would obtain the range 75,500 – 108,000 EJ that would roughly translate into 1,950-2,800 GtC of emissions, which is in the range of our RURR estimates (see Figure 3.2 and Table **B**.2).

Nevertheless, it is important to remark that, for both IPCC and URR-based estimates, the remaining total carbon content is much greater than the identified "carbon budget" for having a likely chance of limiting temperature rises to 2°C (260-410 GtC) (IPCC, 2014a; Zickfeld et al., 2009).

3.2.1.1.2. RURR of uranium:

The level of uranium deployment has indirect repercussions in terms of CO_2 emissions due to substitution effects in the energy mix (e.g., avoiding emissions from fossil fuels). Uranium availability is particularly prone to uncertainties and lack of transparency due to its geopolitical importance (Dale, 2012; NEA and IAEA, 2012). Four RURR levels for 2005 were constructed from the different degrees of assurance of the reported resource categories including undiscovered resources from the Nuclear Energy Agency estimates (NEA and IAEA, 2012) (see Table B.6). Linearly decreasing probabilities were assigned to each RURR level from the most to the least likely categories. The uranium resources considered include conventional resources (from which uranium is recoverable as a primary product, a co-product or an important by-product) and unconventional resources (reliant on currently unexploited techniques in which uranium might only be recoverable as a minor by-product, mainly from phosphate rocks). Uranium from seawater was not considered since its industrial processing would not be possible during this century without a major technological breakthrough (Gabriel et al., 2013).

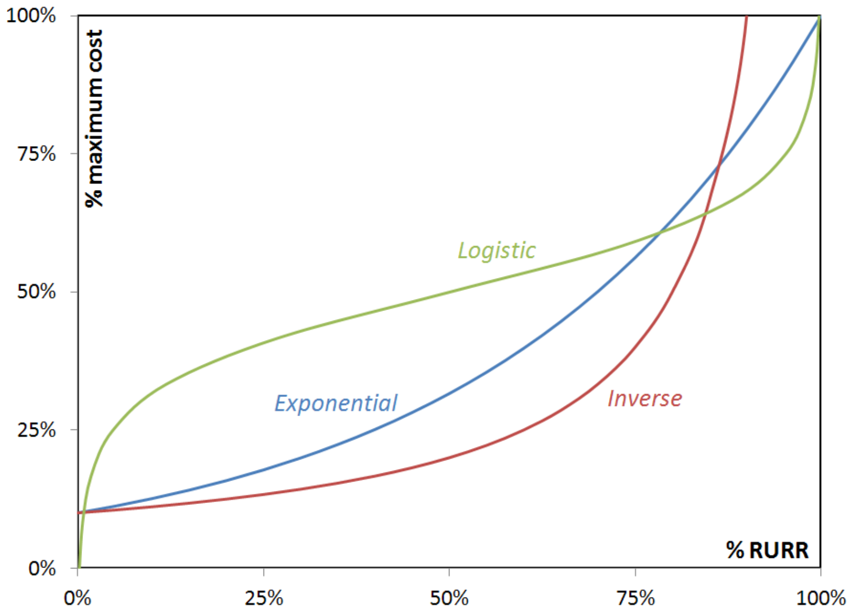
3.2.1.2. Shape of the cumulative supply-cost curves

The cumulative supply curves are upward sloping cost-curves representing the fact that the first deposits exploited are the most accessible and thus the most economically profitable. The increasing demand would imply a continuous shift towards deposits that are less accessible and/or of lower grade and thus more expensive. This effect is somewhat compensated for by technological improvements (GCAM includes an exogenous extraction cost reduction to model this effect for each resource). Depending on the evolution of these factors over time, the supply-cost curve can follow different paths, i.e., the curve can have different shapes.

Depending on the shape, the future technology competition will evolve differently. With a greater steepness (e.g., logistic), substitution processes by other fuels and/or technologies will be boosted.

A review of the literature has revealed that there is a great level of uncertainty about which of the potential shapes is ultimately likely to occur for all depletable resources (Aguilera, 2014; McCollum et al., 2014; McGlade and Ekins, 2015; MIT, 2010; NEA and IAEA, 2012; Remme et al., 2007; Rogner, 1997). Specifically, three main patterns have been identified and integrated into the analysis in this chapter: inverse, exponential and logistic (Figure 3.3, see Supplementary Information for the equations). Due to the uncertainty in the assessment of the actual shape for the depletable resources, we assign an equal probability weight (1/3) to each shape considered (inverse, exponential and logistic).

Figure 3.3: Three main supply-cost curve shapes identified in the literature review as a function of RURR and maximum cost



Source: own work.

In order to keep the modifications to the minimum, we keep the cost of the last grade available from the GCAM as the maximum cost. Thus, each cumulative supply-curve is dependent on only three parameters: the cost of the last (most expensive) grade, the

RURR and the shape of the curve. Next, these continuous curves are discretized by grades in order to fit the modelling of GCAM. In the case of uranium, preliminary analyses revealed that the outputs were insensitive to uranium cost-curve shape leading to the removal of this parameter for further analysis.

3.2.1.3. Equilibrium climate sensitivity (ECS)

This parameter characterizes the global surface temperature response to increased GHG concentration on timescales of several centuries (Knutti and Hegerl, 2008; Previdi et al., 2013) and is recognized as one of the key uncertain parameters in climate change projections beyond a few decades (IPCC, 2014c; Knutti and Hegerl, 2008; Webster et al., 2012; Wigley and Raper, 2001). However, there are different types of ECS depending on the feedbacks considered. "Fast" ECS includes the feedbacks occurring on time-scales of decade(s) that scale with temperature (water vapour, lapse rate, clouds and surface albedo); accordingly, it is usually applied in integrated assessment modelling of climate change, typically focusing on projections up to 2100 (IPCC, 2014a; Meinshausen et al., 2011a; Rogelj et al., 2012). In this way, surface albedo feedbacks associated with changes in land ice (e.g., continental ice sheets, mountain glaciers) and vegetation are either not considered or are part of the forcing, which may ultimately result in an underestimation of the climate response (Previdi et al., 2013).

In this study, we apply the ECS probability distribution function estimated by Rogelj et al. (2014) that is consistent with the overall consensus understanding of ECS of the IPCC-AR5, which stated that ECS is: likely (>66%) in the range of 1.5–4.5°C, extremely likely (>95%) larger than 1°C, and very unlikely (<10%) larger than 6°C (see Figure B.2d for the ECDF) (IPCC, 2014c). At present, these values seem to be rather robust estimates as they have not changed much in the last decades and are supported by recent studies (Knutti and Hegerl, 2008; Rogelj et al., 2012). In relation to this, the applied ECS estimate from Rogelj et al., (2014) is actually very close to the estimate fitting the IPCC-AR4 consensus that was applied in the IPCC-AR5 to homogenize the climate response of the emissions delivered by all the reviewed scenarios (IPCC, 2014a; Rogelj et al., 2012). Thus, the implementation of this ECS estimate in the same modelling framework (MAGICC) allows us to robustly compare the results of our study with the IPCC-AR5 review of scenarios.

3.2.2. GCAM-MAGICC model and applied baseline scenario

GCAM is a global IAM available under the terms of the ECL open source license version 2.0 (Brenkert et al., 2003; Calvin et al., 2011; Clarke et al., 2007; Kim et al., 2006). In this chapter, we use the standard release of GCAM 3.2 with the non-renewable energy supply-cost curves and ECS values specifically modified in each scenario (see Appendix A for a full description of the model). GCAM is a partial equilibrium (dynamic-recursively solved for every 5 years in the period 2005–2100) global model, integrating the global economy, energy, agriculture and land use systems. Although the model is regionally disaggregated, for each run we construct global supply-cost curves for each resource since in this version the model assumes global energy markets. It includes a representation of the climate system, the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) 5.3 (T. M. L. Wigley and Raper, 1992; Wigley and Raper, 2002) which is similar to the version 6 applied in the IPCC-AR5 review of baseline scenarios (Meinshausen et al., 2011a). MAGICC total radiative forcing output has been adjusted to the RCP definition excluding mineral dust, nitrate and the effect of land albedo (Thomson et al., 2011). However, the general structure is unidirectional: the exogenous socioeconomic inputs drive the energy extraction and the associated GHG that subsequently induce the temperature increase (with no damage function).

The exogenous socioeconomic inputs of the baseline scenario from the standard GCAM 3.2 release were slightly modified in order to produce a climate response in the middle of the range of the IPCC-AR5 review of baseline scenarios to reach 7.5 W/m^2 and 4ºC by 2100 (IPCC, 2014a). The applied scenario applies conventional assumptions for baseline scenarios: global population peaks at almost 10 billion people in 2070 and then slowly declines in the line of the median scenario from the UN World Population Prospects (UN, 2015), and global gross domestic product increases at an average rate of +2.4% between 2005 and 2100. The Supplementary Materials provide more details on the applied baseline scenario.

3.2.3. Uncertainty and sensitivity analysis

Monte Carlo simulation is performed to obtain the probability distributions of three outputs Y: cumulative CO_2 emissions, radiative forcing and temperature change. GCAM is run with 1,000 scenarios that are obtained by random sampling from the probability distributions of the 10 inputs X_i (conventional oil RURR, gas RURR, coal RURR, unconventional oil RURR, uranium RURR, conventional oil shape, gas shape, coal shape, unconventional oil shape, and equilibrium climate sensitivity). Total natural gas is considered as a single input since the GCAM model does not distinguish between the conventional and unconventional gas resource. For coal, conventional oil and conventional gas, since we have a large set of studies with no preference of any particular one, we consider the estimates as equally probable. Therefore, in the Monte Carlo analysis we randomly sample an entry from the data set, which is equivalent to sampling form the ECDF. Table 3.1 compiles the methods and references applied to build the probability distribution of the inputs; while Figure B.2 shows their ECDF.

Table 3.1: Information source for the probability distribution of model inputs

Input		**Probability distribution**
RURRs	• coal • conventional oil • conventional gas	Sampling ECDF from Dale (2012)'s filtered dataset
	• unconventional oil • unconventional gas	Discrete triangular distribution with probabilities of 0.2, 0.6, and 0.2 for low, best guess and high estimates from Mohr et al., (2015)
	• uranium	Linearly decreasing probabilities for four RURR levels from NEA and IAEA (2012) (see Table B.6)
Shape of the cumulative supply-cost curves		Equal probability weight (1/3) to each shape considered (inverse, exponential and logistic, see section 3.2.1.2)
ECS		ECDF from Rogelj et al., (2014)

Notes: ECS: equilibrium climate sensitivity. ECDF: empirical cumulative distribution function.

The generated output distributions are visualized in Figure B.2 and relevant statistical information is presented in Tables B.4 and B.5**.** In the light of the results presented in these tables (95% confidence intervals of quantiles and standard error of the mean), the number of scenarios (n=1,000) was judged to be sufficient to provide robust results.

To determine which of the uncertain inputs (X) are responsible for producing uncertainty in the outputs (Y), we calculated the squared standardized regression coefficients (SRC^2) (Saltelli et al., 2004). These are obtained by normalizing the slopes obtained from a multivariate linear regression applied to the results of the Monte Carlo Simulation (*eqs. 3.2*, *3.3* and *3.4*).

$$Y = \sum b_i \cdot X_i + a \qquad \textit{eq. 3.2}$$

$$SRC^2{}_i = (b_i \cdot \frac{\sigma_{X_i}}{\sigma_Y})^2 \qquad \textit{eq. 3.3}$$

$$R^2 = \sum_i (SRC^2{}_i) \qquad \textit{eq. 3.4}$$

The SRC^2 approximates the first-order contribution of the inputs to the output variance. Figure B.4 displays the evolution of the SRC^2 over time for the three outputs Y. R^2 represents the coefficient of determination of the total multivariate regression. All computations for the uncertainty and sensitivity analysis were performed using R version 3.1.2 (R Core Team, 2014).

For a review of methods and some applications of uncertainty and sensitivity analysis applied to IAMs of climate change see Van Vuuren et al., (2008) and Anderson et al., (2014) Of course, more parameters than the ones considered in the analysis are uncertain in the model such as future population evolution, GDP growth, technology costs, etc. (Gillingham et al., 2015; McJeon et al., 2011) However, in this chapter we are interested in the role of resource-related uncertainties.

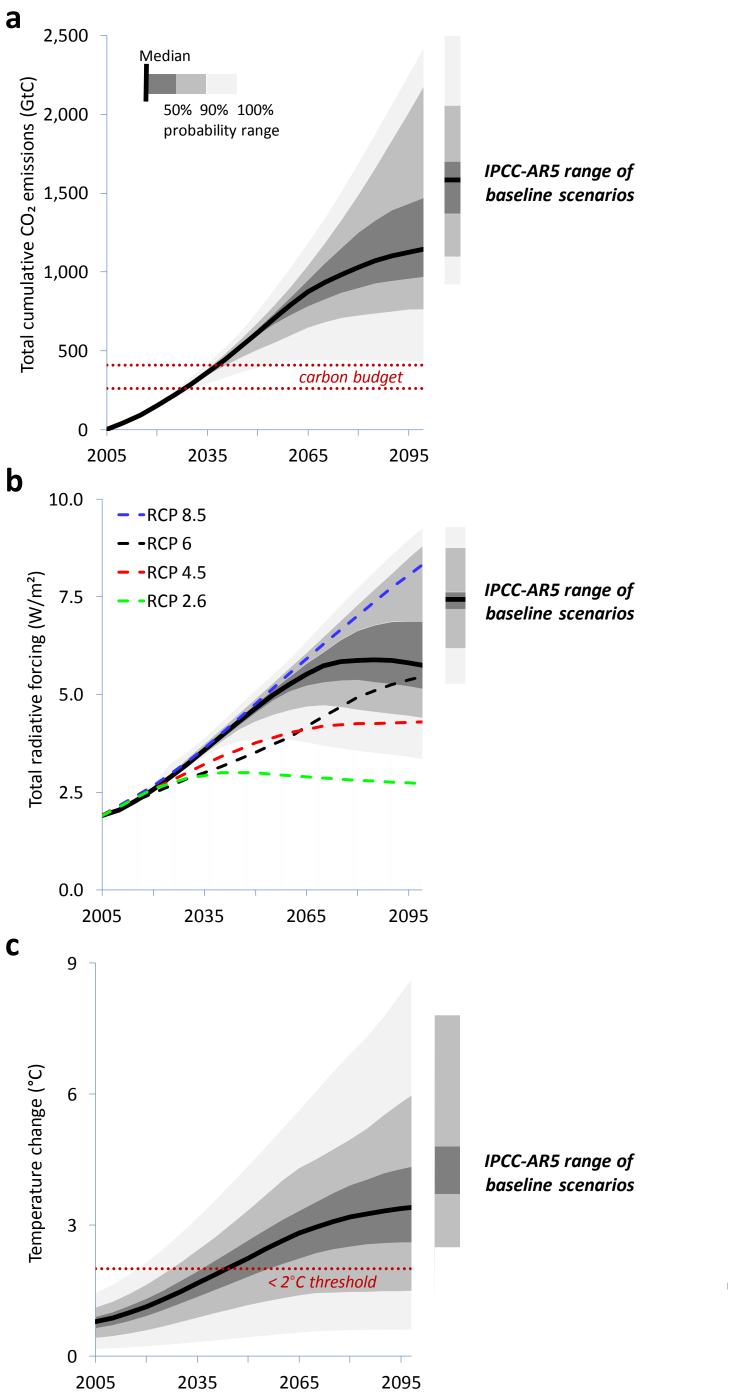
3.3. Results and discussion

We summarise the 1,000 Monte Carlo simulations with interquartile and 5-95th percentile ranges as well as the minimum and maximum pathways obtained in terms of total cumulative CO_2 emissions (Figure 3.4a), total radiative forcing (Figure 3.4b) and temperature change since pre-industrial period (Figure 3.4c). For each variable, the outputs are compared with the results from the IPCC-AR5 review of baseline scenarios, where 1,184 scenarios from 31 models were assembled through an open call to ensure the consistency of the dataset (IIASA, 2014; IPCC, 2014a). Around 300 of them were identified as baseline scenarios, i.e. scenarios that ultimately serve as the reference for developing climate policies. The report's review and statistical analysis of outputs characterize the current state-of-the-art of the integrated assessment modelling of climate change, providing a benchmark for comparison.

Our results show that the median cumulative emissions by 2100 reach a 30% lower level than the median of current baseline scenarios, and that the interquartile range of emission we obtain is 970-1,470 gigatonnes of carbon (GtC) compared to the IPCC's 1,370-1,700 GtC. The inflection point of the median cumulative emissions around the middle of the century indicates that most fossil fuel resources are by then entering the depletion phase, driving the transition to renewable energies. By 2100, this leads to a median value that roughly coincides with the 10%-percentile of the IPCC-AR5 review of baseline scenarios (1,150 GtC). In fact, the probability that annual emissions exceed current levels at the end of the century is less than 25% even though the total median primary energy consumption doubles over the same period.[49] Although our results show that the high emission estimates are less probable, we also observe that the lowest cumulative CO_2 emissions path obtained in the Monte Carlo Simulation exceeds the "carbon budget" to limit warming to below 2°C by the year 2100 (Figure 3.4**a**).

[49] This result is consistent with the evolution in the energy mix in a scenario applying the median values of our RURR estimates. In such scenario, renewable energy would represent 36% of the cumulative primary energy consumption of the period 2005-2100 (50% in 2050-2100), reaching 80% by the end of the 21st Century.

Figure 3.4: Pathways of total cumulative CO_2 emissions, total radiative forcing and temperature change (2005-2100) and comparison with the IPCC-AR5 range of baseline reviewed scenarios for 2100



Notes: Shaded areas depict the uncertainty ranges (whole range, 5-95%, 25-75%), the black line represents the median. Numeric values are provided in Table B.3. a, Total cumulative CO_2 emissions from industrial processes, fossil fuel combustion and land-use change. The dotted lines depict the "carbon budget" range estimated by the IPCC-AR5; b, Total radiative forcing (TRF). For comparison, the four Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011b) are indicated (blue, black, red and green dashed lines); c, Global surface temperature change since the pre-industrial period. The dotted-line indicates the 2°C threshold.

Source: own work; IPCC-AR5 range of baseline scenarios from (IPCC, 2014a).

Using total radiative forcing (TRF) enables us to compare our results with the Representative Concentration Pathways (RCPs), which constitute the new common set of scenarios developed as a standard basis for near and long-term climate modelling experiments. Four reference pathways (with no associated probabilities) have been defined by the climate research community spanning the range of 2100 radiative forcing values found in the literature: 2.6, 4.5, 6 and 8.5 W/m^2 (van Vuuren et al., 2011b).[50] Comparing our simulations to the RCPs', we observe that the median TRF values of the 1,000 Monte Carlo simulations closely follow the RCP8.5 path during the first half of the century (Figure 3.4**b**). However, during the second half, the increase in TRF slows down rapidly and then levels off, diminishing slightly at the end of the century and ending up close to the RCP6 level in 2100. By the end of the century, the two highest emissions pathways RCP6 and RCP8.5, where the baseline scenarios currently lie, have probabilities of being feasible of just 42% and 12% respectively, due to the likely depletion of fossil fuels during the second half of the 21st Century (Figure 3.4**b**). However, at the same time, our simulations show that it is also unlikely to end up at low levels of radiative forcing: by 2100, the interquartile range is 5.0-6.8 W/m^2, well over the safe thresholds to avoid dangerous effects (i.e., 2.6 W/m^2).

By comparing our results in terms of cumulative CO_2 emissions with the previous set of scenarios SRES (2000a) from IPCC, similar conclusions in relation to the likelihood of climate change pathways are reached (see Figure B.5). By the end of the century, the high emission scenarios A1, A2 and A1G, where the baseline scenarios used to lie at the time, have probabilities of being feasible of 29%, 22% and 13%, respectively. For the rest of scenarios B2, A1T and B1, implicitly entailing increasing levels of policy intervention,[51] the probabilities of being feasible raise to 64%, 79% and 90%, respectively. In this sense, the RCPs represent a continuation of the SRES scenarios.

In terms of temperature change, we find an 88% probability of surpassing 2°C and a 63% probability of it surpassing 3°C by 2100 (Figures 3.4c and 3.4a). Moreover, there is a 50% probability of the 2°C level being reached between 2035 and 2055 (Smith et al., 2009). These results are in accordance with the implications of burning all currently proven fossil fuel reserves (McGlade and Ekins, 2015; Meinshausen et al., 2009). As a consequence of the "fat tail" in the ECS distribution, we find a 15% probability that temperature change will be more than 5°C by the end of the century. The 50% confidence interval for temperature change by the end of the century is 2.6-4.4°C; this result again lies near the lower bound of the range of baseline scenarios in the literature reviewed by the IPCC-AR5 (3.7-4.8°C) (IPCC, 2014a). Thus, despite the

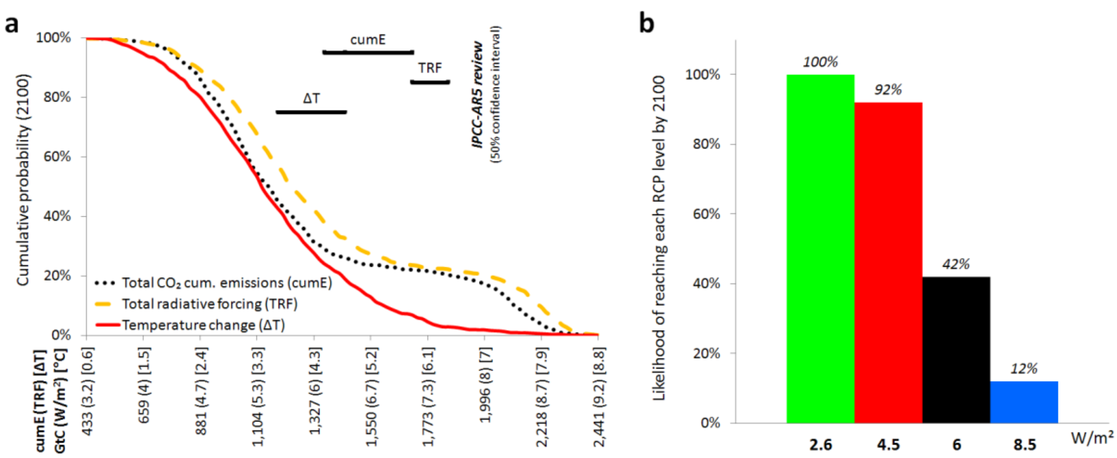
[50] Note that the name of the RCP scenarios does not necessarily correspond to the TRF value for 2100 (e.g., RCP6 "only" reaches 5.5 W/m^2 that year) (van Vuuren et al., 2011b).

[51] Differently to RCPs, all the SRES storylines were defined as baseline scenarios (IPCC SRES, 2000a). However, it has been showed that some of these SRES scenarios would actually require some policy interventions, even implying a "great transition" towards sustainable development in some cases (Girod et al., 2009; Pielke et al., 2008).

fossil fuel depletion provoking an earlier than expected transition to renewable energy sources, the increase in global temperature would still be well over the 2ºC threshold.[52]

The cumulative probability of emissions and TRF for the year 2100 depicts a bimodal distribution with a relative maximum at high levels between the RCP6 and RCP8.5 pathways by the end of the century (Figure 3a). Thus, there is a relatively low, but significant, probability of reaching high emission and associated TRF pathways by the end of the 21st century, i.e. that fossil fuels do not deplete before the end of the century. In other words, the combined upper range of our RURR distributions contains the current consensus on abundant availability implemented in the baseline scenarios of current IAMs of climate change. The global sensitivity analysis reveals that coal RURR uncertainty is, by far, the most determinant factor among the fossil fuel resources considered in the uncertainty of emissions and TRF by the end of the century (Table 3.2). This indicates that the simulations leading to high emission pathways are being ultimately driven by the high values in the coal RURR estimates. As evidenced by inter-comparison analyses (IPCC, 2014a; McCollum et al., 2014), most models use harmonized default assumptions about coal estimates that lie in the higher regions of our coal URR review. This uncertainty could be reduced by a coordinated international effort devoted to evaluating coal availability at a global scale, as has already been proposed for the case of the USA (NAS, 2007). The importance of coal resource uncertainty is somewhat lessened when analysing the temperature change, which is mainly driven by the uncertainty in ECS (Table 3.2 and Figure B.4).

Figure 3.5: Likelihood of climate outcomes in 2100. (a) Cumulative distributions of outputs; (b) Likelihood of reaching each RCP level by 2100



Notes: Cumulative distributions of outputs: total CO_2 cumulative emissions 2006-2100 (cumE), total radiative forcing (TRF), and temperature change in relation to preindustrial levels (ΔT), and comparison with the 50% confidence interval from the IPCC-AR5 review of baseline scenarios (IPCC, 2014a). The evolution of the cumulative distributions over time is shown in Figure B.3.

Source: own work.

[52] Confidence is increasing that even such a temperature change may pose significant risks (Hansen et al., 2016, 2013; Lenton et al., 2008; Smith et al., 2009). In this sense, we still find a 95% of surpassing 1.5°C by 2100.

The evolution over time reveals that conventional oil resource uncertainty is also especially relevant to total cumulative CO_2 emissions and TRF during the first half of the 21st century. On the other hand, the shape parameter of the supply-cost curves has a weak influence on the uncertainty of the outputs in comparison to the RURR (see Figure B.4). For the evolution of SRC^2 over time and the individual contributions of other inputs see the Figure B.4.

Table 3.2: Fraction of variance in climate outcomes for the year 2100 explained by the main inputs (squared standardized regression coefficients, SRC^2)

	Total cumulative CO_2 emissions	Total radiative forcing	Temperature change
Conventional oil RURR	0.014	0.020	0.003
Unconventional oil RURR	0.003	0.007	0.002
Natural gas RURR	0.022	0.043	0.012
Coal RURR	**0.730**	**0.676**	**0.138**
ECS	-	0.017	**0.702**
Other inputs	0.004	0.005	0.001
Total (R^2)	0.774	0.766	0.857

Notes: For total cumulative CO_2 emissions and total radiative forcing, the coal RURR explains 73% and 68% of the uncertainty respectively, whereas for temperature change, coal RURR explains only 14%, with equilibrium climate sensitivity (ECS) explaining 70%. Total (R^2) represents the coefficient of determination of the total multivariate regression.

Source: own work.

The majority of previous URR studies applied a deterministic approach focusing solely on fossil-fuel related emissions, finding levels of cumulative CO_2 emissions by 2100 below the RCP6 scenarios (Brecha, 2008; Chiari and Zecca, 2011; Doose, 2004; Höök and Tang, 2013; Jones and Warner, 2016; Kharecha and Hansen, 2008; Mohr et al., 2015; Nel and Cooper, 2009; Ward et al., 2012, 2011). Hence, their conclusions were limited to indicate that the highest IPCC emission scenarios were incompatible with fossil fuel resource endowments (as also found in Chapter 5, see Figure 5.13). In contrast, we find a 42% probability of cumulative CO_2 emissions being above 6 W/m^2, which indicates that these previous studies by following a deterministic approach were not accounting for values in the upper ranges of fossil fuel availability estimates from literature.[53]

[53] Similar conclusions are obtained in relation to the assessment of the SRES scenarios by previous URR studies.(IPCC SRES, 2000a) In fact, many of these studies, carried out in the 2000s, compared their outcomes with this set of scenarios finding that the highest SRES

3.4. Policy implications

In this section we highlight two major policy implications of the obtained results in view of (1) the likelihood assessment of climate pathways and (2) the likely transition to renewable energies.

Firstly, our results confirm the need for urgent global coordinated action to avoid dangerous climate change (88% probability of surpassing 2ºC by 2100). Our analysis constitutes an opportunity to revisit the likelihood controversy concerning future climate change that arose after the publication of the SRES in 2000 (IPCC SRES, 2000a), when the approach shifted to consider emission scenarios as being "equally sound", with no associated probabilities. At the time, this shift was questioned, pointing out the difficulty of effectively orientating decision-making in such a framework since climate change mitigation and adaption is ultimately a risk management challenge (Mastrandrea and Schneider, 2004; Schneider, 2002, 2001; van Vuuren et al., 2008; Wigley and Raper, 2001). However, the calls to provide a subjective probability assessment for the set of scenarios based on expert opinion collided with the divergent views of participants in the scenario design process (Schneider, 2001). Since no likelihood or preference is attached to any of the RCPs (van Vuuren et al., 2011b), the new common set of climate scenarios, the assignment of probabilities to scenarios remains an open debate in the design and application of climate scenarios. In fact, the process of estimating absolute probabilities for different scenarios necessitates the comprehensive integration of all relevant sources of uncertainty, many of which remain extremely difficult to estimate, due to the existence of unknowns such as future human behaviour. In this sense, our approach constitutes a workable alternative focusing instead on the compatibility of the proposed pathways with physical resource restrictions. Thus, the obtained results could assist the climate policy making process in cases where the equal probability assumption may act as an obstacle.

Secondly, fossil fuels are able to supply easily manageable, high-quality energy flows to human societies due to their particular physical-chemical properties (e.g. high power density, storable, inert at standard ambient conditions, etc.). In contrast, renewable energies are characterised by lower power density and EROEI levels, being critically affected by their intermittence and variability and requiring additional infrastructures to ensure the continuity of supply (e.g. overcapacities, storage, transportation grids, etc.). Advanced industrial economies currently rely on large flows of fossil fuel resources, resulting in a relatively low cost of the energy system when comparing with the investments and operating cost that a renewables-based energy system would require (Hall and Klitgaard, 2012; Smil, 2015, 2008; Trainer, 2012, 2010). Thus, since current baseline scenarios do not envisage the likely depletion of fossil fuels this century, they might be neglecting the efforts required to achieve the necessary transition to renewables and might be therefore underestimating the cost of the future energy system. For example, comparing the energy costs of a scenario applying the median

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emission scenarios A1, A2 and A1G were incompatible with fossil fuel resource endowments (see Figure B.5).

values of our RURR estimates with a scenario with the energy endowments consistent with the IPCC-AR5,[54] the end-user electricity price is found to almost double (+80%) and the refined liquids price to increase more than 3-fold by 2100 (results not shown). Actually, these price increases are much higher than common projections from baseline scenarios in IAMs of climate change (IPCC, 2014a). Thus, although an effective policy to mitigate emissions to safe levels would certainly require more rapid reductions in fossil fuel use than their likely geological depletion rates, the mitigation policies would actually take place in a context of "higher than expected" penetration of renewable energies. Therefore, if current baseline scenarios are underestimating the future deployment of renewable energies, this would imply that current climate policy scenarios are overestimating the mitigation effort required to reduce GHG emissions to safe levels. For example, comparing again both scenarios with different fossil fuel endowments, the cumulated mitigation cost of reducing the emissions to limit the temperature increase to 2ºC by 2100 would be around 30% lower in the scenario applying the RURR estimates comparing to the one consistent with the IPCC-AR5.

Timely and adequate research and development (R&D) investments for modern renewable energies and related technologies (e.g. storage) are critical to successfully achieve the energy transition (Armaroli and Balzani, 2011). Our results suggest that renewable energies, that have traditionally received a minority share of funds for R&D in relation to the other technologies and fuels (IEA, 2010), should be prioritized in relation to other fossil-based low carbon technologies such as CCS. Anticipatory strategies to address fossil fuel depletion combined with a proactive climate policy could foster the speed-up of the learning curves of the renewable technologies, eventually contributing to reduce the overall transition costs.

3.5. Limitations of the analysis

Despite the vast uncertainties related to uranium availability due to its geopolitical relevance, the sensitivity of the climate outputs to the uranium RURR is found to be negligible (see Table 3.2 and Figure B.4). Because only the *Nuclear Energy Agency* reports uranium estimates for some regions of the world without any likelihood metric, the derived input distribution in this work is questionable. Still, since baseline scenarios in GCAM do not generally depict a higher share of the nuclear technology along the century, our findings with regard to climate change pathways would remain unchanged. Though, larger uranium availability may eventually affect solely the findings in relation to the transition to renewable energies in the electricity sector.

The transition to renewable energies faces its own challenges related with their low current deployment and biophysical characteristics in comparison with fossil fuels (de Castro et al., 2013b; Hall and Klitgaard, 2012; Smil, 2015, 2008; Trainer, 2012). However, the feasibility and timing of this transition could not be analysed in detail in

[54] For more details about this scenario see the section B.1 "GCAM baseline scenario" in the Appendix B.

this study since constraints to the diffusion of emergent technologies (Iyer et al., 2015) as well as geological limitations to the extraction rate of non-renewable fuels (Brecha, 2012; Miller and Sorrell, 2014) are not implemented in the standard version of the GCAM model.

Uncertainty and sensitivity analysis are dependent on the quality of the input distributions. In this sense, Dale (2012)'s dataset, from which the data for conventional oil, conventional gas and coal are taken, is a compilation of all the historic RURR estimates found literature. It does not include a comparative review of the quality, confidence and trustworthiness of the different datasets. Although these estimates are found to be in broad agreement with a recent review of the RURR of fossil fuels (see Table B.2) (Mohr et al., 2015), further work might be directed to improve the dataset's quality. Additionally, it was found that the shape parameter of the supply-cost curves has a weak influence on the uncertainty of the outputs in comparison to the RURR (see Figure B.4). In fact, the examination of individual scenarios from the Monte Carlo analysis reveals that most fossil-based technologies are not substituted by renewable energy technologies until fossil fuels are not depleted. However, this result depends on model exogenous assumptions on future technology costs of renewable energies, which was beyond the scope of the present analysis.

The transition to renewable energies would actually take place in a context of more expensive energy inputs. However, this reduced availability of energy inputs would include a monetary but also an energetic dimension. In fact, fossil fuel supply in the second half of the 21st century would be dominated by low grade and unconventional fuels, whose extraction requires comparatively higher energy investments than conventional fuels (i.e. are characterised by lower EROEI).[22,88] Moreover, renewables itself are characterised by low EROEI levels and require substantial levels of overcapacity and/or storage to tackle their intermittence and variability. Thus, current integrated assessment modelling of climate change would benefit from the adoption of a net energy analysis approach instead of focusing solely on primary energy flows.[87]

3.6. Conclusion

Fossil fuel resources availability is a key driver of emissions pathways, though the uncertainty in this parameter has not been sufficiently analysed in baseline emission scenarios. The integrated assessment models of climate change assume very high endowments of fossil resources, assuming that future discoveries and technological improvements will make available the energy resources demanded by the economy at an affordable cost. In turn, the application of the URR approach suggests that the exploitation of fossil fuel resources during the 21st century will likely decline globally even in the absence of policies promoting the transition towards renewables. In particular, our results show that more investments are required to enable the energy transition, while the additional mitigation measures would in turn necessitate a lower effort than currently estimated. In relation to the likelihood of climate change pathways, we find that the two highest emissions pathways from the IPCC (RCP6 and RCP8.5), where the baseline scenarios currently lie, have probabilities of being feasible of just 42% and 12% respectively. Hence, the integrated analysis of resource availability and climate change arise as an essential condition to obtain consistent climate pathways. Our results demonstrate that combining meta-analysis of current data from other disciplines within IAMs helps to improve the consistency of climate scenarios by shedding light on important factors and processes that may previously have been excluded or underestimated.

The URR approach recognizes that the assessment of the long-term availability of non-renewable resources requires an operational framework able to balance the opposing forces of technological development and geological resource quality decline with the aim of providing robust static estimates. However, it is sometimes argued that the URR is not a particularly useful metric when estimating recoverable resources since the socio-economic and technological context is always evolving. This argument is supported by the fact that not all attempts at its estimation in the past have been particularly successful (Rogner, 2012). However, the URR approach has also provided some relevant predictions that were not foreseen by the standard resource economics approach, which has even led influential international agencies such as the IEA or IMF to reconsider their methodologies for modelling the availability of fossil fuel resources (Benes et al., 2012; WEO, 2013).

Resources should be continuously reassessed in the light of updated information such as new geologic knowledge, progress in science and technology, and shifts in economic and political conditions. Accordingly, it would be recommendable to update on a regular basis the assumptions on recoverable resources of IAMs and to test the sensitivity of the results to the uncertainty on these inputs. This is especially valid for unconventional fuels, given that a reduced fraction has only recently become economically profitable. In this sense, future work may include this updated analysis effort as well as the extension of the analysis to study the interaction with other sources of uncertainty.

The following two chapters (Chapters 4 and 5) focus on the feasibility and timing of the transition to renewables by integrating two aspects that were not considered in this analysis: constraints to the diffusion of emergent technologies, as well as geological constraints to the extraction rate of non-renewable fuels.

CHAPTER IV

4. The transition towards renewable energies: Physical limits and temporal conditions[55]

In Chapter 3, it was found that accounting for uncertainty on fossil fuel resources availability has substantial implications for the assessment of future climate pathways. However, the detailed analysis of the implications for the energy transition requires a framework that includes, at least, temporal constraints with regard to: (1) the extraction rates of non-renewable fuel stocks, and to (2) the diffusion of new technologies. Since these features are not implemented in the standard version of the GCAM model, an alternative approach was taken by developing and applying a different model.

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., 2014b). 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 (2010b, 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 discovered 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

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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, 2007, 2006; Höök and Aleklett, 2009; Laherrère, 2006; Mohr and Evans, 2011, 2009; 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 Chapter 2) may include these restrictions, although in practice they are often not implemented in their standard versions (Iyer et al., 2015; 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).

The modelling of the energy-economy system requires distinguishing the extracted energy resources from their final uses, since not all energy types are directly interchangeable and, in some cases, a shift to an alternative energy resource might require major technological and even social adaptations. In this chapter we focus on two of the most important energy carriers: electricity and liquid fuels, which altogether represent around 80% of the total primary energy use at global level (WEO, 2014). We specifically centre on the substitution of oil in one of its main uses, transport; and in the substitution of non-renewables by renewable energies in the electricity sector. For this, we build a simple model of the world energy-economy system; a broader model including all economic sectors and fuels is presented and applied in Chapter 5.

The substitution of oil in the production of liquid fuels is highly problematic, since currently only biofuels can replace oil directly in most of its uses. However, biofuels display much lower land use efficiency and EROEI rates than oil-based fuels. Although second generation biofuels are expected to reach better levels of performance, the improvements will need to be substantial to become a large scale alternative to oil (Field et al., 2008; Papong et al., 2010; Pimentel et al., 2009).

Another alternative, although it may not be fully compatible with existing engines and fuel distribution infrastructures, is the replacement of oil by electric vehicles. However, the technical specifications of electric vehicles are currently much inferior to internal combustion engines (ICE), mainly in terms of travel range, which means that not all transport services can be currently replaced. In addition, modern battery technology requires substantial amounts of rare elements. These and other limitations, such as the need to increase total electric energy production, have been noted in numerous studies and are examined in detail in this chapter (AEE, 2009; Dings, 2009; FTF, 2011; Florian Hacker et al., 2009; Offer et al., 2010). Other alternatives for the reduction in the dependence of oil are based on the use of public transport, natural gas, and ways of saving oil, such as an increase in non-motorised transport, improvements in heat insulation, urban planning, and so on. They all depend on social changes and new infrastructures and are not included in the model version presented in this chapter.

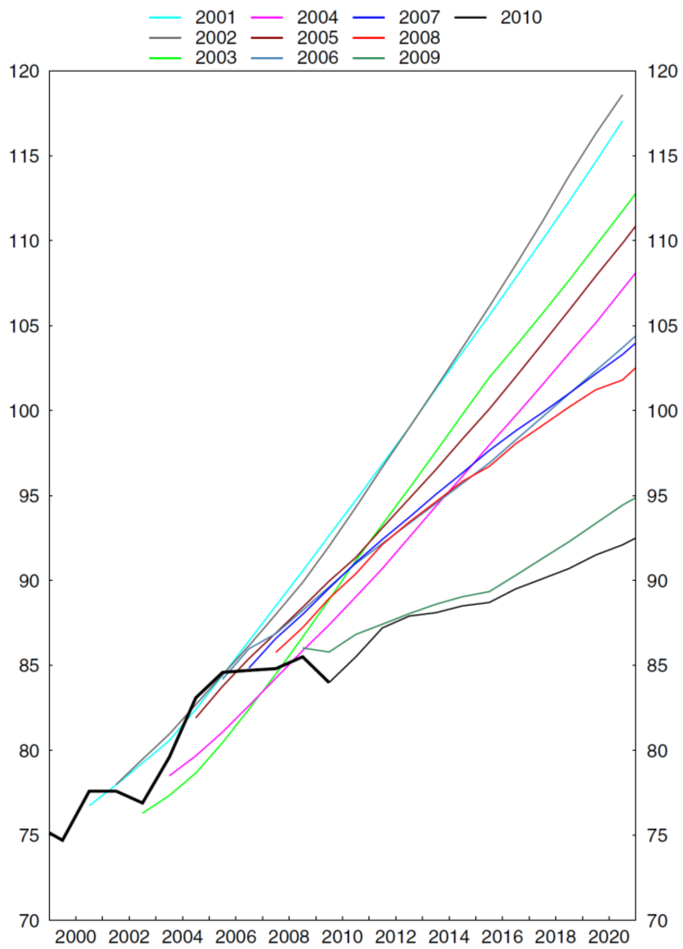
Most analysis have found that the replacement of non-renewable fuels in the generation of electrical energy is less problematic than in transport (e.g. (IPCC, 2014a)). In fact, there are currently renewable technologies with quite acceptable costs, EROEI rates and efficiency rates (e.g. wind and hydro power), and with a significant deployment potential (e.g. thermoelectric solar power and off-shore wind power) (Gupta and Hall, 2011; Heinberg, 2009; Murphy and Hall, 2010a). Although the variability and intermittency of renewable energy hinders the introduction of these technologies and requires additional infrastructures (i.e. storage, distribution grids, overcapacity) (Trainer, 2012), in the present chapter we have not tackled this problem.

This chapter updates, develops and applies a dynamic model derived from the one used in Mediavilla et al., (2011), to assess the fundamental aspects of the transition towards renewable energies. The model represents a consistent framework accounting for the physical limits and temporal conditions that transition policies cannot surpass. *Thus, the objective of the model is not to predict the future behaviour of the world energy-economy system, but to establish which transition policies are not feasible according to the depletion curves estimated by different experts and published in the literature.*

4.1. Global energy-economy model

In recent decades, many global energy-economy models have been developed (e.g. (Hourcade et al., 2006), see also the overview of energy-economy-climate models in Chapter 2). However, few 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 4.1**). 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 4.1: EIA forecasts of oil production (2001-2010)



Source: Benes et al., (2015).

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. (de Castro et al., 2009), and Dale et al., (Dale et al., 2012b).

In previous studies, the authors have analyzed the global energy-economy-climate system with a fully endogenised model, i.e. including dynamic feedbacks between all the main subsystems (de Castro, 2009; de Castro et al., 2009). In this sense, the current model has a simpler structure. However, the model presented in this chapter allows integrating the estimates of different experts and analysing their implications for the energy transition. Thus, the model can be used to obtain an overall perspective of the global energy question. The model includes the following aspects at global level:

- Economic growth and related demand of liquid fuels and electricity.
- Depletion curves of natural non-renewable resources (oil, gas, coal, uranium and lithium).
- Technical alternatives to oil in transportation: electric vehicles and biofuels.

- Generation of electrical energy from two aggregated sources: renewable and non-renewable.

The basic structure of the model can be seen in Figure 4.2. Future world economic activity is approximated by global GDP evolution, and used to estimate the global demand for oil and electricity extrapolating past intensity trends. Different assumptions, depending on the scenario, are taken for the future evolution of GDP. The stocks of natural resources are found in the lower part of Figure 4.2: oil and non-renewable electricity (subject to extraction rate constraints), biofuels and renewable electricity (not exhaustible, but finite).

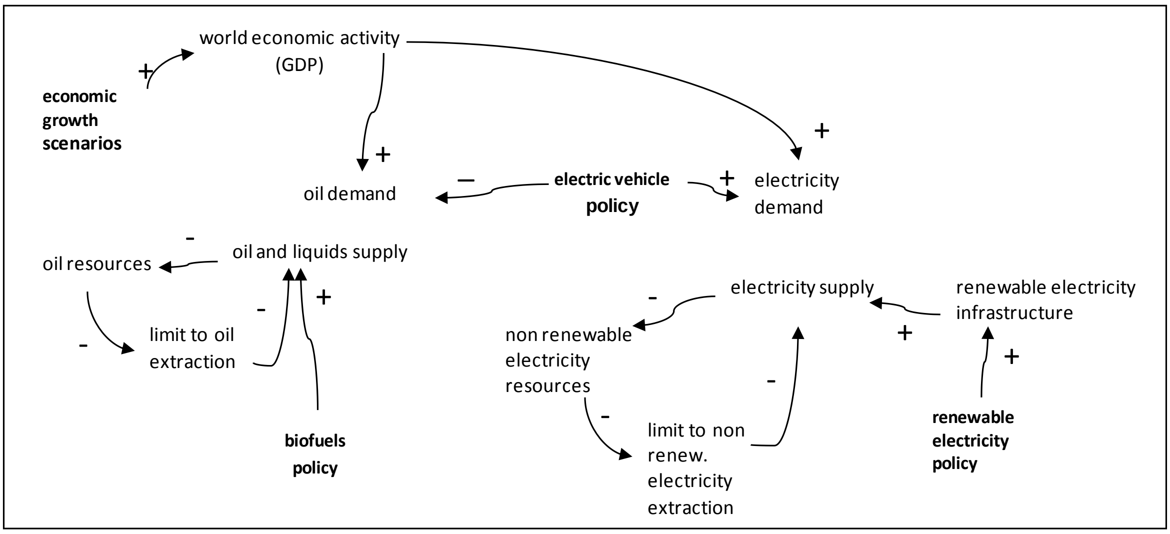
The relationship between the economy and the energy systems in this model can be described as dual:

- **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. 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.

Therefore, this model does not include an energy-economy feedback, i.e. it is rather a model of maximum physical restrictions. By omitting the energy-economy feedback we disregard the factors, such as prices, that tend to make the economy evolve. Some of these feedback patterns emphasise economic depressions, such as in the “oil shocks”, when oil scarcity drives economic recession. The recession can curtail investments in exploration and new oil fields developments, worsening in turn the oil crisis that may further aggravate the economic depression. Inversely, oil scarcity might also boost efficiency gains and substitution processes. The final outcome is in fact a result of both opposing forces, as history demonstrates. Our model must be understood, therefore, as a consistent “framework” accounting for the physical limits and temporal conditions of the transition towards renewable energies.

Finally, the main assumptions and policies studied in the model for building scenarios are shown in bold in Figure 4.2: economic growth, electric vehicle policy (including hybrid vehicles) and investment in renewable electricity (renewable electricity policy). Since the model focuses on policies and technologies available at the moment, its temporal scope is limited to the short and mid-term, and the scenarios will be projected to 2030/2050. For a more detailed representation, Figure C.1 in Appendix C depicts a simplified diagram with the most significant stocks and variables considered in the model.

Figure 4.2: Causal loop diagram of the model with its basic elements



Notes: The policies are in bold.

4.2. Review of global depletion curves of non-renewable energy resources

There exists an extensive literature providing global depletion curves considering geologically constrained extraction rates based on a diversity of techniques (Aleklett et al., 2010; ASPO, 2009; EWG, 2008, 2007, 2006; Höök et al., 2010; Laherrère, 2006; Mohr and Evans, 2011, 2009; Patzek and Croft, 2010; Skrebowski, 2010) (see Figures 4.3-4.6). These curves 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 and under some future technological development assumptions.

The following subsections discuss the depletion curves of non-renewable energy resources found in the literature by fuel (oil, gas, coal and uranium) with the objective to select some robust projections to be used afterwards in the scenarios (section 4.6). Those curves that are consistent with historical data and assessed as representatives of the state-of-the art are selected as central (i.e. reference) cases for the simulations. Additionally, the projections from the World Energy Outlook "Current Policies scenario" (WEO, 2010), essentially following the energy demand-driven paradigm, are represented for comparison.

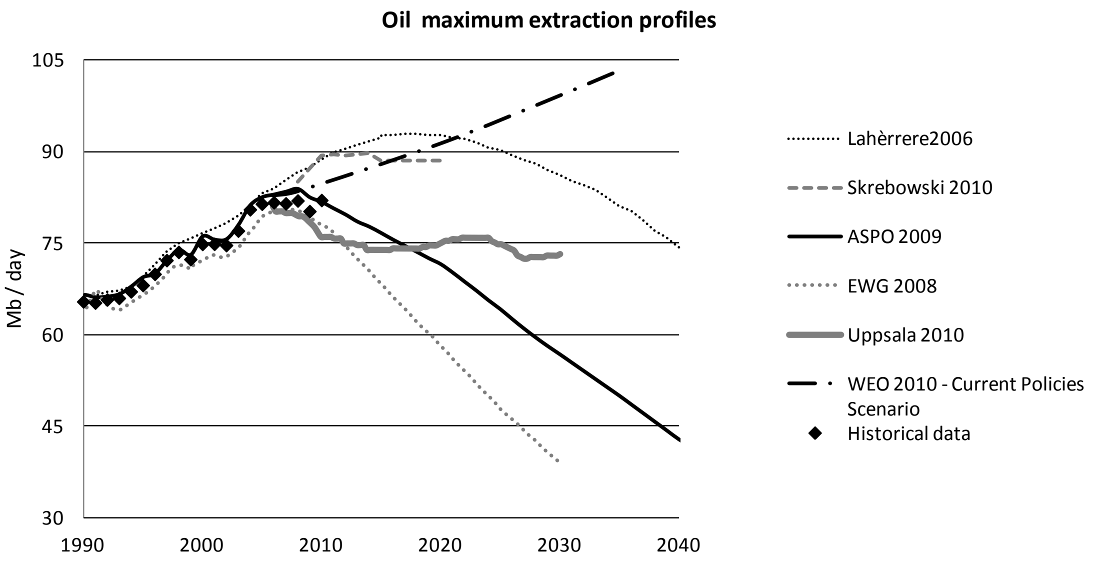
4.2.1. Oil

Figure 4.3 shows the projections found in the literature for oil extraction (Aleklett et al., 2010; ASPO, 2009; EWG, 2008; Laherrère, 2006; Skrebowski, 2010) compared with the projection of the Current Policies Scenarios of the IEA (WEO, 2010). Among the depletion curves, two main trends are foreseen: on the one hand, some analyses project that global oil extraction will reach a peak followed by a an irreversible decline in the next decades (e.g. (ASPO, 2009; EWG, 2008; Laherrère, 2006)), whereas other estimates find instead profiles that follow an undulating plateau, although providing data for a shorter timeframe (e.g. (Aleklett et al., 2010; Skrebowski, 2010)). 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 for the last five years, stagnated since 2005 (despite the fall in demand due to the global economic crisis did not happen until 2009). 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.

Hence, two central estimates for the scenarios are selected: ASPO (2009) and Aleklett et al., (2010). The former estimates an annual decline of approximately 2% from the present time and the latter a production plateau until 2030. In scenario 4a "BAU more oil" of section 4.6.5, the estimate of Laherrère (2006) for total oil has been considered. The consistency of the analysis with this highest estimate that exceeds past data for the last years is assured by the implementation of maximum extraction curves dependent solely on demand, as explained in section 4.2.5.

Finally, it should be remembered that the exact data for oil extraction are difficult to compare between different studies due to the different criteria that each author uses to define what is regarded as oil (conventional, unconventional, including refinery gains, etc.). Slight disparities between the real data and estimates (like those shown in Figure 4.3) are therefore inevitable.

Figure 4.3: Summary of depletion curves for oil by different authors and historical data of extraction (1990-2010)



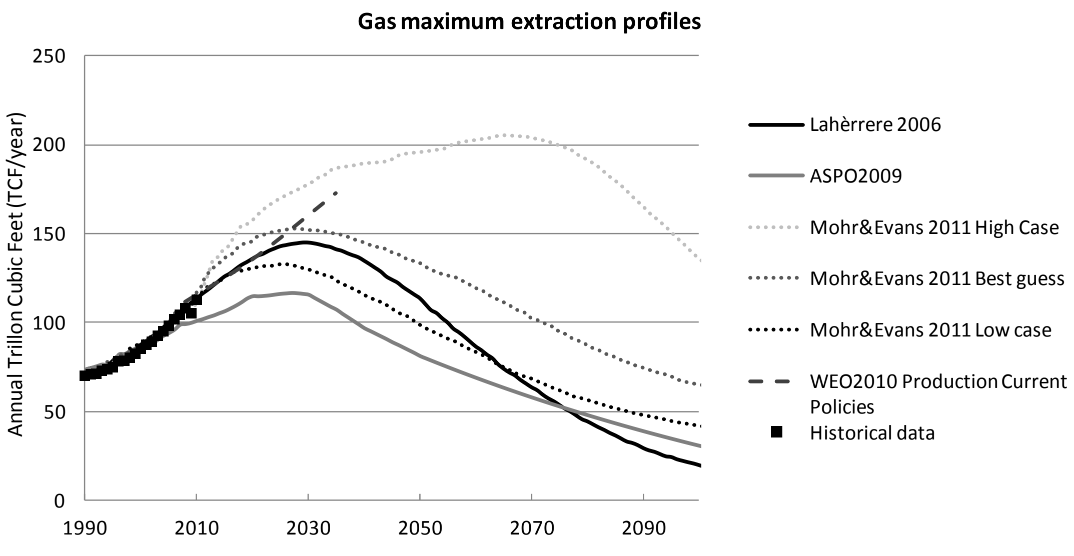
Notes: Million barrels of oil per day (Mb/day).

Source: Historical data from BP (2011).

4.2.2. Natural gas

Figure 4.4 shows the projections found in the literature for natural gas extraction (ASPO, 2009; Laherrère, 2006; Mohr and Evans, 2011) compared with the projection of the Current Policies Scenarios of the IEA (WEO, 2010). We observe that ASPO (2009)'s estimate for the last years is below recent historical data of production, looking outdated. Mohr and Evans (2011) 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 and Evans' (2011) two lower cases, although with a greater steepness after reaching the peak. The "high case" from Mohr and Evans (2011) assumes that very large amounts of unconventional gas (coal bed methane, shale gas and tight gas) would be available in the future (RURR of 11 ZJ) in comparison with the other estimates (vs. 2.1 ZJ considered by Lahèrrere (2006)). As a consequence, this high case is above the range of the rest of forecasts. Therefore, we decide to take Lahèrrere (2006)'s estimate for our central scenario. The projection of the IEA is only consistent with the "high case" of Mohr and Evans (2011).

Figure 4.4: Summary of depletion curves for gas extraction by different authors and historical data of extraction (1990-2010)



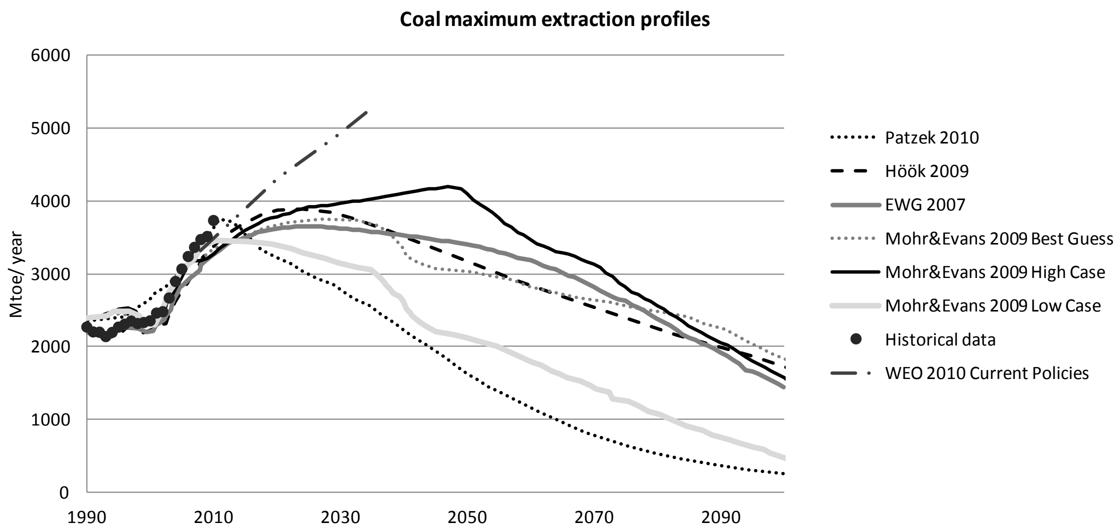
Notes: Trillion cubic feet per year (TCF/year).

Source: Historical data from BP (2011).

4.2.3. Coal

Figure 4.5 shows the different estimates for coal extraction that have been collected from the literature (EWG, 2007; Höök et al., 2010; Mohr and Evans, 2009; Patzek and Croft, 2010) compared with the projection of the Current Policies Scenarios of the IEA (WEO, 2010). The "high case" coal estimation from Mohr and Evans (2009) is selected for our central scenario because the particularities of coal as a solid mined resource are taken into account in this study, while the other studies (EWG, 2007; Höök et al., 2010; Patzek and Croft, 2010) are based on logistic curves similar to those used for oil. The liquid nature of oil makes fast extraction in mature fields impossible, no matter how much infrastructure is used. Since coal is a solid mineral, more infrastructure and extraction effort can replace the low quality of the resource. If the maximum extraction level is higher, this means that, with the same amount of ultimate recoverable resource, the extraction rate can achieve higher levels and subsequently deplete the resource faster. Moreover, Mohr and Evans (2009) "high case" matches better with past historical extraction than other studies (e.g. (EWG, 2007) and Mohr and Evans (2009)'s best guess). For the scenarios 4a "BAU more oil" and 4b "BAU less coal" in section 4.6.5 the estimate from (Höök et al., 2010) was considered. The projection of the IEA estimates that coal extraction will continue the trends from the 2000s decade, surpassing 5,000 Mtoe in the year 2035.

Figure 4.5: Summary of depletion curves for coal extraction by different authors and historical data of extraction (1990-2010)



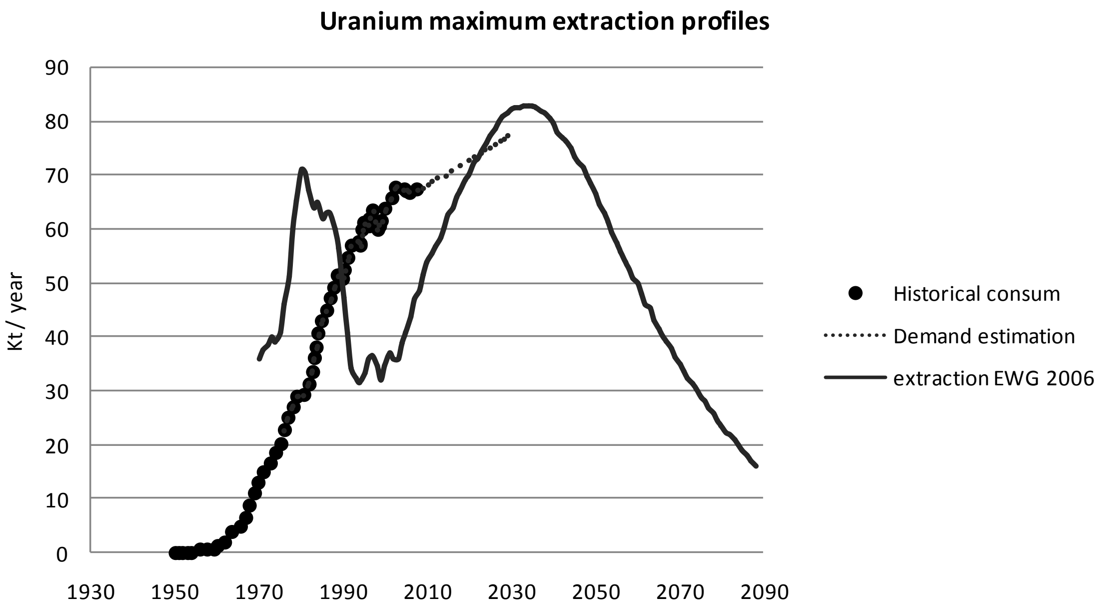
Notes: Mtoe per year.

Source: Historical data from BP (2011).

4.2.4. Uranium

Finally, Figure 4.6 shows the only uranium depletion curve found in the literature, produced by the Energy Watch Group (EWG, 2006), that we therefore apply in our central scenario. We consider that the technologies that could potentially increase the fissile material from 50 to 100 times, like fast breeders and the so-called fourth generation reactors, will not be available in the next decades and therefore are not taken into account in this model. We also assume in our model that in the future there will be enough reactors in the world to use all the available uranium, which may be optimistic, since Schneider et al. (Schneider et al., 2009) conclude that the current trend of the build up of new reactors is too low to even maintain current nuclear electricity production.

Figure 4.6: Depletion curve, demand estimation and historical consumption (1955-2005) of uranium



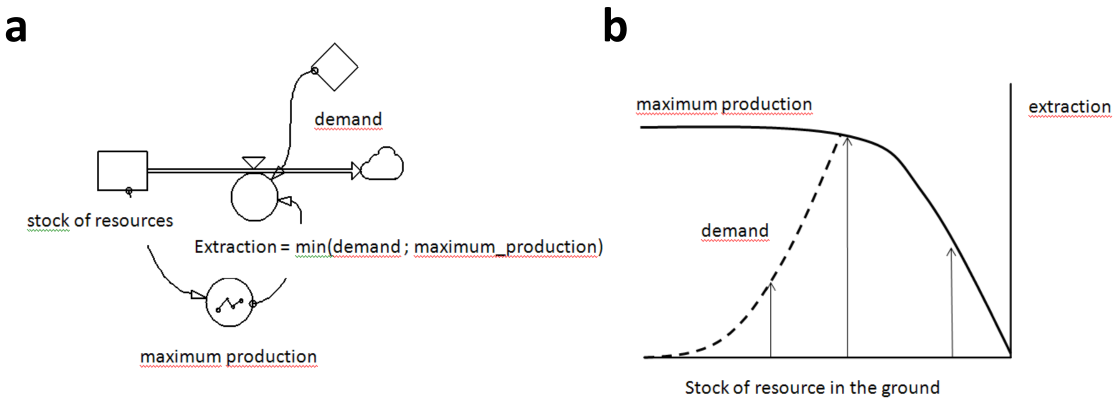
Notes: Thousand tonnes per year. The figure shows that part of the historical consumption has been met with the uranium stocks extracted in previous decades.

Source: Historical data from (EWG, 2006).

4.2.5. Integration of the depletion curves in the model

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 4.7a). 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 4.7b).

Figure 4.7: Integration of depletion curves in the model. (a) SD model. (b) A curve of maximum extraction (solid) compared with the demand (dashed)



Source: own work.

Figure C.2 in Appendix C shows the maximum extraction curve used in the model for the non-renewable fuels involved in electricity generation (coal, gas and uranium). The curve represents the usable electrical energy in annual electric terawatt hour (TWh/yr). To calculate this we have used the conversion of primary energy in EJ to electrical TWh, using present efficiencies: 0.33 for nuclear (IEA 2010), 0.35 for coal and 0.5 for gas (de Castro, 2009; WEO, 2010). In the case of natural gas and coal, we have ruled out the non-electrical uses of the fuels taking the data of past years' consumption (IEO, 2010): 33% of the gas and 63% of the coal was used for electricity generation. In the model, these shares are maintained in the future.

The x-axis represents the stock of non-renewable electric energy available, according to the estimated resources of fossil and nuclear fuels and the equivalent electric energy they would provide. The y-axis represents the maximum extraction rate that could be reached depending on the stock of the resource that is remaining. Accordingly, when the resources diminish, the maximum extraction decreases until it reaches zero when the resource is totally exhausted.

4.3. Oil substitution

As seen in the previous section, oil is the energy resource whose decline is estimated the nearest in time, being likely that we have already reached the peak of extraction. Oil production has been stagnated from 2004 ((BP, 2011), see also

Figure **4.3**), some years before the 2008-09 economic crisis lowered the energy demand. In fact, the (WEO, 2010) stated that the peak in the extraction of conventional oil production happened in the mid-2000s. The effects of this reduction in the supply of oil on the world's socioeconomic system will be framed by the importance of oil in the economy and by the difficulties in implementing adaptation or mitigation policies contributing to reducing the demand.

After the oil shocks in the 70s, it was possible to considerably decrease the oil intensity of world's economy. This was achieved in part by replacing the oil used to generate electricity by other fuels such as coal and gas. However, this step cannot be taken now, as the share of oil to produce electricity is small at a global scale (6% in 2011 (WEO, 2012)).

The most immediate technological substitutes for the consumption of oil in transport are biofuels and electric and hybrid vehicles. Efficiency improvements are also expected through improvements in the engines and the shift to lighter vehicles. This is actually the case of hybrid vehicles, which represent smaller oil consumption per vehicle. Vehicles using hydrogen, synthetic fuel or biogas are not considered here due to their early developmental stage. Other ways of saving energy, such as railways and changes in mobility patterns require more profound social transformations and costly infrastructures and are also not included in this model version.

4.3.1. Biofuels

Biofuels are the most immediate replacement for oil derivatives, but suffer from some serious disadvantages. Their EROEI has been widely researched and some studies report extremely low values (in some cases even less than one) (Field et al., 2008; Papong et al., 2010; Pimentel et al., 2009). In addition, they require large areas of fertile land (currently estimated at between 35 and 110 MHa/Gb, (FTF, 2011)). However, considering the surface used to grow biofuels in 2008 according to (UNEP, 2009) (36 MHa), and the oil equivalent produced that year (0.305Gb), their productivity today is 118 MHa/Gb, which is slightly above the highest estimate reviewed by (FTF, 2011). Although improvements might be expected in the future with the eventual development of advanced biofuels, the fact is that the biofuels are currently being grown on some of the planet's best land, and the potential surface occupation reduction is critically constrained by the biophysical limits of photosynthesis (Michel, 2012).

A simple analysis of the data shows that, with their current performance, biofuels cannot become a global alternative to oil. The replacement of the oil currently consumed by current biofuels would require 3,540 MHa of land, which represents 232% of all the currently available arable land on the planet (FAOSTAT, 2015). For a target aiming to substitute 60% of the oil (i.e. the share used currently for transport), the land requirements would be 140% of the arable land.

The IEA proposes, in its 450 Scenario (WEO, 2010), an increase in the production of biofuels from 1.1 Mb/d in 2009 to 8.1 Mb/d in 2035 (from 0.433 Gb/yr to 3.18 Gb/yr). We consider this estimate as the maximum level in our "high case" for biofuels.

For the biofuels "low case", we apply Field et al. (2008)'s estimate, assuming that 386 MHa of marginal land can be devoted to growing biofuels (with a lower productivity than today's average due to the inferior land quality), resulting in 27 EJ/yr of gross heat content as the upper limit of net plant production. Assuming that the efficiency of the conversion into liquid fuels is 0.2 and that the EROEI rate is 6 (between 2.63 and 8.86 of the Brazilian ethanol estimated by (Ramírez Triana, 2011)), the resulting net energy in the form of liquid fuels would be 4.5 EJ/yr, which is 2.53 Gb/yr.

4.3.2. Electric vehicles

The introduction of electric and hybrid vehicles is another technological alternative to replace oil. One of the crucial limitations of electric vehicles is their low functionality, especially in terms of the capacity for energy accumulation: 15 times less storage than conventional ICEs, 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. Due to this low accumulation capacity, only lighter vehicles are usually considered as candidates to be purely electrical, and even in those texts where purely electric vehicles are also considered for freight transport, such as (IEA, 2009), the goals are very modest and are restricted to "light commercial and medium-duty freight-movement". Since the consumption of light vehicles takes up practically half the oil used for transport (IEA, 2009), around 30% of the current world oil consumption could eventually be substituted by electric and/or hybrid vehicles.

Yet, electric vehicles have some positive aspects. For example, 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 required electricity consumption for each Gb of replaced oil would be 530 TWh (5.71 EJ/Gb). In order to grasp the magnitude order of the additional electricity requirements, we can estimate that, taking this ratio and the consumption of oil of the year 2010, the substitution of 30% of the world oil consumption by electric vehicles would require around 30% of the total electricity production of that year.

Another limit that should be taken into account when analyzing the potential of electric vehicles is that of the materials needed for the batteries. The most promising batteries at the moment are lithium-ion batteries, each electric vehicle requiring between 9 and 15 kg of lithium mineral. Lithium reserves are estimated as being 4.1Mt, although some authors claim that 11Mt could be exploited (F. Hacker et al., 2009). Angerer (2009) estimates 6 Mt of global reserves and, according to his data, if lithium consumption for applications unrelated with electric vehicles continues to rise at the present rate, by 2050, 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 (the 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 vehicles 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 intensive 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.

The IEA proposes in its (IEA, 2009) report, a “Blue EV Success” scenario which foresees 57% electric cars, 37% hybrid vehicles and 5.7% internal combustion vehicles by 2050. We shall propose this scenario as the “high case” for electric vehicles, as it is the most favourable from the point of view of the replacement of oil considered by the IEA. We place a limit of 900 million electric vehicles in circulation (lithium restriction) and suppose that hybrid vehicles consume 40% less than petrol vehicles (currently the figure is 30%). We regard this policy as optimistic because electric vehicles are finding serious problems in entering the market at global level due to their current high price and low autonomy. We (arbitrarily) establish the “low case” in half the number of electric cars (27%) by 2050, and the same proportion of hybrid vehicles as before.

4.4. The replacement of electric energy

The replacement of electricity currently generated with fossil fuels is possible through technologies that are already in use, some of them being already mature technologies. Hydroelectric energy is a technology that is near to saturation at global scale, and is only capable of a moderate growth (double output by 2050, following (WEO, 2008) estimates); whereas the new forms of renewable energy (e.g. wind, solar photovoltaic and thermoelectric) are capable of greater growth (as they have not been substantially deployed).

We have fixed the techno-sustainable biophysical potential for these forms of renewable energy at 2.7TW of average electric power (not installed power), based on the studies from de Castro (de Castro, 2012) and de Castro et al., (2013b, 2011). This potential is significantly lower than that of other authors; for example, Schindler and Zittel (2015) forecast 500EJ/yr (16TW) (for 2100), Teske et al., (2011)) 273EJ/yr (8,64TW) in 2050, the US EIA (IEO, 2010) forecast 125EJ/yr (4TW) in 2035, and Jacobson and Delucchi (2011) 360EJ/yr (11.5TW). De Castro et al.,'s studies show that obtaining more than 3TW of renewable electricity might be an extremely difficult and costly task that would require large amounts of land, materials and capital. In this context, energy efficiency and savings are expected to play a key role when the monetary and biophysical burden of expanding the electric production from renewables becomes significant.

Krewitt et al., (2009) report the following current capital costs for different renewable technologies:1,370 $/KW for wind energy, 3,480 $/KW for off-shore wind and 6,340 $/KW for solar-thermal energy. We consider an average cost of the installation of new renewables in the higher bound of the range in order to take into account that their intermittence increases the costs and also because, in the long run, prices might tend to increase because of the saturation of locations and the rising cost of minerals that can be expected after oil's decline (Trainer, 2012). Thus, we consider an average cost of 6,000 $/KW with 2,000 hours in use per year, and estimate that the new infrastructures needed to accumulate the energy means that the costs must be multiplied by four (Trainer, 2012). If we took a lower estimation for the cost of the renewable energy, such as 1,370 $/KW, the resulting cost would be divided by 3.5.

We also take into account the EROEI rate, as these new installations require energy inputs to be built. We assume that all the energy comes from oil and liquid fuels, as this is the worst scenario (since oil is the scarcest source of non-renewable energy in the model). We take an average EROEI rate of 8 for all renewables technologies (other analysis such as (Hall et al., 2009; Heinberg, 2009), for example, estimate higher EROEI rates, but without considering the energy to build additional storage infrastructures).

It is also necessary to highlight that the considered data in this analysis for land occupation, cost, EROEI rate and biophysical potential of these technologies are among the lowest in the literature. We are therefore being comparatively more pessimistic about the possibilities of these technologies than about electric vehicles and biofuels. In this way, the basic results of the model are more revealing, as it will be seen in the next section.

Electricity generation from renewable energies increased at a +2.5% annual growth in the period 1980-2005 at global level (BP, 2011). From the mid-2000s, modern technologies such as wind and solar photovoltaic began to be deployed at substantial levels, allowing a doubling in the annual growth rates of electricity generation from renewables in the period 2005-2010. 2010 was the year with the highest growth in that period (+8%). Since further promotion of renewable technologies is expected at global level due to their improving performances and decreasing costs (REN 21, 2012), this level is considered as the central value for the scenarios. Additionally, we consider the possibility that electric renewables might grow at higher levels than in the past (+10% annual growth).

Two additional assumptions are taken for simplicity: (1) the growth of electric renewable energy is modelled independently from demand and potential shortages, and (2) priority is given to renewable forms of energy in consumption compared with non-renewable energy.

4.5. World economic growth and energy demand

One way of analysing the relationship between the economy and oil is through oil intensity (amount of oil consumed per unit of GDP). In recent decades, the introduction of improved technologies and substitution with other energy sources has resulted in a reduction in the oil intensity of the economy (see **Figure 4.8**). It is possible that this trend will continue in the future, although it is also foreseeable that it will become increasingly difficult to reduce it further due to thermodynamical constraints. Thus, we assume that the future demand for oil is determined by the interaction between the level of economic activity and the oil intensity in the economy in a given time. Thus, in this model, the evolution in oil intensity in the economy depends only on time.[56] Technological progress reduces oil intensity by time, but these reductions are increasingly small due to the existence of thermodynamical limits to substitution processes (Stern, 2011). Hence, we assume that world oil intensity exogenously evolves following the form of a curve that decays exponentially with time:

$$oil_{intensity}(t) = \frac{oil\_production(t)}{GDP(t)} = a \cdot t^{-b} \qquad \textit{eq. 4.1}$$

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

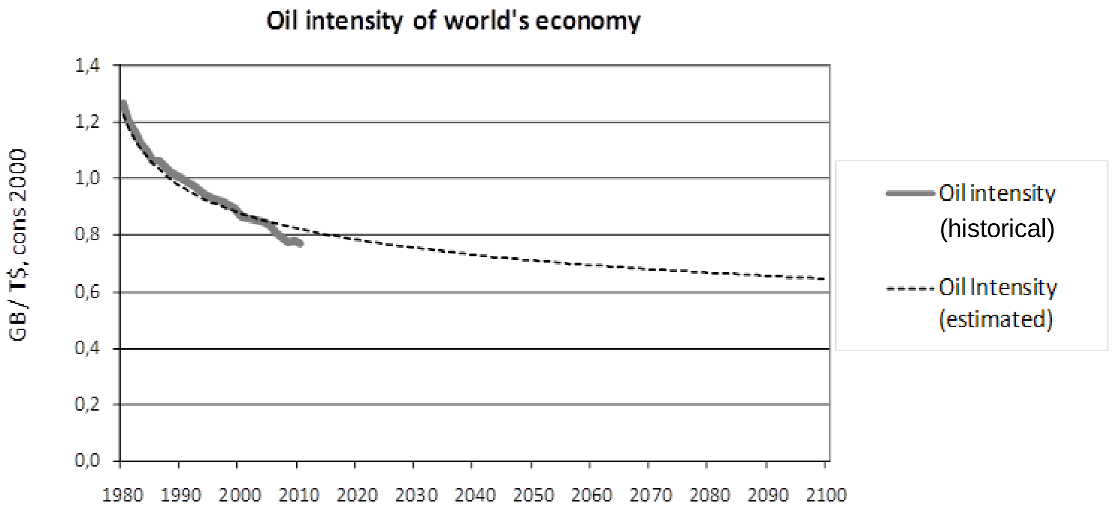
[56] It would be an improvement to refine the model so that other variables can be included, such as future oil prices, as it would make the complex more complex. An alternative to endogenising oil prices might be to consider exogenous assumptions on oil prices. Since these are subject to a great level of uncertainty, it was decided to simplify the analysis.

To estimate the parameters *a* and *b* in *eq. 4.1* we have used the following data for the period 1977-2010:[57] for the world GDP from the (World Bank database, 2015) at 2000 US$ constant prices in T$/yr ($10^{12}$$/yr), and the world oil production in Gb/yr (BP, 2011). The estimated parameters would result in the following equation:

$$oil_{intensity}(t) = 1.5874 \cdot 10^{-3} \cdot (t - 1976)^{-0.1869}, R^2 = 0.97 \qquad \textit{eq. 4.2}$$

The historical data for oil intensity and its estimation to 2100 following *eq. 4.2* can be seen in Figure 4.8.

Figure 4.8: Past and estimated oil intensity of the world's economy



Notes: Gbarrels of oil per T$ (constant dollar 2000).

Source: Historical data from World Bank database (2015).

[57] Data before 1977 have not been considered since during the 70s there was not a clear trend in the decline of global oil intensity.

4.6. Scenarios and results

In this section, the data discussed in the previous sections are introduced in the dynamic model. By default, the central estimates for oil, coal, gas and uranium discussed in section 4.2 are considered. Additionally, assumptions must be made about the exogenous assumptions and policies to be defined by the users, which are:

- **Economic growth** (expressed as a rate of growth of GDP at constant 2000 prices).
- **Introduction levels of electric and hybrid vehicles**. This is expressed in terms of the share of vehicles in the fleet that are electric/hybrid, and the amount of oil (Gb) they save. Notice that the number of electric vehicles depends on the total number of vehicles, which depends on the GDP, since the demand of oil for transportation is a fixed amount of the total oil demand (which is also function of GDP). The introduction of electric vehicles is modelled as a linear function of time, meeting the targets described in section 4.3.2.
- **Potential of biofuels** expressed in terms of Gb/yr of oil equivalent. While their potential is not reached, biofuel production grows following current trends.
- **Growth rate of renewable energy**. The installed potential of renewable electricity grows exponentially, a fixed percent each year of the installed capacity, while the hours of production per year are constant. Electricity is measured in terms of the electric energy delivered per year in TWh/yr.

Different scenarios can be built by varying these assumptions and policies, in order to answer questions such as:

- Which levels of economic growth will be possible without a change in the oil-economy relationship, and what changes would be required in order to overcome an eventual peak oil?
- Is it possible to continue with the economic growth and consumption patterns of recent decades, relying on the adaptation to peak oil based solely on technological replacements?
- Would the substitution of ICEs by electric vehicles represent a challenge to satisfy the electric energy demand?
- What physical and temporal limitations exist in the transition towards the generation of 100% renewable electricity?

4.6.1. Overview of the scenarios

Five scenarios are simulated in order to answer the research questions. Table 4.1 summarizes the main inputs of each of the scenarios developed in the next sections. In the case of non-renewable resources estimates, the central cases are applied unless stated otherwise:

Table 4.1: Overview of the scenarios

Scenario		Annual GDP growth	Alternative transport policy (Biofuels & electric and Hybrid vehicles)	Annual growth electric renewables	Non-renewable energy resources estimates
1. Business as usual		+2.9%	High case	+8%	Central estimates
2. Low GDP growth		+0.2%	High case	+8%	Central estimates
3. Low transport substitution policies		-0.5%	Low case	+10%	Central estimates
4	**a. “BAU less coal”**	+2.9%	High case	+8%	Central estimates; Höök et al., (2010) for coal
	b. “BAU more oil”	+1%	High case	+8%	Central estimates; Laherrère (2006) for total oil

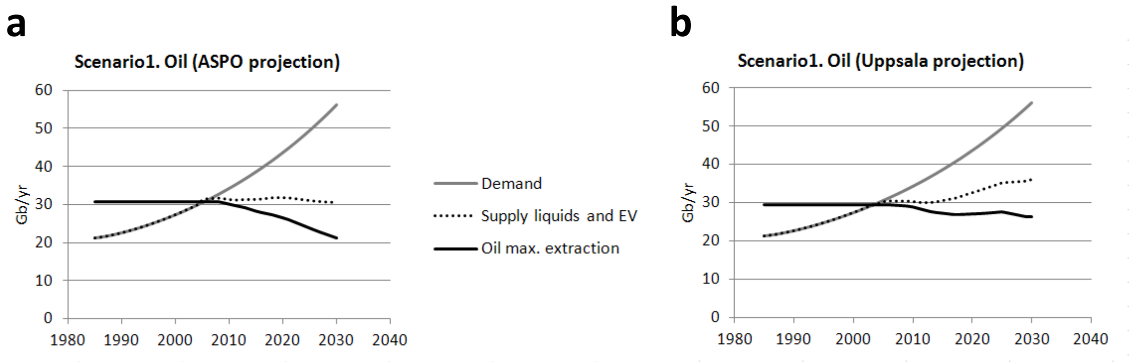
Notes: The central cases for non-renewable energy resources estimates are: ASPO (2009) and Aleklett et al., (2010) for oil, Lahèrrere (2006) for gas, Mohr and Evans (2009) “high case” for coal and EWG (2006) for uranium. BAU stands for business as usual.

4.6.2. Scenario 1: “Business as usual” (BAU)

Firstly, we shall see how the model behaves assuming a continuation of the economic growth of recent decades (+2.9%/yr) without any significant change in consumption patterns (energy intensity continues its downwards trend) and with large investments in biofuels and electric vehicles. In this scenario we consider the “high case” for biofuels and electric vehicles, whereas renewable electricity is set to grow at +8% annually. We consider two different estimates for oil: (1) ASPO (2009) that projects an imminent peak and decline, and (2) the projection from the team from the Uppsala University (Aleklett et al., 2010), that projects an undulating plateau to 2030.

The results of this scenario are shown in Figures 4.9-4.11. Figure 4.9 depicts the temporal evolution of oil demand, the oil maximum extraction according to the estimates of ASPO (left panel) and Uppsala (right panel) and the total amount of oil equivalent that can be obtained from biofuels and the equivalent savings from electric and hybrid vehicles. Figure 4.9 shows that, even considering a “high case” for these substitutes, the resulting supply is much lower than the demand. According to the estimates for peak oil considered, and assuming the most optimistic cases for biofuels and electric vehicles, the supply cannot meet the demand with the economic growth and consumption patterns of the last few decades.

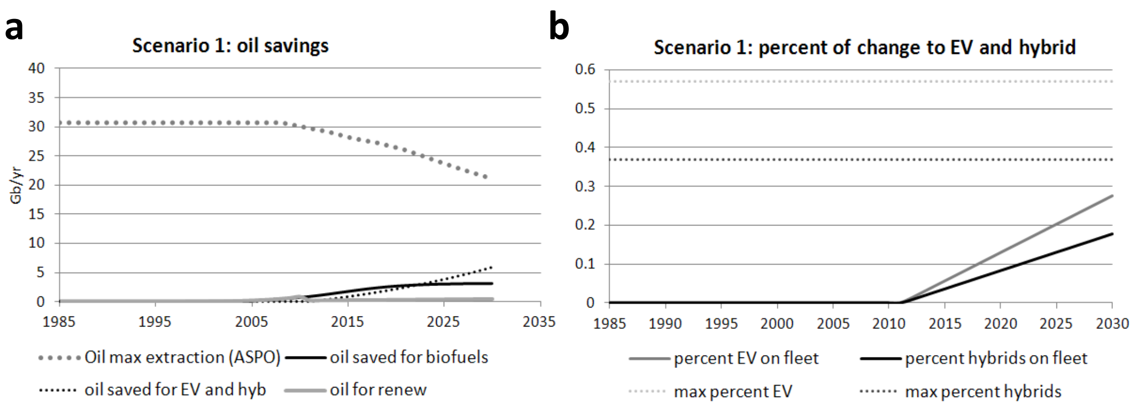
Figure 4.9: Scenario 1 "Business as usual". Oil demand and supply



Notes: The economic growth and the oil intensity trends of past decades are extrapolated. "High case" for electric vehicles and biofuels. *Demand* is the oil demand as driven by GDP growth; *Supply liquids and EV* is the supply of oil including biofuels and oil saved by electric and hybrid vehicles; *Oil max extraction* is the oil extraction estimated by ASPO (a) and Uppsala (b). Gb/yr

Figure 4.10a shows the amounts of oil saved by each policy. The oil saved by biofuels soon stagnates reaching its potential at around 4 Gb/yr, while that of the electric vehicle grows along all the period studied surpassing equivalent savings of around 5 Gb/yr. Figure 4.10b represents the share of electrical and hybrid vehicles in the fleet; by 2030 their introduction is half way to the objective of the policies (set for 2050).

Figure 4.10: Scenario 1 "Business as usual" scenario. Oil savings

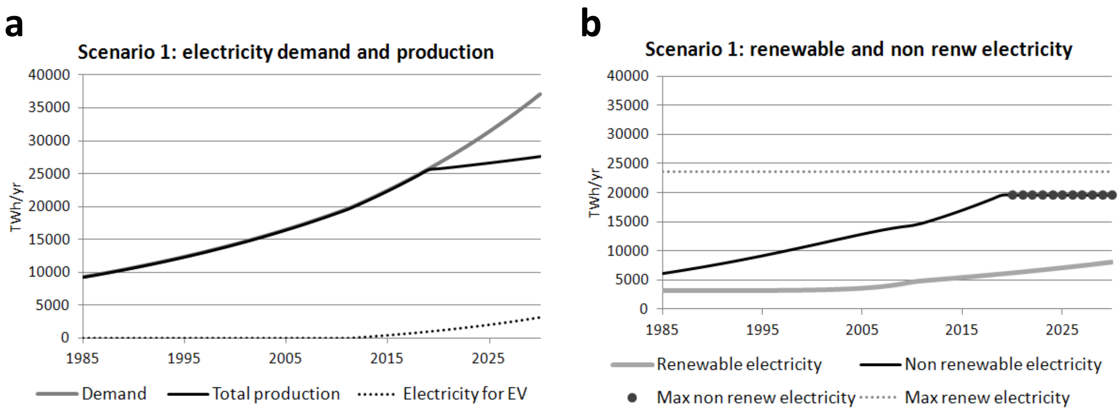


Notes: (a) oil saved by electric vehicle and biofuels (high case) as compared to oil maximum extraction considering ASPO (2009). *Oil for renew* is the oil required to build the infrastructures for renewable electricity. (b): share (from 0 to 1) of electrical and hybrid vehicles in the fleet.

Electricity generation does not exhibit such immediate limitations. Figure 4.11a shows that demand and supply (generation) of electricity meet until approximately the year

2020. In Figure 4.11b, the electricity production is disaggregated into renewable and non-renewable sources. The electricity generation from non-renewables increases until 2020, when it reaches the limits of the combined maximum extraction rates of gas, coal and uranium, stagnating thereafter (instead of a peak). After 2020, the growth of renewable electricity generation (+8% per year in this scenario) does not compensate for the growing demand and the stagnation of the generation of electricity from non-renewable fuels. In Figure 4.11a, the electricity demanded by electric vehicles is represented separately. By 2030, electric vehicles would consume around 15% of global electricity consumption. Thus, the substitution of ICE vehicles by electric and hybrids would imply a relatively modest increase in global electricity consumption.

Figure 4.11: Scenario 1 "Business as usual". Electricity supply and demand



Notes: The economic growth and the oil intensity trends of past decades continue. "High case" for electric vehicles and biofuels. Growth of renewable electricity at +8%/yr. (a) demand and total production of electricity (renewable and non-renewable). *Electricity for EV* is the demand of the electric vehicles (this is also included in the curve of demand). (b) production of renewable and non-renewable electricity. Non-renewable electricity reaches its maximum extraction plateau by 2020. *Max non renew electricity* is the curve of maximum extraction that combines gas, coal and uranium peaks. All data in TWh/yr.

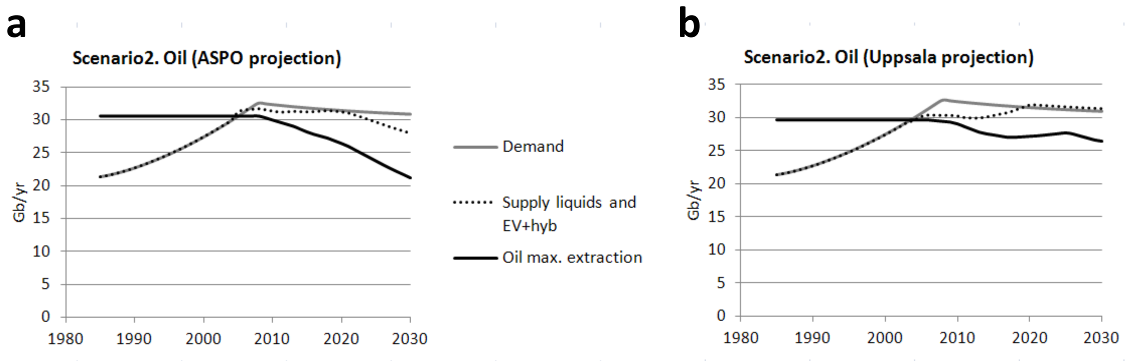
In this scenario, the investment in renewable energy reaches 0.14% of the GDP in 2030 (110 G$/yr) and the energy invested in new renewable installed capacity, derived from its EROEI rate, appears to be negligible compared with global energy consumption (see the variable *Oil for renew in the* Figure 4.9a).

The main conclusion extracted from the first scenario would be that: *considering the estimates of depletion for non-renewable fossil fuels resources from the literature, and assuming that energy intensity evolves following past trends, it would not be possible to assure the supply of energy required by economic activity growing at past trends. From now on, substantial savings in oil consumption would be needed beyond the technical substitution by electric vehicles and biofuels.*

4.6.3. Scenario 2 "Low GDP growth"

Since scenario 1 "Business as usual" turned out to be unfeasible, in this section we consider an alternative scenario with a lower growth of GDP in order to avoid the mismatch between oil supply and demand. The rest of assumptions considered in the previous scenario are maintained: "high cases" for oil substitution by electric vehicles and biofuels, both ASPO and Uppsala estimates for oil depletion, oil intensity of the economy, +8% annual growth of electricity generated by renewables.

Figure 4.12: Scenario 2 "Low GDP growth". Oil supply and demand



Notes: The economic growth is set to +0.2% and the oil intensity trend of past decades continue. "High case" for electric vehicles and biofuels. *Demand* is the oil demand as driven by GDP growth; *Supply liquids and EV* is the supply of oil including biofuels and oil saved by electric and hybrid vehicles, *Oil max extraction* is the oil extraction estimated by ASPO (2009) (a) and Uppsala (b). All data in units of Gb of oil equivalent per year.

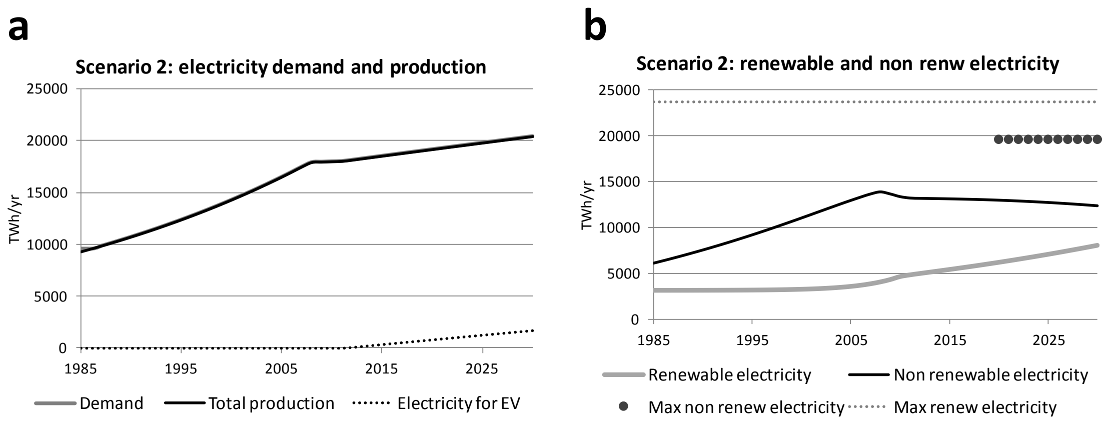
Figure 4.12 shows that when global economic growth is stopped (+0.2% annually), the supply approximately satisfies the demand for both ASPO and Uppsala oil depletion curves during the period studied.

It should be noted that the demand for liquids and EV of this scenario (Figure 4.12) gets a much lower value than the equivalent curve of scenario 1 (Figure 4.10), since the policies of electric and hybrid vehicles are set as a share of the total amount of vehicles and, if the economy growth at a lower rate, the demand for transportation and the number of electric vehicles decreases accordingly.

The perspectives for electrical energy can be seen in Figure 4.13. Both renewable and non-renewable electricity generation grow at a moderate rate without supply constraints; most of the growth in electricity demand is due to the introduction of the electric vehicles. In fact, the growth in electricity consumption in this scenario is so low that, even under the extreme case that investment in renewable electric energy would drop to zero, difficulties in meeting demand would not arise before 2100 (result not shown). On the other hand, as economic growth is lower than in Scenario 1, the investment in renewable energy reaches a higher share of global GDP (0.26% by

2030, 110 G$/yr). Figure 4.13b shows that in this scenario, the transition to renewables is accelerated: the electricity generated by non-renewable electricity declines after 2011 due to the combined effects of the assumption of the preference of the renewable over the non-renewable electricity generation and the low electricity demand.[58]

Figure 4.13: Scenario 2 "Low GDP growth". Electricity supply and demand



Notes: The economic growth is set to 0.2% and the oil intensity trend of past decades continues. "High case" for electric vehicles and biofuels. Moderate growth of renewable electricity (8%). (a) demand and total production of electricity (renewable and non-renewable). *Electricity for EV* is the demand of the electric vehicles (this is also included in the curve of demand). (b): production of renewable and non-renewable electricity. Non-renewable electricity reaches its maximum extraction plateau by 2020. *Max non renew electricity* is the curve of maximum extraction that combines gas, coal and uranium peaks. All data in TWh/yr.

The results obtained in this scenario indicate that, even with optimistic replacement policies and economic growth near to stagnation, it will be difficult to meet the demand for oil. If ASPO estimates are correct, and oil production is going to peak and not reach a plateau, even very high policy cases for biofuels and electric vehicles will only be able to postpone the problem.

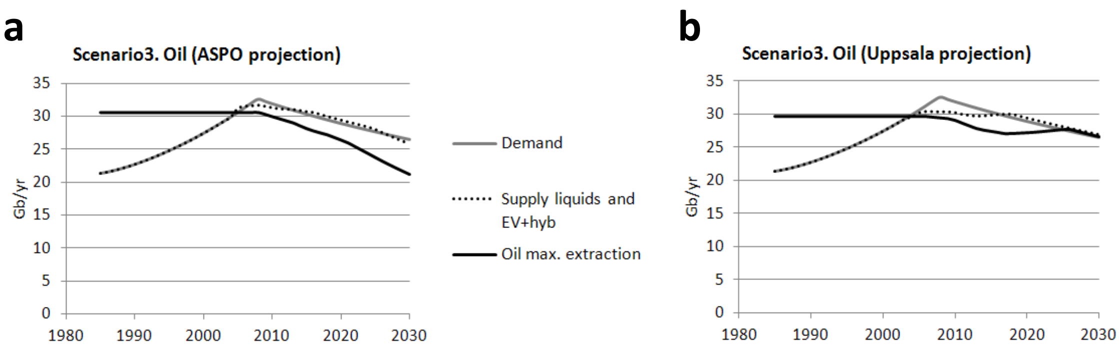
In this scenario, by 2030, the amount of oil replaced by electric vehicles and biofuels is similar (3.2 Gb/yr). However, the implications in terms of land use are very different: 371 MHa of land would be required to produce this energy from biofuels considering current global average performance (see section 4.3.1), in contrast with the 7.6 MHa needed to generate the additional electricity for electric vehicles using solar photovoltaic energy. The land required for biofuels would be very large, in the magnitude order of the current direct land occupation for human settlement and infrastructures (200–400 MHa) (de Castro et al., 2013b). The different power densities of each fuel and the efficiencies of the final energy use, make that *biofuels for ICE occupy almost 50 times more (fertile) land than electric vehicles fed with solar power.*

[58] We are conscious that it might not be very realistic to assume that, with a stagnant economy, humankind would decide not to burn the remaining coal and gas and invest in renewable energy sources.

4.6.4. Scenario 3 "Low transport substitution policies"

Scenario 3 explores the implications for the energy transition under low oil substitution policies by electric vehicles and biofuels. Additionally, renewable energy technologies are assumed to grow at a higher pace (+10%/yr). Here too, economic growth is adjusted to assure that supply approximately satisfies demand considering both ASPO and Uppsala oil projections (see Figure 4.14). This results in a negative GDP growth of around -0.5% per year. *This scenario shows that the global economy might be forced to contract in the absence of strong technological substitution policies and a structural change in the economy.*

Figure 4.14: Scenario 3 "Low transport substitution policies". Oil supply and demand

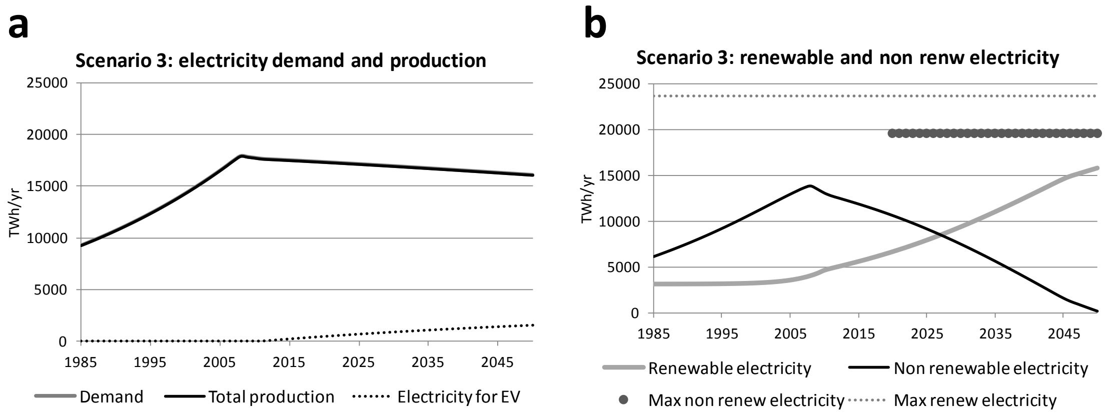


Notes: The economic growth is set to -0.5% and the oil intensity trend of past decades continues. "Low case" for electric vehicle and biofuels. *Demand* is the oil demand as driven by GDP growth; *Supply liquids and EV* is the supply of oil including biofuels and oil saved by electric and hybrid vehicles; *Oil max extraction* is the oil extraction estimated by ASPO (2009) (a) and Uppsala (b). All data in units of Gb of oil equivalent per year.

The perspectives for electricity can be seen in Figure 4.15 where the time frame has been extended to 2050. In this scenario, the demand for electricity decreases significantly reaching a level below current consumption in 2050. Thus, the growth of +10%/yr of renewable electricity is sufficient to satisfy the electricity demand until the mid-Century. In this scenario, the non-renewable electricity generation decreases since our model gives preference to renewable energy sources over the non-renewable ones (as in scenario 2, see section 4.1).

In this scenario, investments in renewable energies would reach a maximum of 180 G$/yr by 2030 (0.5% of GDP) and 271 G$/yr by 2050 (0.84% of GDP), with a cumulated value of 7,070 G$ during the period 2010-2050. Assuming the low cost of renewable infrastructures (as described in section 4.4), these numbers would be: 77 G$/yr by 2050 (0.24% of GDP) and 51 G$/yr in 2030 (0.14% of GDP). In any case, a detailed economic analysis would be necessary to conclude whether these costs represent a burden to the global economy, which is beyond the objectives of this study.

Figure 4.15: Scenario 3 “Low transport substitution policies”. Electricity supply and demand



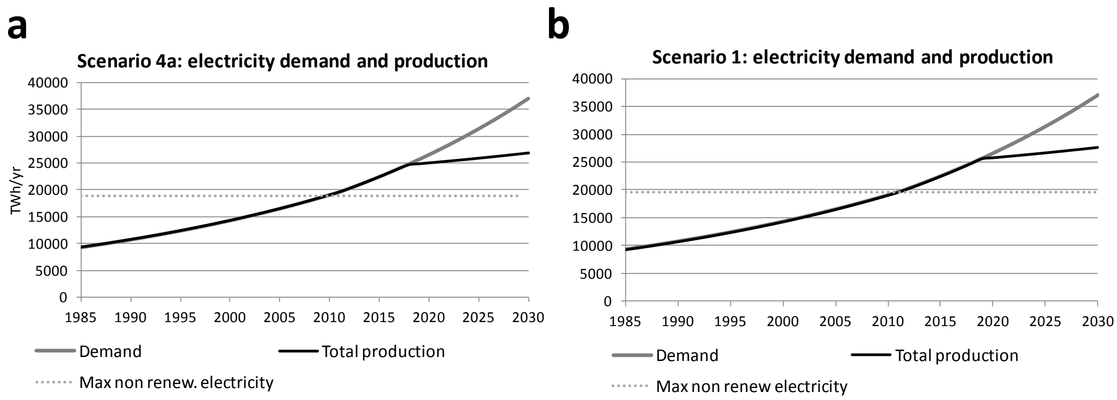
Notes: The economic growth is set to -0.5% and the oil intensity trend of past decades continues. “Low case” for electric vehicles and biofuels. High growth of renewable electricity (10%). (a) demand and total production of electricity (renewable and non-renewable). *Electricity for EV* is the demand of the electric vehicles (this is also included in the curve of demand). (b) production of renewable and non-renewable electricity. Non-renewable electricity reaches its maximum extraction plateau by 2020. *Max non renew electricity* is the curve of maximum extraction that combines gas, coal and uranium peaks. All data in TWh/yr.

4.6.5. Scenarios 4a and 4b: “BAU less coal” and “BAU more oil”

The results of the simulations of scenarios 1 to 3 indicate that oil is going to be the first restriction, electricity seeming less critical. Previous scenarios have considered the central depletion curves for oil, coal, gas and uranium as discussed in section 4.2. These depletion curves were on the lower range of the literature review for oil, while the highest found projection for coal was selected (Mohr and Evans (2009) high case). In this section, we explore the cases where less coal might be ultimately extractable (scenario 4a), and a more optimistic curve for future oil extraction (scenario 4b), keeping the central estimates for gas and uranium, as well as the rest of assumptions of the model as in the scenario 1 “Business as usual”.

- **Scenario 4a: “BAU less coal”.** This scenario is based on Höök et al., (2010)’s depletion curve for coal and ASPO (2009) estimate for oil. A “Business as usual” economic growth (+2.9%/yr), high policy case for biofuels and electric vehicles and +8% annual growth for renewable electricity are assumed. Figure 4.16 compares the results for the electricity demand and supply for this scenario with the scenario 1 (the results for oil being unchanged). Figure 4.16 shows that the difference between those two runs is very small. Thus, c*hoosing a lower estimate for coal does not alter the main results of the model*.

Figure 4.16: Scenario 4a "BAU less coal". Electricity demand and supply



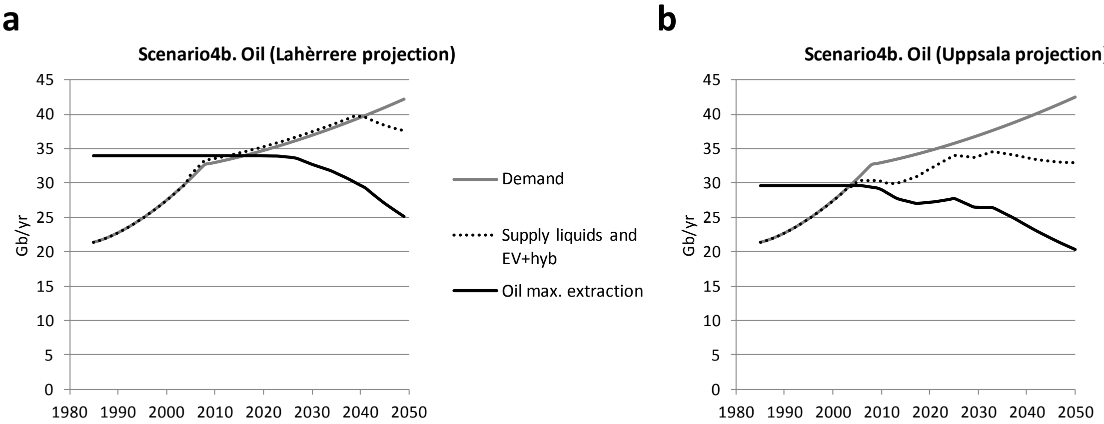
Notes: Demand and total production of electricity (renewable and non-renewable). The economic growth is set to +2.9% annually ("Business as usual"), high policy case for biofuels and electric vehicles, growth of renewable energies is set to +8% annually. (a) scenario 4a (with low estimates for coal); (b) scenario 1 (with high estimates for coal). All data in TWh/yr.

- **Scenario 4b: "BAU more oil"**. This scenario is based on a high estimate for oil, that of Laherrère (2006) (the highest found in literature, see
- Figure **4.3**). High development case for biofuels and electric vehicles and +8% annual growth of renewable electricity are assumed. Finally, economic growth is adjusted to assure that supply approximately satisfies demand, resulting in a GDP growth of around +1% per year.

Figure 4.17a shows the results for oil for this scenario, while the right panel depicts the results considering instead Uppsala projection for oil extraction. In fact, considering Lahèrrere's estimate for oil and adjusting the annual economic growth to +1%, the oil supply meets the demand for the next decades (until almost 2040). *This indicates that the consideration of Lahèrrere's estimate does change substantially the results of our model*. The high economic growth of past decades cannot continue if the energy-GDP relationship does not change abruptly (as in previous scenarios), but some economic growth is still possible, clearly differing from the stagnation obtained in scenario 2.

Since the main difference between ASPO's and Lahèrrere's projections relies in the amount of non conventional oil that can be extracted, scenario 4b represents a future where economic growth is still possible with the same energy-oil evolution of past decades at the cost of high environmental impacts.

Figure 4.17: Scenario 4b "BAU more oil". Oil supply and demand



Notes: The economic growth is set to +1% annually and the oil intensity trend of past decades continues. The oil projection is set to (a) the highest estimate, that of Lahèrrere (2006); and (b) that of Uppsala's. "High case" for electric vehicles and biofuels. *Demand* is the oil demand as driven by GDP growth, *Supply liquids and EV* is the supply of oil plus biofuels and oil saved by electric and hybrid vehicles. All data in units of Gbarrels of oil equivalent per year.

4.7. Discussion on the model

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

The model is designed to study whether a short-term reaction is possible in the face of the eventual near depletion of fossil fuels, and therefore it focuses on the best policies and technologies available at the moment. However, to study the energy transition in greater detail, it would be necessary to analyse all possible mid-term and even long-term options, such as the use of natural gas in transport, biogas produced from waste, substitution of fuels for heating, savings and efficiency policies, etc.

This model does not study in depth other options involving the electrification of energy consumption that currently depends on other energy carriers such as oil. As a result, in this model, the consumption of electric energy does not increase significantly. However, with the decline in oil extraction, there might be a shift towards electric final energy uses, increasing the demand of electricity in the future. In that case, the peak of electricity generated by non-renewable resources could be reached earlier, making the role of renewable energies more relevant. It would also be preferable to include the variability of renewable energy in the model to estimate the additional cost related with the required infrastructures (e.g. overcapacities, storage, transportation grids, etc.). In relation to the techno-sustainable potential assumed in the model for renewable electric energies, it is noteworthy that the consideration of a potential in the low range of the literature does not alter the main conclusions. The integration of the EROEI of renewable energies does not substantially increase the additional energy requirements of the system. This result is somehow expected due to the simplifying assumptions used in modelling renewable energy technologies, their relative low penetration in all scenarios and the omission of other energy services in the modelling framework.

In this chapter, the world economy is modelled in a very stylized way, only using an aggregated function of oil intensity. A regional or sectoral-based study would allow disaggregating policies and responses. For example, different countries and sectors have different vulnerabilities to oil depletion (e.g. (Kerschner et al., 2013)). The oil-GDP relationship might also change abruptly and we might see higher economic growth than the one considered in these scenarios while oil declines, but considering such social and economical changes is beyond the reach of the presented analysis. This chapter just states that the trends of previous decades cannot continue considering *only* currently envisaged technological changes. It would also be interesting to introduce a feedback between the energy and the economy in future studies, as this is a very sensitive characteristic of the model.

4.8. Concluding discussion

The model presented in this chapter is a global-aggregated dynamic model of the energy-economy system at global scale focusing on the transition from fossil fuels (notably oil) to renewable electric fuels. Despite its simplicity and aggregate nature, it enables some quite clear conclusions to be drawn.

The main conclusion reached is that, according to the experts' estimates of non-renewable depletion curves existing in the literature, peak oil would be the first restriction we shall have to face, being not easy to overcome with the currently available technologies. Neither biofuels nor electric vehicles offer a satisfactory solution in the short term to maintain current trends in energy consumption and economic growth. Thus, we find that there is a substantial risk that patterns of economic growth and energy intensity reduction from previous decades might not be maintained in the future. If the hypotheses of “low cases” and the projections of non-renewable energy resources in the literature are accurate, we might face continuous economic recessions. Overcoming the fall in oil production would thus require much greater changes in energy intensity than those achieved in recent decades.

Electric vehicles could be a partial solution to attenuate oil dependency, but their large deployment is challenged by their low current performance. Biofuels are a much worse alternative from the point of view of land efficiency, since the occupation of land is currently up to fifty times greater than the equivalent land needed by an electric vehicle powered with solar energy. Thus, their large-scale use at global level would compete with other land uses such as food production and habitat conservation.

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

The replacement of electric energy produced from fossil and nuclear fuels with renewable energy seems less challenging, as the peaks of natural gas and coal are not so imminent and the technologies for producing electricity from renewable energies are available. In the case that world economic growth may slow down due to an eventual peak oil, the demand for electricity would also likely fall. In this scenario, a moderate growth in electric generation from renewable energies would be able to satisfy a large share of the demand, contributing to reduce the GHG emissions.

The model is only intended to be an aid to understanding the feasibility of alternatives that may be able to adjust energy supply and demand on a world level, based on the experience of previous decades and the available information about resources and technologies. The model does not and cannot predict the energy or economic future because many aspects have not been taken into account. Many more features would have been required to be included to study the interaction between all energy sources and economic sectors at global level, as well as a greater regional disaggregation to analyse national energy policies in the global context. Hence, the model presented in this chapter has been used as a framework for the development of a much more complex model in the next chapter 5 integrating all energy sources and economic sectors.

CHAPTER V

5. Fossil fuel depletion and socio-economic scenarios: An integrated approach[59]

As described in Chapter 1, concerns about the depletion of non-renewable energy and materials, as well as limits to the ecosystem's assimilation capacity of residues have been raised in the social, political and business arena for some decades. Consequently, renewable energies, particularly solar and wind, are viewed as fundamental feature in the transition to a low carbon economy (IPCC, 2014a; Smil, 2010). While depletion estimation for individual fuels following different approaches are relatively abundant (see chapters 4 and 5 for an overview), few studies have focused on the objective of performing a comprehensive analysis including estimates for all fossil fuels (Aleklett, 2007; EWG, 2013; Laherrère, 2006; Maggio and Cacciola, 2012; Mohr, 2012; Valero and Valero, 2010), and even fewer have analyzed the whole energy system including renewable energy sources and the interactions among them (de Castro, 2009; Nel and Cooper, 2009; Zerta et al., 2008). In this chapter, a new energy-economy-climate model, the *World Limits Model* (WoLiM), is presented and applied to analyze the feasibility of different energy transition and climate pathways. This model is, in fact, a continuation of previous System Dynamic models developed (see (de Castro, 2009; Mediavilla et al., 2013a, 2011) and the previous chapter 4). WoLiM is a structurally-simple and transparent model that integrates data from many different sources (socio-economic, geological and technological), designed to analyse global panoramas. The model includes in a dynamic framework: the exhaustion patterns of non-renewable resources and their replacement by alternative sources of energy, the estimations of the development and market penetration of alternative technologies, the energy demand of the global economy under different socio-economic scenarios, the sustainable potential of renewable energy sources, and the estimations of CO_2 emissions related to fossil fuel consumption.

After its description, the model is applied to analyse future energy transition and associated climate pathways. In order to deal with the complexities and deep uncertainties inherent to these societal developments, we apply the scenario methodology, which has become very popular in recent GEAs, such as the IPCC's Assessment reports (IPCC, 2007a, 2001a; IPCC SRES, 2000a), the UNEP's Global Environmental Outlook (UNEP, 2012, 2007, 2004) or the MEA (2005). In this approach, each storyline entails the representation of a plausible and relevant story about how the future might unfold. The chapter, therefore, quantifies and implements five

[59] This chapter has been published as: Capellán-Pérez, Iñigo, Margarita Mediavilla, Carlos de Castro, Óscar Carpintero, and Luis Javier Miguel. "Fossil Fuel Depletion and Socio-Economic Scenarios: An Integrated Approach." *Energy* 77 (December 2014): 641–66. doi:10.1016/j.energy.2014.09.063.

representative storylines identified in GEA studies (van Vuuren et al., 2012b) and use them as input policies of the WoLiM model. *By using this methodology, we replicate the usual visions of the future explored by these international agencies*, *allowing them to be confronted with the case of the energy development constraints which, to date, have not being taken into account* (Aleklett et al., 2010; Dale, 2012; Höök and Tang, 2013). For example, some international economic organizations such as the OECD (2012b) project that global GDP will grow at around 3% per year over the next half century, increasing almost 3-fold between the years 2010–2060. It is also projected that global GDP distribution among countries will be very different from now: e.g. China and India would account for almost 50% of global GDP by 2050, up from less than 13% today. However, all these projections lack a proper discussion about how scientific knowledge on constraints in resource availability, likely future scarcities and some other economic uncertainties may affect these forecasts.

The chapter is organized as follows: section 5.1 overviews the model and its main hypothesis and limitations. Section 5.2 describes the modelling of non renewable and renewable energy sources. Section 5.3 explains the estimation of energy demand and section 5.4 describes the calculation of CO_2 emissions. Scenarios and results are described in sections 5.5 and 5.6. Finally, conclusions are drawn in section 5.7.

5.1. Overview of the WoLiM model

As discussed in Chapter 4, few models in the literature explicitly recognize constraints to the extraction rate of non-renewable resources (e.g. peak oil) and relate them to economic growth (Dale et al., 2012b; de Castro, 2009; Mediavilla et al., 2013a; Nel and Cooper, 2009). The WoLiM model does recognize such limits and adopts the URR approach, which is an expert-estimate of the total amount of resource that will ever be recovered and produced (see Chapter 3 for details).

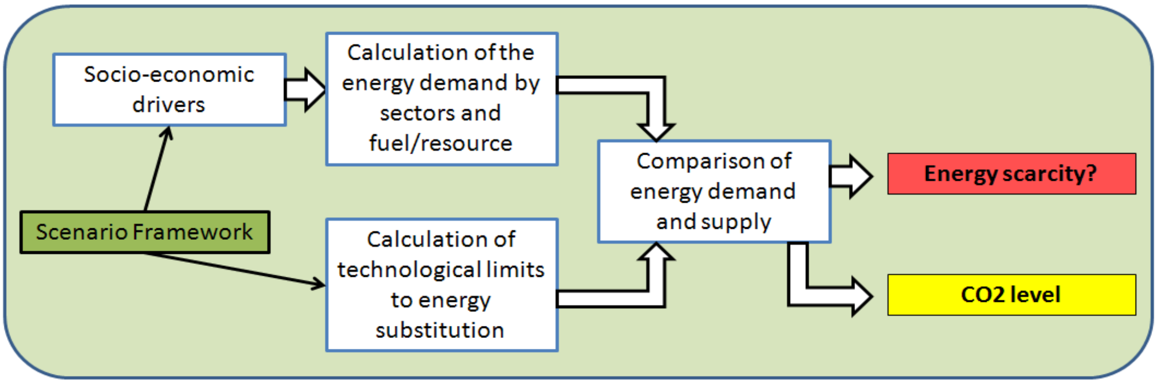
The WoLiM model,[60] which continues previous work by (de Castro, 2009; de Castro et al., 2009; Mediavilla et al., 2013a) (see also Chapter 4), includes the following trends in a dynamic framework:

- 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.

[60] For a full description of the WoLiM model see the Technical Report: (Capellán-Pérez et al., 2014b).

WoLiM is based on a sequential structure (see Figure 5.1) 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 (scenario methodology is described in section 5.5). Socio-economic assumptions drive global energy demand 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 emission and concentration levels are computed.

Figure 5.1: Basic logic functioning of the WoLiM model



Source: own work.

Although the model is based on SD, this version is not as feedback-rich as SD models tend to be, and key variables of the model are exogenous. We simplify the model ignoring the influence of energy scarcity in the economy, which makes WoLiM, basically, a dynamic model of energy demand and technology trends versus physical restrictions.[61] The reason for the simplification in this model version is double: first, the lack of consensus in the literature about the quantification of the impact of energy scarcity on future economic growth,[62] and second, that the integration of this feedback tends to drive the system into collapse (de Castro et al., 2009; Nel and Cooper, 2009). With regard to the relationship between the economy and the energy systems in this chapter we keep the dual specification described in Chapter 4.

[61] Another significant feedback, such as the impact of climate change on the economy (Smith et al., 2009; Stern, 2013), is not considered either, but there are some important loops included which make WoLiM a feedback model, such as the fossil fuel extraction and the renewable energy dynamics. See section 4.2.5 and Appendix D.4 for more detailed explanations.

[62] Although some authors analyze this relationship (e.g. (Hirsch, 2008)), there is no well-developed and widely accepted theory on this topic. Despite increasing criticism, most macroeconomic models still pay very little attention to energy resources (Ayres et al., 2013; Bithas and Kalimeris, 2013).

Note that the WoLiM model outputs will only be valid as far as it does 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, the point in time and the sector (or "scarcity points", as they are called in section 5.6) when and where the supply might not meet the demand

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

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

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

- Energy intensities of each economic sector: transportation, electricity, industry and buildings.
- Energy demands of each fuel (liquid fuels, gas, electricity, etc.) for each sector. In order to find out the share of each fuel, historical trends have been extrapolated (unless a specific policy is applied).
- Stocks and flows of non renewable resources (oil, gas, uranium, coal) whose depletion dynamics were described in the previous chapter in section 4.2.5.
- Stocks that describe the infrastructure of renewable energies (solar, wind, hydroelectric, etc.) whose growth is determined by the policies applied (see Appendix D.4 for a detailed description).
- Stocks that represent the introduction of the alternative policies (biofuels, EV, efficiency, etc.), described in Appendix D.5.
- CO_2 emissions and concentration levels related to fossil fuel use.

An overview of the model (Forrester diagram) can be seen in the Figures D.1 and D.2 in Appendix D.1.

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 5.2). A detailed description of these scenarios and policies is given in section 5.5.

Once a scenario is set, the estimation of the energy demand is calculated as the product of the exogenous GDP by energy intensity. Demand is organized into 3 aggregated sectors: Transportation, Electricity and IB (Industrial and Buildings, without electricity). Each sector's energy demand is generated through sectoral energy Intensities (details in section 5.3). These energy demands are divided into demands of different energy sources following past trends: electricity from different sources, liquid fuels, etc.

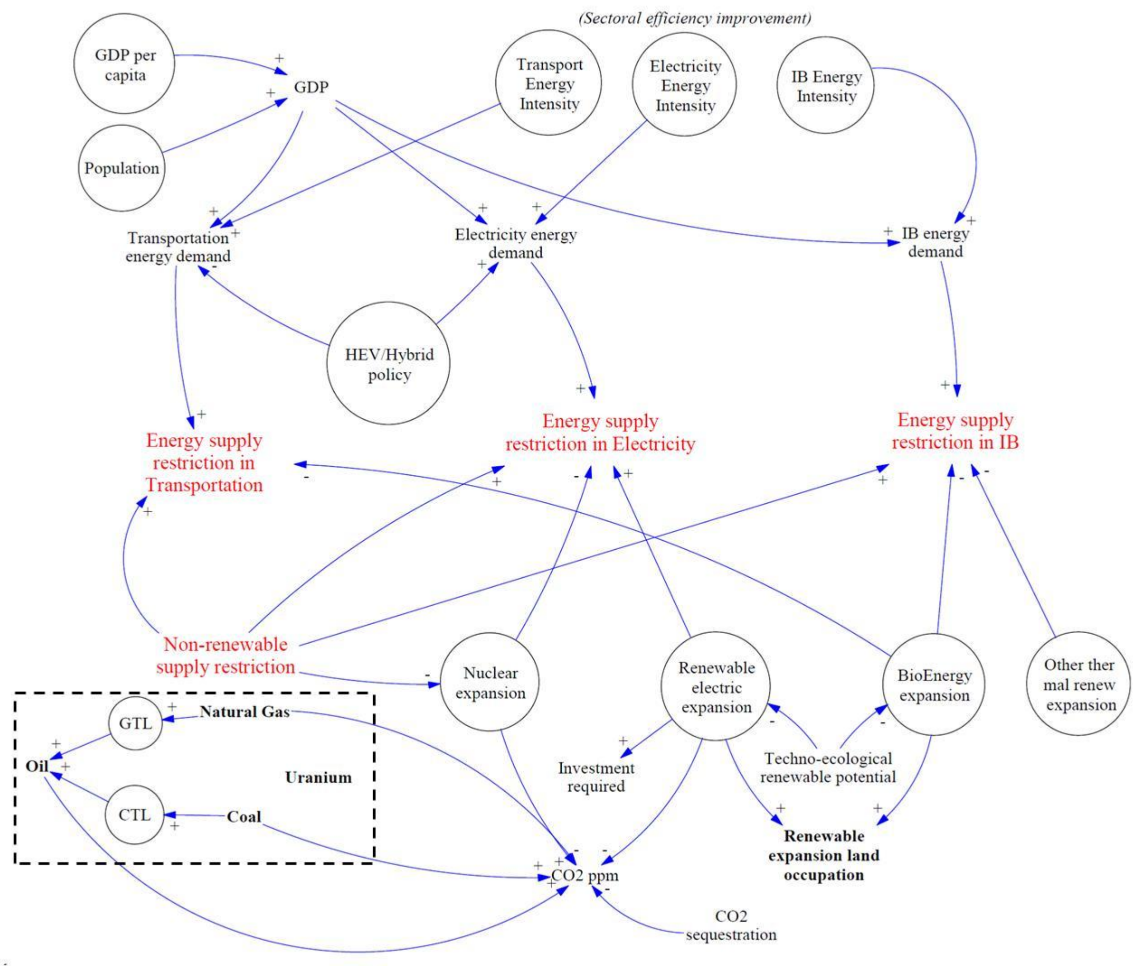
The non-renewable energy extraction (coal, oil, uranium, gas) is compared with demand, taking into account that it is restricted by their maximum extraction curves (see section 4.2.5). The model includes the estimations of expansion of several technologies (renewable electricity, bio energy, nuclear, coal-to-liquids (CTL), gas-to-liquids (GTL), etc.). Each scenario considers different policies for the expansion of each technology. Finally, CO_2 emission and concentration levels to 2050 and the end of the century are computed.

Priority is given to renewable energy (once the infrastructure is built, all the energy generated is used), and the rest of the demand is divided between the non-renewable energy sources, maintaining past ratios (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 (e.g. (WEO, 2012)), we consider this analysis valid in the medium term (~2050).

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

The following subsections describe the energy resources modelling (section 5.2.1 for non renewables and section 5.2.2 for renewables), the energy demand estimation through sectoral intensities (section 5.3) and the estimation of CO_2 emission and concentration (section 5.4). In the model, we discuss the assumed potential of energy resources until 2050; therefore, nuclear fusion is not considered since the ITER and DEMO projects estimate that the first commercial fusion power will not be available before 2040.

Figure 5.2: Causal loop diagram of the model with its basic elements



Notes: Scenario elements and policies are circled. IB is the acronym for Industrial and Buildings sector.

5.2. Energy resources modelling

5.2.1. Non-renewable energy resources

Non-renewable energy resources are modelled in WoLiM following the methodology applied in Chapter 4 by converting the depletion curves into maximum production curves as a function of remaining resources. The following resources are considered: conventional oil, unconventional oil, natural gas, coal and uranium. Here, we build upon the previous discussion, but updating the literature review and considering a wider range of cases in relation to the future availability of resources. For some resources, we provide a “Best Guess” and “High Case” estimation based on the literature range; “Best Guess” considered the most probable (i.e. central case); and “High Case” the one of highest resources (see Table Table 5.1).

For conventional oil, since the recent estimations of different authors tend to converge (de Castro, 2009; Maggio and Cacciola, 2012; Sorrell et al., 2009), and in order to reach stronger conclusions, the highest estimation for conventional oil found in the literature has been implemented: the high case (URR=3,000 Gb) from Maggio and Cacciola (2012).

Unconventional oil extraction, not considered in Chapter 4, is modelled here following the approach applied by de Castro et al., (2009) by extrapolating the 4.5% annual growth from past trends for the central scenario and 6.6% annual growth as high case, as estimated by (Grushevenko and Grushevenko, 2012; Söderbergh et al., 2007). An URR of 750 Gboe is considered for non conventional oil after a review of other studies (ASPO, 2009; de Castro, 2009; Guseo, 2011; Laherrère, 2006).

For natural gas, two depletion curves are considered in the scenarios: a best guess following Laherrère (2010a), which assumes a combined URR for conventional and unconventional resources of 13,000 tcf (13.6 ZJ), and a higher scenario assuming that unconventional gas could expand significantly more under certain favourable conditions (“best Guess” of Mohr (2012) with URR=19,100 tcf).

For coal, the updated “High case” curve Mohr (2012) is considered. For uranium, the projection by Zittel (2012) is applied, which includes new (more costly) ore-reserves categories, as estimated by the *Nuclear Energy Association*.[63]

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

A summary of the considered estimates can be found in Table 5.1 (see also Figures D.3-D.6 in the Appendix D).

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

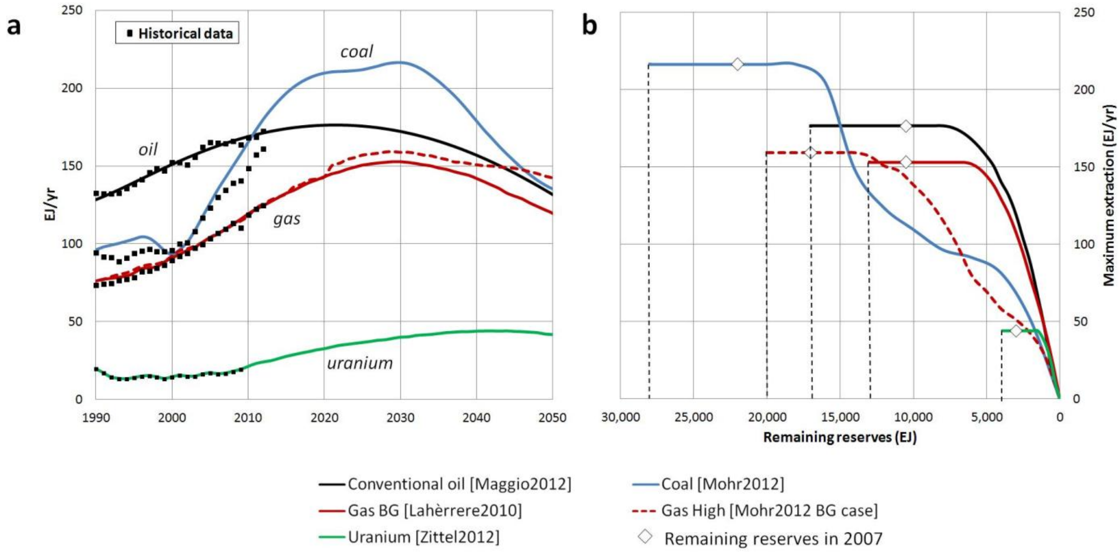
Table 5.1: Non-renewable energy resources used in the model

Resource		**Reference**	**Description**	**URR**	
Oil	Conv.	(Maggio and Cacciola, 2012) high scenario.	Hubbert method.	3,000 Gb	16.71 ZJ
	Unconv.	*Best Guess:* Own projection based on (de Castro et al., 2009)	Extrapolation of past trends deployment (+ 4.5 %/yr)	750 Gb	4.2 ZJ
		High case: (Grushevenko and Grushevenko, 2012)	High deployment rate (+ 6.6 %/yr)		
Natural gas		*Best Guess*: (Laherrère, 2010a) Best Guess	Hubbert method: "creaming curve".	13,000 tcf	13.6 ZJ
		High Case: Best Guess from (Mohr, 2012)	12,900 tcf of conventional + 7,200 tcf of unconventional.	19,100 tcf	19.9 ZJ
Coal		(Mohr, 2012)	High Case, static. Mining model extraction.	670 Gtoe	27.8 ZJ
Uranium		(Zittel, 2012)	Hubbert method, considering RAR (<260 \$/KgU) and IR of NEA.[a]	9,360 KtU	3.9 ZJ

Notes: RAR: reasonably assured resources; IR: Inferred resources; NEA: Nuclear Energy Association.

The maximum extraction curves as a function of time of the central scenarios are shown in Figure 5.3.

Figure 5.3: (a) Energy resource extraction curves as a function of time from the original references; (b) Curves of maximum extraction in function of the remaining reserves for all the non-renewable resources



Notes: The y axis represents the maximum achievable extraction rate (EJ per year) associated to the remaining reserves (EJ). For each resource, the extreme left point (that coincides with the maximum value of reserves) represents its URR. Thus, as extraction increases and the remaining reserves fall below the point where the maximum extraction can be achieved, the extraction is forced to decline following the estimations of the studies selected. They also show by a rhombus the 2007 level of remaining reserves for each resource. Primary Energy. See section 4.2.5 for wider explanations.

5.2.2. Renewable energy sources

Renewable energy sources are usually considered to be abundant; therefore, the technological limits are assumed to be unreachable for decades, and the concern is on the economic and political constraints (IPCC, 2011). In this section we discuss the techno-ecological potential of the main renewable energies, taking into account several constraints usually not considered that limit their practical availability based on the works from de Castro et al., (de Castro et al., 2014, 2013b, 2011).[64]

5.2.2.1. Bioenergy

Bioenergy provides approximately 10% of the global primary energy supply and is produced from a set of sources (dedicated crops, residues and Municipal Solid Waste (MSW), etc.) that can serve different uses (biofuels, heat, electricity, etc.). Its techno-

[64] For a detailed analysis of the modelling see (Capellán-Pérez et al., 2014b).

ecological potential estimation critically depends on future land availability since its land requirements are huge and the foreseeable needs of land for food and infrastructures for the growing population poses a limit on its expansion (de Castro et al., 2013a). The potential of bioenergy has been established in the model based on the land surface that could be dedicated to it. It varies between occupations similar to present value (maximum of 100 MHa) and a maximum of 200 MHa (for a complete description see Appendix D.6).

5.2.2.2. Electrical generation from renewable energy sources

The most promising electric renewable sources of energy are solar and wind (Smil, 2010). However, recent assessments applying a top-down methodology, which take into account present and foreseeable efficiencies and surface occupation, suggest that their potential is greatly limited by technical and sustainable limits[65] (de Castro et al., 2013b, 2011). The evaluation of the global technological wind power potential applying conservation of the energetic balance on Earth leads to a global potential of 30 EJ/yr (de Castro et al., 2011). The estimation of the real and future density power of solar infrastructures taking into account current efficiencies and surface occupation of technologies (4-10 times lower than most published studies) leads to a potential of approximately 60-120 EJ/yr (de Castro et al., 2013b). Following these considerations, the global techno-ecological potential of electric renewable energy is estimated at 150 EJ per year (5 TW_e/yr) (see Appendix D.7). Since the estimations considered in WoLiM are in the lower range of the literature, Appendix D.3 provides a summarized comparison and discussion with other estimates.

In terms of investment and costs, we compute the investment for building new plants and to replace or re-power the already existing ones following (Teske et al., 2011), grid reinforcement costs following (Mills et al., 2012), and balancing costs as modelled by (Holttinen et al., 2011)[66] (see Table D.2 in Appendix D.7). For a detailed description of the modelling of electrical generation from renewable resources see (Capellán-Pérez et al., 2014b).

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

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

5.2.2.3. Thermal renewable sources of energy

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. Consequently, we decided to focus in this chapter on the Transport and Electricity generation sectors, while maintaining a high level of aggregation in IB sectors. Thus, the thermal uses of renewable energies (e.g. solar, geothermal) are not explicit in the model, nor are they assigned to a concrete technology (except for the 3rd generation biomass residues). Energy transition policies include a switch to renewable, more efficient systems, as well as improvements in construction (e.g. in order to enhance isolation and access to natural light) or even changes at a higher level (e.g. district heating), in the same way as done in World3 (Meadows et al., 2004). These policies are modelled as target-policies of market penetration level for a given year (see Appendix D.5 for a description of the modelling).

5.3. Energy demand estimation

A diversity of techniques can be used for estimating the energy demand for an economy or sector. Since the model is highly aggregated, the Energy Intensity method, that has already been used in similar studies (Furtado and Suslick, 1993; Saddler et al., 2007) has been applied. This method is simple because it does not explicitly include the price mechanism and the economic structure. The reason for this simplification is that the time-frame of this analysis is of several decades and it has been argued that in the medium run GDP growth and technological improvements dominate over variations of fuel prices when determining the behavior of the demand of energy sources (de Castro, 2009; Furtado and Suslick, 1993; Saddler et al., 2007). In fact, it has been showed that prices and costs can falsely signal decreasing scarcity. For example, Reynolds (1999) demonstrate that, when considering the size of the resource base as unknown (or ignored), it is possible to have several years of increasing production simultaneous with lower prices and costs until a sudden, intense price rise occurs with a huge cut in production, similar to the oil shock in 2007-08 (Hamilton, 2009).

Considering the sectoral Energy Intensity as the energy used by a sector divided by the total GDP of the economy, the methodology to estimate the energy demand for each of the sectors involves three steps:

1- Assume future evolution of GDP (set exogenously depending on the scenario),
2- Estimation of the evolution of the energy intensity for each sector (econometrically calculated in this study),
3- Finally, multiplying the GDP by the energy intensity of each sector (I_i), the energy demand for that sector (E_i) is obtained dynamically, see *eq. 5.1* below:

$$E_i(t) = GDP(t) \cdot I \cdot (t) \qquad \textit{eq. 5.1}$$

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

A conventional way for characterizing the evolution of energy intensity over time is shown in *eq. 5.2* (Schenk and Moll, 2007), which can also be written as in *eq. 5.3*, where annual sectoral intensity ($I_i(t)$) decreases each year at a constant rate (a) in relation to the previous year ($I_i(t-1)$):

$$I_i(t) = I_i(t=0) \cdot (1-AEI)^t \qquad \textit{eq. 5.2}$$

$$I_i(t) = I_i(t=0) \cdot (1-AEI)^t = (1-AEI) \cdot I_i(t-1) = a \cdot I_i(t-1) \qquad \textit{eq. 5.3}$$

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 World Bank database (2015) is used for the historical series of world GDP at constant prices in US2011 T$ and Total Primary Energy (PE) demand, IEA ETP (2010) for Transportation PE use and the US EIA database (2015) for the electrical generation. The regressions were performed for the periods 1971-2010, 1971-2007 and 1980-2010, respectively. IB PE intensity was calculated internally in the model for the calibration period (1990-2010) due to the lack of reliable global data as the subtraction of Total energy minus Transport and Electrical sector (generation and losses).

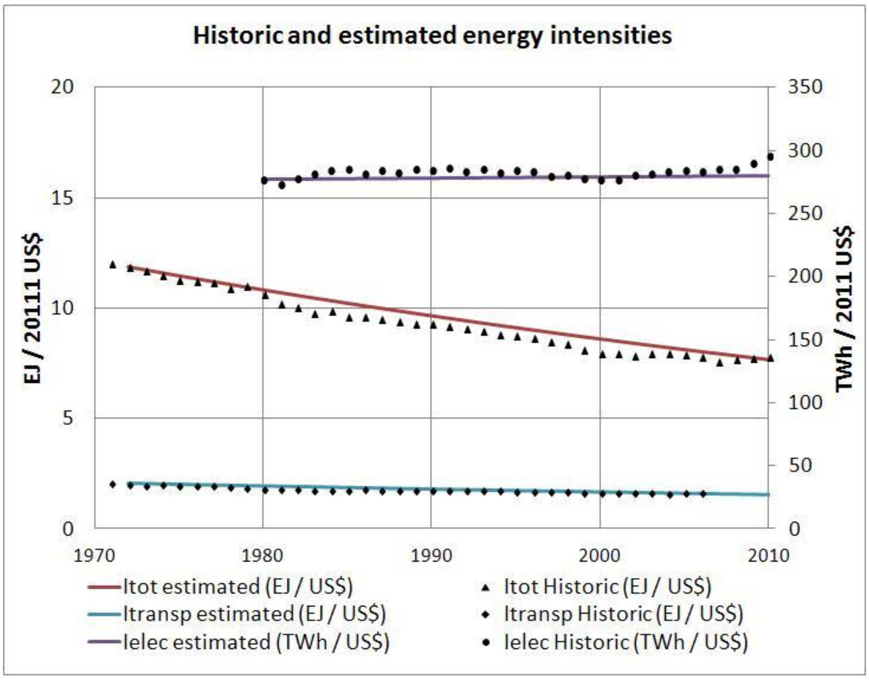
The results of the sectoral historic World energy intensity regressions are shown in Table **5.2** and Figure 5.4. They indicate that, in the last 40 years, the world TP energy intensity has improved at a yearly average rate of 1.15 %, but that, since 2000, its value has remained constant at around 8 EJ / 2011 US$. Transport and Buildings primary energy intensities have also improved in the last decades, although at smaller rates (0.7% and 0.5% respectively). Finally, the electricity generation intensity has remained stable at 275 TWh/2011 US$ since 1980.

Table 5.2: Results of the sectoral energy intensity estimations for Total, Transport, and Electricity generation and IB

Energy sector	Sectoral Energy Intensities	Units	Period of estimation
Total PE demand	(R^2=0.999)	EJ / US$	1971-2010 (regression)
Transport PE demand	(R^2=0.999)	EJ / US$	1971-2007 (regression)
Electricity generation	(R^2=0.999)	TWh/ US$	1980-2010 (regression)
IB PE demand		EJ / US$	1990-2010 (calibration)

Notes: All dollars in the chapter are in 2011 US$. PE: Primary Energy. Total, Transport, and Electricity generation intensities are obtained from the regression, while the IB is derived from the calibration of the sector in the model.

Figure 5.4: Historic and estimated energy intensities by sectors



Notes: Itot refers to Total Energy Primary intensity (EJ/US$), Itransp to Transportation intensity (EJ/US$), and Ielec to Electrical generation intensity (TWh/US$). All dollars in the paper are in 2011 US$.

In order to account for the biophysical and thermo-dynamical limits in the substitution of inputs in production in the medium and long-term (e.g. (Ayres, 2007; Ehrlich, 1989; Stern, 1997)), the following expression of the energy intensity (*eq. 5.4*) as proposed by (Schenk and Moll, 2007) is used for the scenarios:

$$I_{tot} = I_{min} + (I_{t=0} - I_{min}) \cdot a^t \qquad \text{eq. 5.4}$$

AEI represents the Annual Efficiency Improvements, thus, the parameter "a", or (1-AEI), accounts for technological change, and I_{min} is a horizontal asymptote that represents the minimum value of the energy intensity. Both values will vary depending on the scenario storyline and quantification (see section 5.5). The studies of (Baksi and Green, 2007; Lightfoot and Green, 2002) are used as a reference.[67] Sectoral primary energy demand is dynamically corrected to take into account the fact that renewable technologies are more efficient that fossil-fuel based ones in terms of primary energy.

5.4. CO_2 emissions and concentrations

The model computes the CO_2 emissions associated with the use of fossil fuels: coefficients from BP (BP, 2013) for conventional fuels and from (Brandt and Farrell, 2007; Howarth et al., 2011) for unconventionals. Biofuels are far from being neutral carbon emitters due to Indirect land use changes; in accordance with (European Commission, 2010; Fargione et al., 2008; Haberl et al., 2012; Searchinger et al., 2008) we assign a similar emission power than to conventional natural gas (see Table 5.3).

Table 5.3: CO_2 emissions for non-renewable resources used in the model

Resource		Reference	Value [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)
Biofuels		(see justification in text)	2.35 (as for conventional gas)

In order to assess climate change, the net[68] CO_2 emissions are converted to concentration levels which assume that, in the period studied, the ocean and ground

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

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

will continue to absorb 45% of total emissions as in the past (Canadell et al., 2007). Due to the high inertia and long-term scope of climate change, the emission projections are extended until 2100, as the IPCC usually does, with the aim of comparing concentration levels in at least the order of magnitude.

5.5. Scenarios and policies

As described in section 5.1, the WoLiM model needs assumptions about the world socio-economic evolution (such as economic and population growth or technological progress) as external inputs to run the simulations. In order to establish those policies in a coherent and sensible way, we have applied the scenario methodology. Testing SD models and obtaining results from them can be a cumbersome task when the models have many policies that can be varied at the same time. Scenario methodology offers an approach to deal with the limited knowledge, uncertainty and complexity of natural and social sciences and can be used to group the variations of policies into coherent and meaningful scenarios. Each scenario (or storyline) represents an archetypal and coherent vision of the future -which may be viewed positively by some people and negatively by others (IPCC SRES, 2000a; MEA, 2005).

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

5.5.1. Description of the scenarios

In this section, a summary of the most important characteristics of the different scenario families identified in GEA studies by van Vuuren et al., (2012b) is provided, describing first the qualitative features of each scenario[69], and then their quantification. A Business-as-Usual scenario is added as reference that assumes that historical dynamics will also guide the future.[70]

- ***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

[69] We have completed the descriptions from van Vuuren et al., (2012b) with the IPCC SRES (2000a) and the MEA (2005).

[70] In reality van Vuuren et al., (2012b) 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 join them for the sake of simplicity and minimize the number of representative scenarios.

development, poverty alleviation or the environment. The scenario typically assumes rapid technological developments and diffusion, as well as fast 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 (i.e. rising price). Eventually, everyone will benefit from globalization, and technological advances will solve ecological problems (e.g. 'Environmental Kuznets Curve').

- ***Scenario 2: Global Sustainable Development:*** Strong orientation towards environmental protection and reducing inequality, based on solutions found through global cooperation, lifestyle change and technology (more efficient technologies, dematerialization of the economy, service and information economy, etc.). Central elements are a high level of environmental and social consciousness combined with a coherent global approach to sustainable development. Within this scenario family, it is assumed that a high level of international governmental coordination is necessary and possible in order to deal with international problems like poverty alleviation, climate protection and nature conservation. It entails regulation of markets but on a global scale and based on the conviction that the Earth's limits are in sight and that therefore pro-active policies are necessary.
- ***Scenario 3: Regional competition/regional markets****:* Scenarios in this family assume that regions will focus more on their self-reliance, national sovereignty and regional identity, leading to diversity but also to tensions between regions and/or cultures. Countries are concerned with security and protection, emphasizing primarily regional markets (protectionism, deglobalization) and paying little attention to common goods. Due to the significant reduction in technological diffusion, technological improvements progress more slowly.
- ***Scenario 4: Regional Sustainable Development****:* this scenario is the "friendly" version of the previous one, where globalization tends to be voluntarily deconstructed and an important change in traditional values and social norms happens against senseless consumerism and disrespect for life. Citizens and countries must each take on the responsibilities they can bear, providing aid or setting a green example to the rest of the world, from a sense of duty, out of conviction or for ethical reasons or to solve primarily their own problems. In fact, although barriers for products are re-built, barriers for information tend to be eliminated. The focus is on finding regional solutions for environmental and social problems, usually combining drastic lifestyle changes with decentralization of governance.

5.5.2. Quantification of the scenarios

In order to implement these storylines in the model, we must set specific numbers to every assumption and policy. Global[71] scenario quantification is a delicate and inherently subjective task. We have followed other GEA assessments as a guideline; however, divergences in the interpretation and hypothesis considered sometimes emerge and are justified below.

- **Socioeconomic inputs**: exogenous GDP per capita and population evolution estimations were taken from MEA (2005), whose numbers are in fact very similar to the IPCC SRES (IPCC SRES, 2000a).
- **Energy available resources**: in the Scenario 1 storyline (enhanced technological advances in extraction together with an economic short-term benefit priority), we consider that unconventional oil and gas can be extracted at higher rates than for the rest of the scenarios ("High cases" considered in section 5.2). In those scenarios that prioritize the environment over economic growth, we consider that unconventional fuels are not extracted at higher levels than the "Best Guess" case (e.g. (Olmstead et al., 2013; Osborn et al., 2011)).
- **CTL and GTL:** While there is no shortage of liquids in the economy, there is a growth of these technologies following recent past trends: strong growth for GTL and slow for CTL. In the case a shortage in the supply of liquids occurs, a crash program following a logistic curve is launched with a strong growth (considering two scenarios: +15%/yr and +20%/yr, see Table 5.4). For the sake of simplicity, CTL deployment is not constrained, and the yearly growth is set to match current GTL growth.[72] If the crash program is active, but gas and/or coal resources are not able to balance their respective demand, the crash program is stopped under the assumption than in a situation of scarcity, the most efficient uses of fuels will be prioritized.
- **Sectoral efficiency improvements**: Each sectoral efficiency (Transportation, IB and Electrical generation) is governed by its energy intensity (*eq. 5.4*) considering the values for the parameters as shown in Table 5.4 for each scenario. The energy intensity of each sector (and the total energy intensity) can thus be computed when accounting for all the policies (see Figure 5.6 and Table 5.4). Electricity generation intensity is maintained constant along the period, assuming that the current electrification trends will continue in all scenarios (the New Policies Scenario from (WEO, 2011) still projected 1.0 billion people without electricity by 2030). In Scenarios 3 and 4, where deglobalization occurs, a 1.5% yearly decrease in the transport energy efficiency is assumed (i.e., doubling current trends), accounting for an absolute reduction in transport needs but also due to the promotion of public transport in

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

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

Scenario 4.[73] Notice that the evolution of all the energy intensities in our model can be considered optimistic, since in recent years, the yearly sectoral energy intensities averages have decreased at smaller rates than historical values. The total energy intensity has been actually constant since the year 2000, and electricity generation intensity has even increased (Figure 5.4).

- **Nuclear:** Considering the study of the nuclear status in the world by Schneider et al., (2012), the conservation of the already existing capacity at global level in the coming years would already be an optimistic assumption; we thus assign this case to BAU and Scenario 3. For Scenarios 1 and 2, where nuclear may be promoted, we take as reference the World Nuclear Association forecast of 1-2%/year growth for the coming decades (Dittmar, 2013). Finally, for scenario 4, where the environment is actively protected, we program a progressive phase-out as nuclear power stations reach the end of their lifetime.
- **Electric/Hybrid (EV&HEV) transport:** the evolution of hybrid and electric vehicles in our model follow the estimations of EVI IEA (2013). EVI is "a multi-government policy forum dedicated to accelerating the introduction and adoption of electric vehicles worldwide" that seeks to "facilitate the global deployment of at least 20 million passenger car EVs by 2020" (EVI IEA, 2013). We will consider this forecast as an optimistic development and we assign it to scenarios 2 and 3, while for BAU and Scenario 3 we will keep half of the projection. For Scenario 4, we interpret the "lifestyle change" as a higher shift to the alternative transportation modes. After 2020, the growth rate is assumed to increase two-fold for all scenarios, assuming that a shift to alternative mobility systems will, in any case, be promoted, due to the scarcity of conventional liquid fuels in all scenarios (following the results obtained in the previous Chapter 4).
- **Natural Gas Vehicles**: Despite the strong growth in the past decade (+20% per year), the total number of 16.7 million NGVs still pales in comparison to a total worldwide number of around 1,150 million motor vehicles in 2009 (World Bank database, 2015) – i.e.1.45% of the total. Thus, due to the insensitivity of the model to different NGV growth rates (because of reaching the gas peak) the same rate of annual growth consistent with past trends is considered in all scenarios, for the sake of simplicity.
- **Bioenergy:** As stated in section 5.2.2, a very large surface dedicated to bioenergy at a global level is not compatible with future scenarios such as the ones explored in this chapter (see chapter 6 for the implications for land-use dedicated to biomass as a result of the implementation of fragmented climate policies.). As a reference, since the year 2000, the area from Southern countries that has been bought or long-term rented by transnationals and investment funds has been estimated at more than 80 MHa (Anseeuw et al., 2012). Two possibilities of bioenergy expansion are considered. For scenarios 3 and 4 (regionalization), land grabbing is not going to increase significantly from

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

present levels in the future (maximum 100 MHa), since currently, there is a worldwide rush for land (around 1.7% of agricultural area has been reported to have been bought or rented for long periods of time since the year 2000, (Anseeuw et al., 2012)). For scenarios 1 and 2, a "South occupation" that would be deployed in a maximum of 200 MHa is assumed (more details in Appendix D.6 and (Capellán-Pérez et al., 2014b)).

- **Renewable and efficiency improvements in the Industrial and Building sectors**: different levels of penetration by renewable technologies to 2050 are considered. More potential is assigned to Buildings than to Industry (e.g. (European Commission, 2007)).
- **Carbon-climate policies:** Storylines from scenarios BAU and 3 exclude the adoption of carbon valuation. The scenario 1 storyline suggests that measures could be taken, but probably *too late*. Thus, effective carbon valuation only seems probable in scenarios 2 and 4 with proactive environmental protection. Although carbon valuation would intensify the transition to a low carbon economy, we consider that many of the changes it would induce are in fact already implicit in the interpretation of both storylines. Additionally, we consider that a world afforestation program is set from 2020 as proposed by Nilsson and Schopfhauser (1995), who analyzed the changes in the carbon cycle that could be achieved with a large-scale global afforestation program covering 350 MHa. Thus, a maximum carbon capture of 1.5 GtC/year, 50 years after the start of the program, would be attained. Other technologies such as CCS are not considered in this study due to their uncertain future availability and eventual benefits in an energy scarce future (Fischedick et al., 2008; Scott et al., 2013).

Table 5.4 provides a detailed summary of the policies implemented for each scenario.[74]

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

Table 5.4: Hypothesis and policies considered in each scenario

	SCENARIO - INPUT	0 – BAU	Scenario 1 Economic optimism with some market reforming	Scenario 2 Global Sustainable Development	Scenario 3 Regional competition	Scenario 4 Regional sustainable development
Socioeconomic (% 2010-2050)	GDPcap	Hist + 1.9% (1960-12)	+ 3%	+ 2.4%	+ 1.1%	+ 1.9%
	Population	UN Medium-Variant +0.75%	+0.5%	+0.65%	+0.81%	+ 0.8%
Sectoral efficiency improvements	a_{Transp}	Past trends (-0.67%)	Rapid (-0.9 %)	Rapid (-0.9 %)	Deglobalization (-1.5%)	Deglobalization (-1.5%)
	a_{elec}	Past trends (0%)				
	a_{BI}	Past trends (-0.5%)	Past trends (-0.5%)	Past trends (-0.5%)	Past trends (-0.5%)	Past trends (-0.5%)
	I_{min}[a]	25 %	25 %	15 %	25 %	15 %
Resource availability	Non-renewables	Best Guess	Best guess (coal, conv. oil) High case (gas, unconv. oil)	Best Guess	Best Guess	Best Guess
	CTL, GTL	Crash program (+15 %)	Crash program (+20 %)	Crash program (+20 %)	Crash program (+15 %)	Crash program (+15 %)
Electric renewables	Solar PV&CSP	Medium (+15%)	Past trends (+19%)	Very rapid (+25%)	Medium (+15 %)	Very rapid (+25%)
	Wind	Medium (+20%)	Past trends (+26%)	Very rapid (+30%)	Medium (+15%)	Very rapid (+30%)
	Hydroelectric, Geothermal, Bioenergy&Waste	Past trends (slow)	Past trends (slow)	Very rapid (x3 past trends)	Past trends (slow)	Very rapid (x3 past trends)
	Oceanic	Rapid (+20% from 2020)	Rapid (+20% from 2020)	Very rapid (+30% from 2020)	Rapid (+20% from 2020)	Very rapid (+30% from 2020)
Nuclear		Constant	+ 3 % from 2015	+ 1.5% from 2015	Constant	Progressive shutdown
BioEnergy	2nd generation	Slow (+8%, 100 MHa available)	Rapid (+ 20%, 200 MHa available)	Rapid (+ 20%, 200 MHa available)	Slow (+8%, 100 MHa available)	Medium (+15%, 100 MHa)
	3rd generation	Slow (+8% from 2025)	Rapid (+ 20% from 2025)	Rapid (+ 20% from 2025)	Slow (+8% from 2035)	Medium (+15% from 2035)
	Residues	Slow (+8% from 2025)	Rapid (+20% from 2025)	Rapid (+20% from 2025)	Slow (+8% from 2035)	Medium (+15% from 2035)
Thermal renewables & efficiencies	Industrial sector (market share 2050)	Low (12.1%)	Medium (23.1%)	Rapid (37.6%)	Low (12.1%)	Rapid (37.6%)
	Buildings sector (market share 2050)	Low (4.7 %)	Medium (22.6%)	Rapid (48%)	Low (4.5%)	Rapid (48%)
Alternative transport[b]	EV&HEV (market share 2050)	Medium (9%)	Rapid (18%)	Very rapid (36%)	Medium (9%)	Very rapid (50%)
	NGVs	Past trends (+20 % annual)				
Afforestation program		-	-	350 MHa	-	350 MHa

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

5.6. Results and Discussion

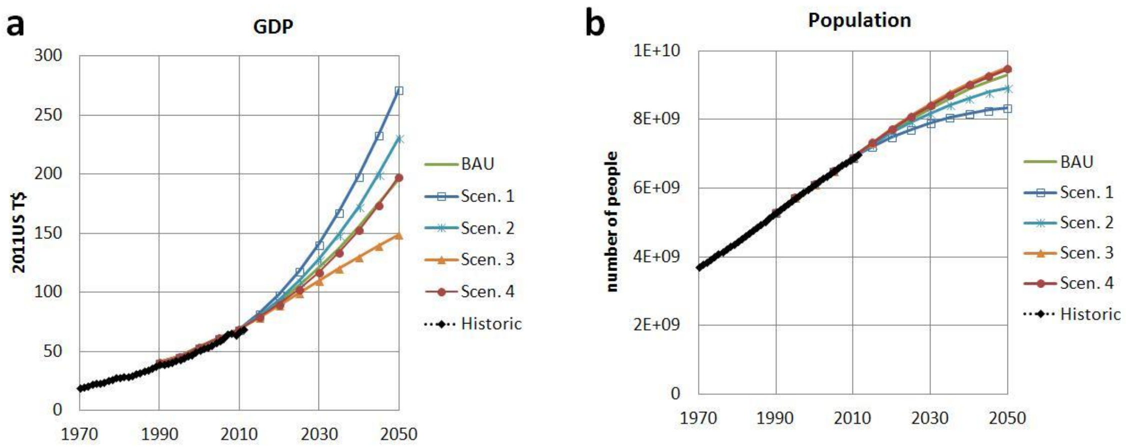
In this section the results of the WoLiM model to 2050 under the scenarios described in section 5.5 are presented. It should be recall that some important issues have not been integrated in the modelling, and that most of these issues have the potential to worsen the results obtained

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

5.6.1. Socioeconomic inputs and sectoral efficiencies

Socioeconomic inputs considered for each scenario are presented in Figure 5.5. Population increase is similar in all scenarios due to its high inertia and estimates vary between 8.3 (Scenario 1) and 9.5 billion people by 2050 (Scenarios 3 and 4). Scenarios are more diverse in terms of GDP: in 2050, Scenario 1 almost doubles the GDP estimated in Scenario 3 (which doubles the 2010 value). Also, the variety of policies and different sectoral efficiency considered unfold in very different (always decreasing) sectoral energy intensity paths (Figure 5.6).

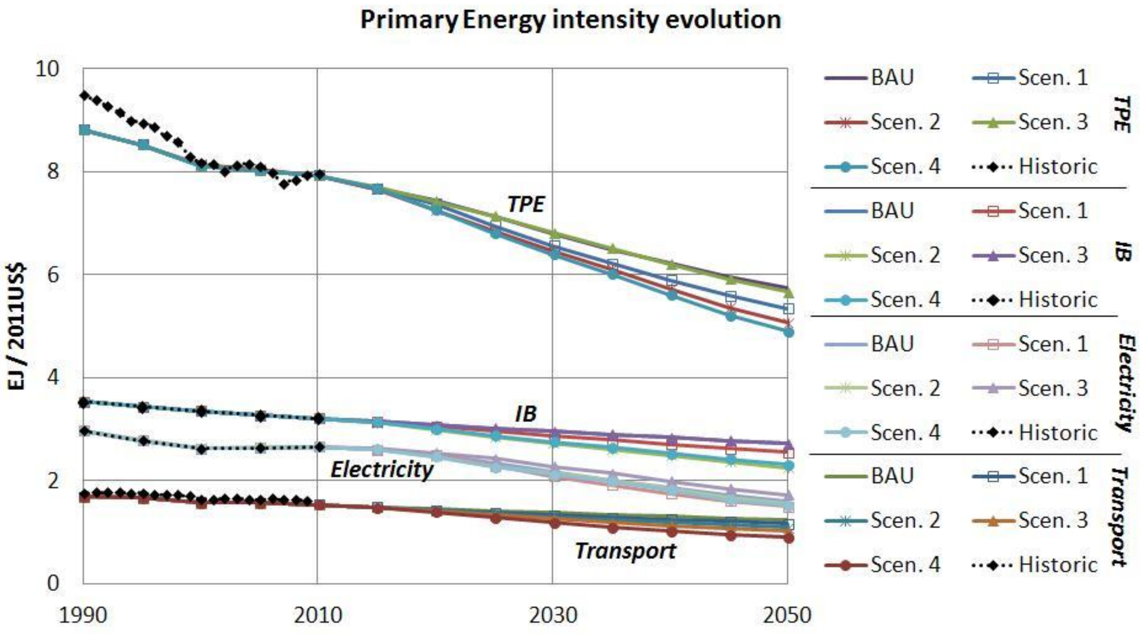
Figure 5.5: Socioeconomic exogenous inputs for each scenario



Notes: Since in this model version no feedbacks are applied, impacts of energy supply scarcity and climate change are not computed in the projections and these variables are thus not modified. GDP in 2011 US$.

Source: Historic data from the World Bank database (2015).

Figure 5.6: Total and by sector Primary Energy intensity evolution for each scenario



Notes: Primary energy intensities in EJ / 2011 US$. Total Primary Energy Supply, IB: Industrial and Buildings sectors. The IB and Electricity PE intensity past evolution are adjusted as explained in Section 5.3. PE stands for primary energy.

Source: Historic data from (IEA ETP, 2010; World Bank database, 2015).

In Table 5.5, the total energy intensity yearly average decrease obtained for each scenario is represented and compared with the declines assumed by IPCC SRES (2000a). Our results are in the range 0.8% - 1.25% and coincide with (Baksi and Green, 2007; Lightfoot and Green, 2002; Pielke et al., 2008), that find greater efficiency improvements as proposed by A1 and B1 scenarios (IPCC SRES, 2000a) implausible due to the biophysical limits in process substitution.

Table 5.5: Total averaged (2010-2050) energy intensity evolution

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

Notes: averaged yearly reduction rates for the period 2010-2050 for the scenarios simulated as a result of the interpretation and quantification of scenarios, and comparison with (IPCC SRES, 2000a) results.

5.6.2. Results by sector and fuel

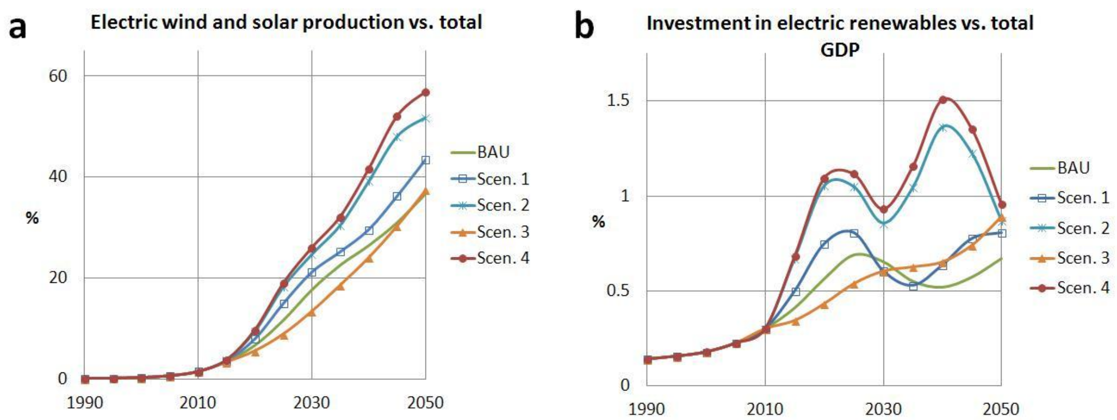
5.6.2.1. Electricity generation

The comparison of the energy generation and demand from different sources can be seen in Figure 5.7. In the scenarios where the renewable technologies are promoted at a very rapid pace (2 and 4), electricity supply is roughly able to fulfill the demand, but in scenarios BAU and 1, renewable electricity cannot sustain the increasing demand by 2030. In Scenario 3, even the smallest growth of the demand cannot be compensated because of the modest growth of renewable technologies.

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

However, the massive expansion of renewable technologies has repercussions. Figure 5.7a shows the proportion of variable electric generation technologies (wind and solar) in function of the total production. In Scenarios 2 and 4, this proportion exceeds 50% of the total generation by 2050, which would imply an important challenge for the integration of intermittent production (Trainer, 2012). In terms of investment (Figure 5.7b), electric renewable deployment investment would remain below 1.5% of the total world GDP of all scenarios and is in the same magnitude order as other studies (e.g. *Bloomberg New Energy Finance*[75] and (Teske et al., 2011)).

Figure 5.7: Renewable energy sources: (a) proportion of variable electric generation vs. total and (b) proportion of the investment in electric renewable related to total GDP

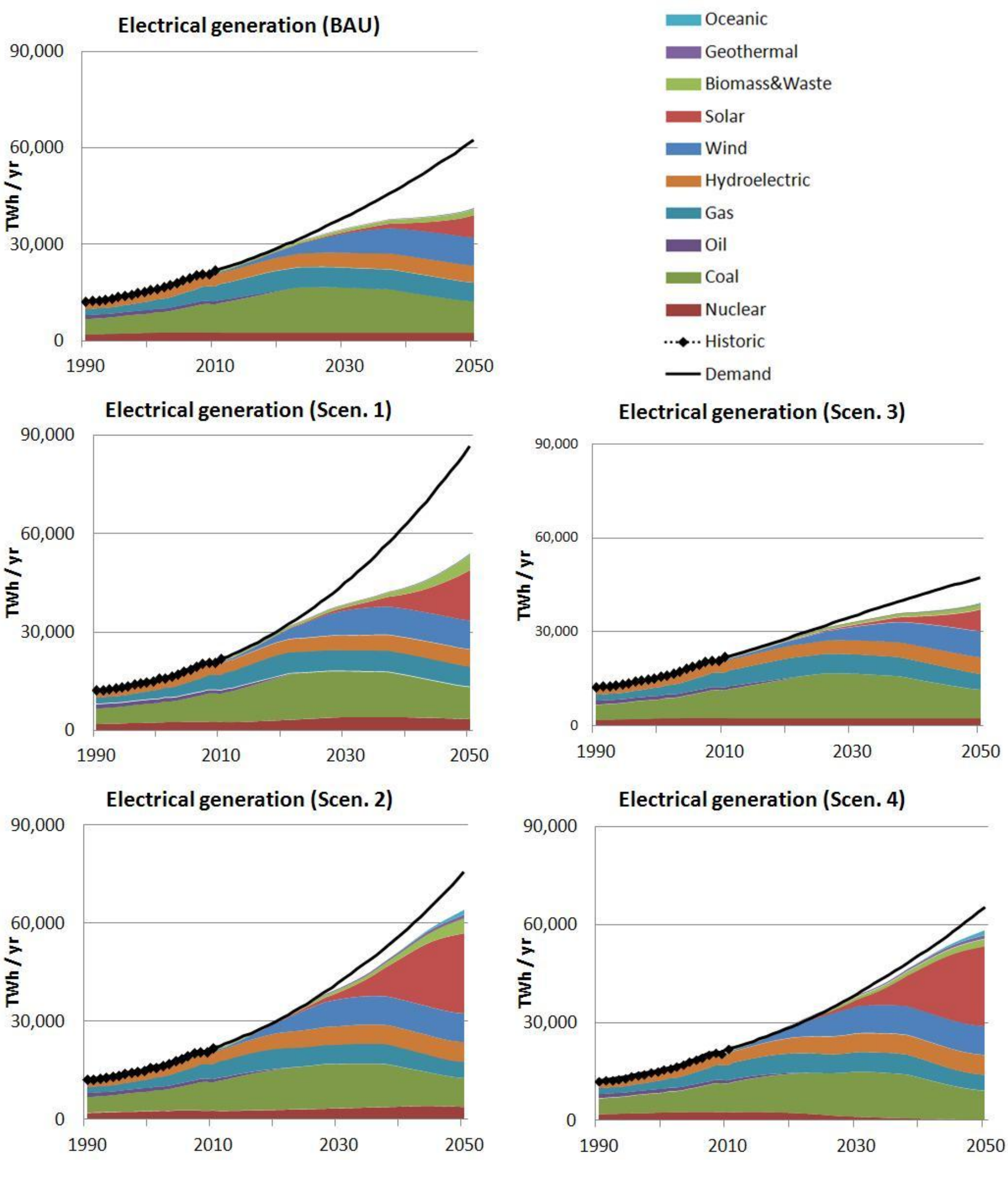


Notes: wind and solar are the variable renewable energy sources.

Source: own work.

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

Figure 5.8: Electricity generation and demand (TWh/yr) by fuel source for each scenario



Notes: Historic electric consumption data increased by transportation losses (9% average) are taken from (US EIA db, 2015).

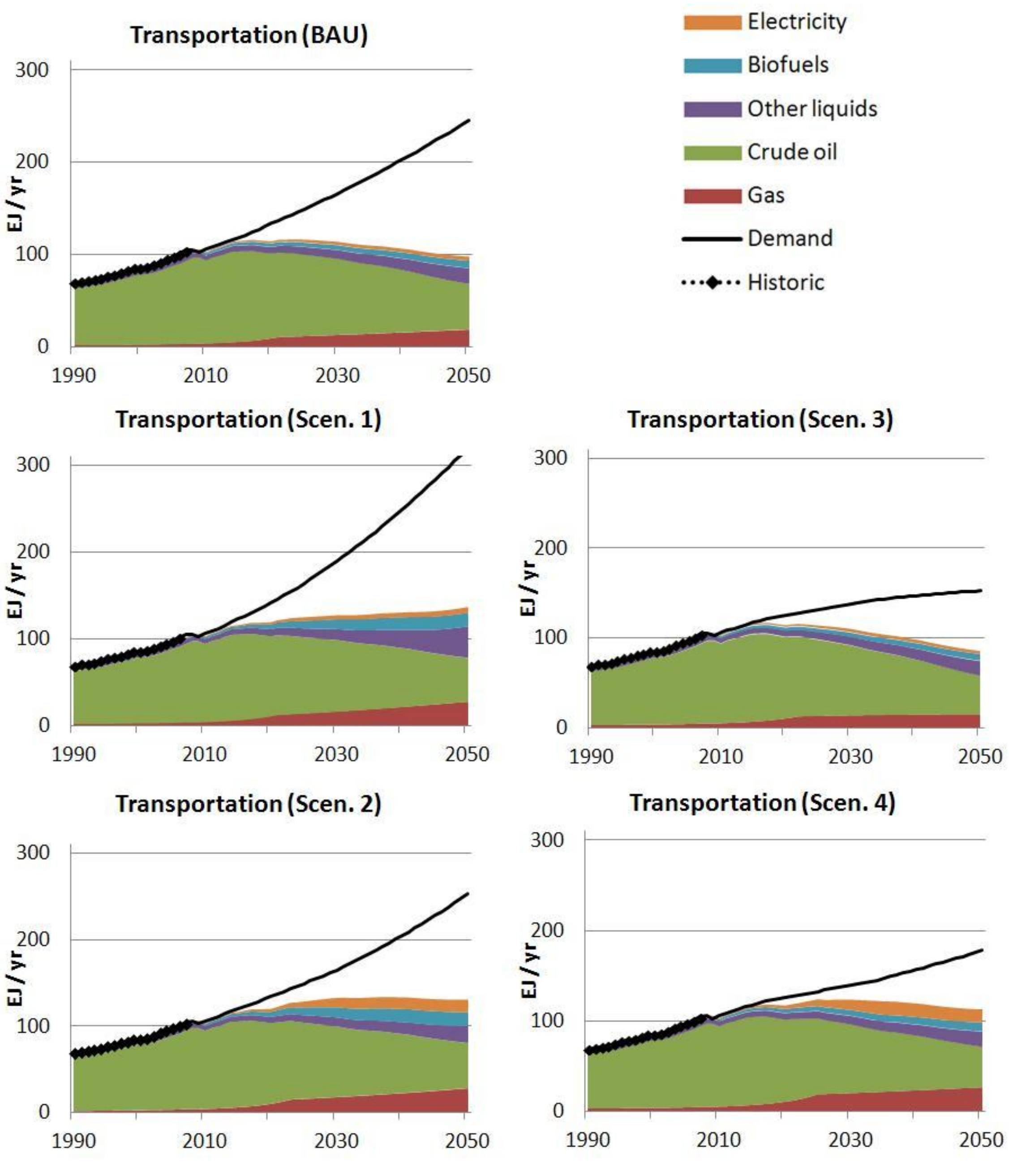
5.6.2.2. Transportation

The comparison of the demand and the supply of energy for transportation can be seen in Figure 5.9. In spite of the diversity of policies applied in the different scenarios, the peak of conventional oil in the early 2010s determines a decline or stabilization of the energy available for transportation. The demand-side policies substantially affect the projected demand, e.g. over 300 EJ/yr by 2050 for the scenario 1, which doubles the demand estimated for that year in the scenario 3. Biofuels, alternative electric and hybrid transport, CTL&GTL (that does not develop significantly in any scenario due to the ending of the crash programs when gas and coal reach their peaks), efficiency improvements, and even the higher development of unconventional oil in Scenario 1, cannot reach a substitution rate able to compensate the conventional oil decline. Thus, these results are consistent with the findings presented in the previous Chapter 4 (see also (Mediavilla et al., 2013b)), and *energy shortages appear in the Transportation sector for all scenarios before 2020* (Figure 5.11).

5.6.2.3. Total Primary Energy Supply

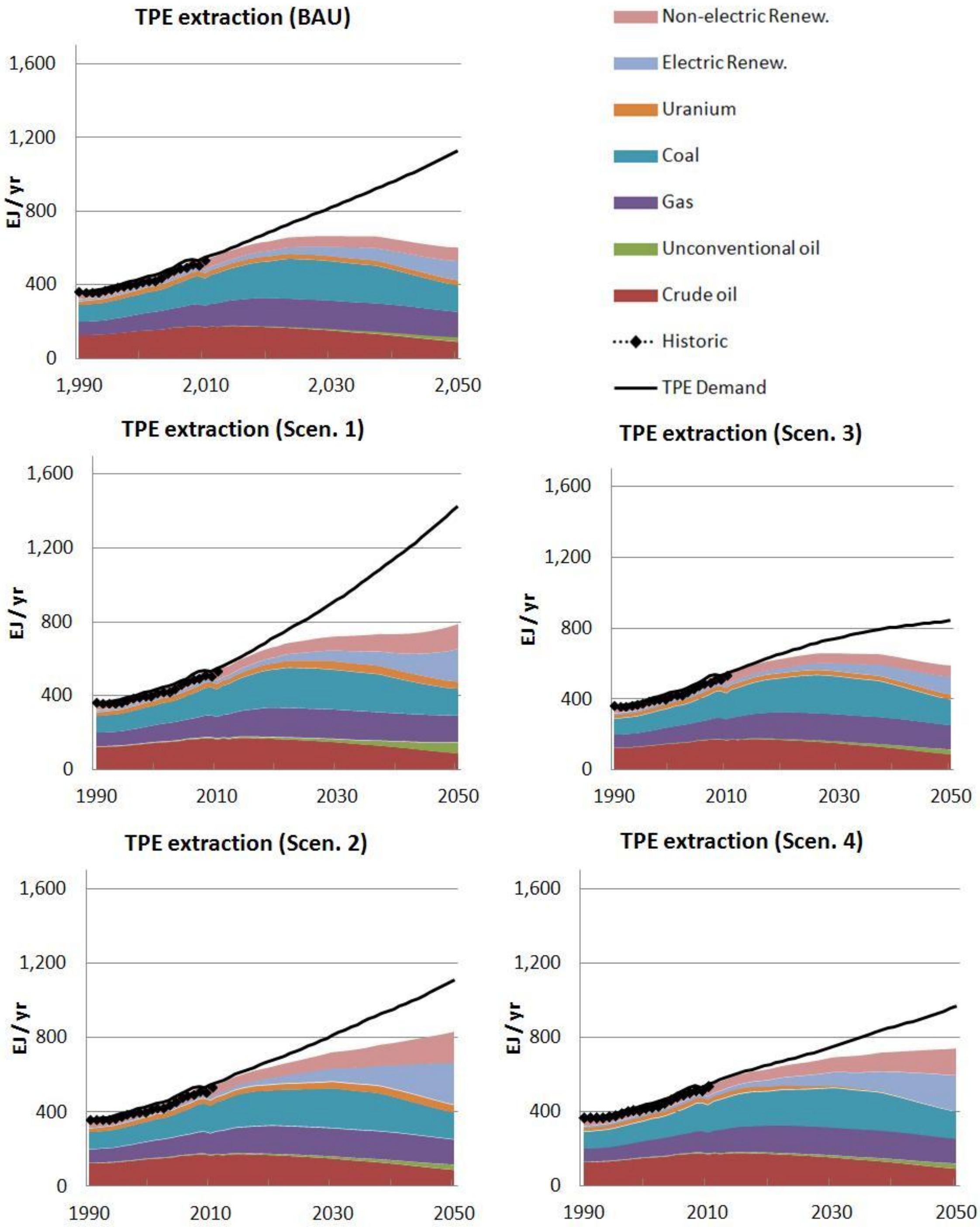
The comparison of the Total Primary Energy demand demand and supply (TPES) can be seen in Figure 5.10. Broadly speaking, TPES remains below 800 EJ/yr in 2050 (around +50% in relation to the 2010 level). Moreover, the past growth trends (+ 2.6%/yr for the period 1965-2012 (BP, 2013)) cannot be maintained and the yearly energy available by 2050 is either decreasing (-0.7 %/yr in scenarios BAU and 3), roughly stabilized (slower growth than 0.5%/yr in Scenarios 1 and 4) or growing slightly (at around 1%/yr in Scenario 2). This occurs because the decrease in fossil fuel extraction can only be partially compensated by renewable energies, alternative policies and efficiency improvements. In fact, between 2020 and 2030, differences between supply and demand appear to be significant in all scenarios (Figure 5.11).

Figure 5.9: Transportation Primary Energy demand and supply by source fuel (EJ/yr) for each scenario



Notes: Historic consumption data is taken from IEA ETP (2010). Other liquids include unconventional oil, CTL, GTL and refinery gains. Note: Primary Energy demand is dynamically corrected to take into account the fact that renewable technologies are more efficient than fossil-fuel based ones.

Figure 5.10: Total Primary Energy extraction and demand by source fuel (EJ/yr) for each scenario.



Notes: Primary Energy demand is dynamically corrected to take into account the fact that renewable technologies are more efficient that fossil-fuel based ones.

5.6.2.4. Comprehensive analysis of scenarios: the Energy Scarcity Matrix

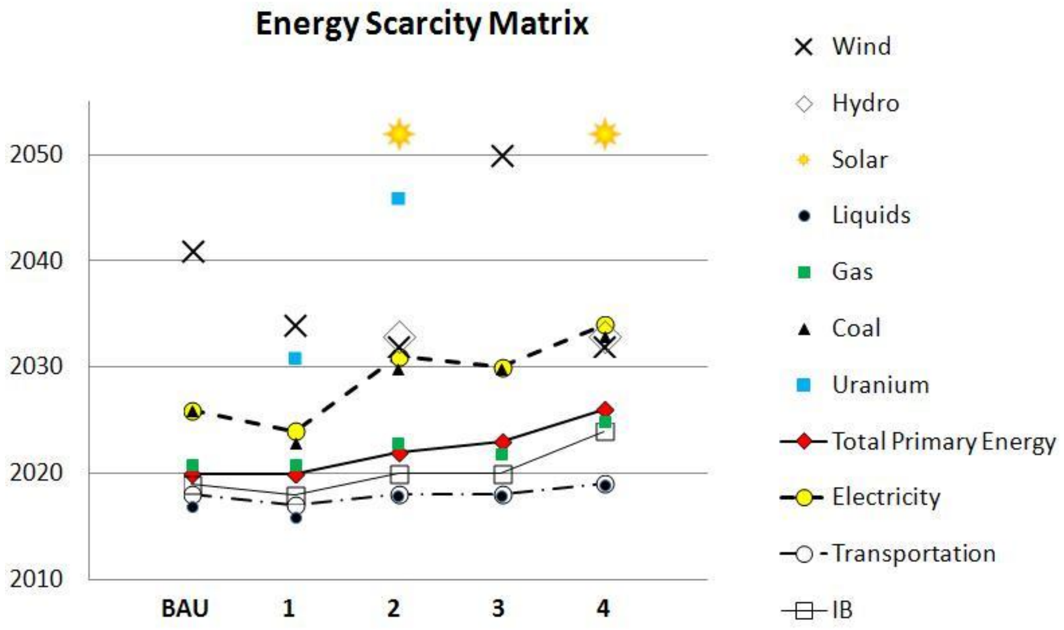
In order to analyze the supply constraints on the demand of each sector and energy resources for all scenarios, we build the "Energy Scarcity Matrix" in Figure 5.11 (see also Table 5.6). In this matrix, for each economic sector and non-renewable resource, each point represents the date when the relative difference between the demand and supply is greater than 5%. We select 5% as a qualitative ad hoc threshold when we estimate that the price-mechanism adaptation could force important socio-economic structural changes that would modify the underlying hypothesis of the scenarios and the model. For renewable resources, each point represents the date when 95% of the considered potential is reached. The Energy Scarcity Matrix allows to identify a trend, since a similar sequence of facts appears for all scenarios:

1- Liquid scarcity in 2015-20 precipitates energy scarcity in the Transportation sector immediately afterwards, and in the IB sector a few years later.
2- Total Primary Energy and gas scarcity roughly coincide in 2020-25.
3- By 2035, coal supply is not able to cover its demand in any scenario. Restrictions in the coal supply could appear sooner than usually expected.
4- Electricity generation for all scenarios is not able to fulfill the demand in 2025-2035.
5- Uranium resources are able to provide the mineral needed to maintain the current yearly production to 2050; however, when even a modest increase in capacity is considered, uranium extraction limits appear.
6- A large expansion of electric renewable energies move us close to their potential limit (e.g. solar), which may even be reached before 2050 (wind and hydroelectric).

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

Finally, in Figure 5.12a, the evolution of the extraction of fossil fuels for all scenarios is represented. In spite of the diversity of policies and assumptions applied (notably for renewable energies development, see Figure 5.12b), a "decline path" for the future extraction of fossil resources emerges, reaching a "plateau" at around 500-525 EJ of TPES between 2020 and 2035, depending on the scenario. This plateau is followed by a reduction between 1 and 1.5% per year.

Figure 5.11: Energy Scarcity Matrix of the scenarios



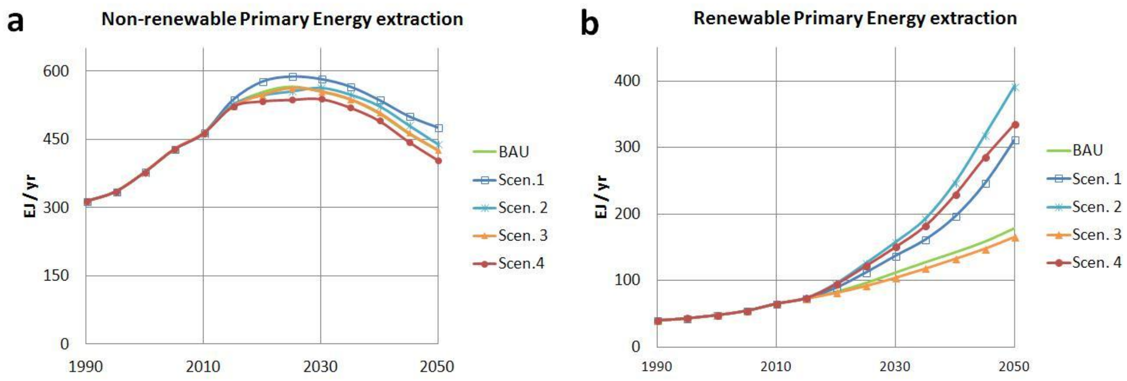
Notes: For each scenario, sector and non-renewable energy resource, we mark the "scarcity point" when the relative difference between supply and demand is greater than 5%. For renewable energies, each point represents the date when 95% of the potential is reached in each scenario. Strong similarities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

Table 5.6: Supply-demand divergence (7%) and potential reached (95%) range in the five modelled scenarios for all fuels and sectors

Fuel / Sector	**Supply-demand divergence (5%)**
Liquids	2015-2018
Gas	2022-2032
Coal	2024-2034
Uranium	2031-…
TPE	2020-2027
Electricity	2025-2036
Transportation	2015-2018
IB	2017-2025
	Potential reached (95%)
Wind	2032-2050
Solar	2052-…
Hydroelectric	2033-…

Notes: Data derived from the Energy Scarcity Matrix from Figure 5.11.

Figure 5.12: Primary energy resources extracted by scenario: (a) Fossil fuel and (b) Renewable energy sources



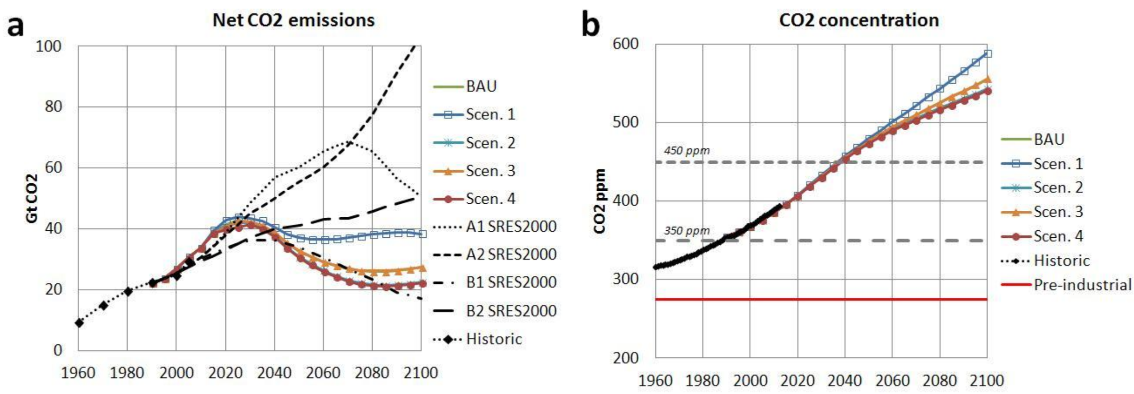
5.6.3. Global warming

The results of CO_2 for all scenarios show a peak of emissions in 2020-2030 at 40-45 $GtCO_2$, which is a value 35-50% higher than 2005 emissions (Figure 5.13a). Scenarios BAU, 2, 3 and 4 project a decline along the century in a path very similar to B1 from IPCC SRES (2000a). Scenario 1, however, maintains higher emission levels, similar to the A2 SRES scenario due to the higher extraction of unconventional fuels.

Likewise, all scenarios project similar CO_2 concentration values in the first half of the century (Figure 5.13b), reaching around 475 ppm by 2050. By the end of the century, all scenarios surpass the 550 ppm level, and Scenario 1 almost reaches 600 ppm. These levels are well over the safe boundaries of 350-450 ppm (Hansen et al., 2011, 2008; IPCC, 2014c; Rockström et al., 2009).[76] In fact, if high concentration levels are maintained during a certain time, anthropogenic climate change could be boosted by (irreversible) slow feedback dynamics (e.g. ice-sheet desintegration). Thus, in all of our scenarios, despite the fact that CO_2 emissions fall because of the peak of fossil fuels, these concentrations during the 21st Century are highly alarming and dangerous. Moreover, we consider our results to be optimistic, since the absorption capacity of natural sinks is likely to decrease as the planet warms (Canadell et al., 2007; Le Page et al., 2013).

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

Figure 5.13: Net CO_2 emissions and concentrations 1960-2100



Notes: (a) Net CO_2 emissions ($GtCO_2$) for each scenario and comparison with the SRES scenarios A1, A2, B1 and B2; (b) Evolution of net CO2 concentration (ppm) for each scenario during 21st Century compared to past historical observations at Mauna Loa and pre-industrial value. Horizontal lines represent the pre-industrial CO_2 concentration value (in red) and two different representative thresholds in the literature: 350 ppm and 450 ppm (in grey).

Some other analysis that have studied the links between the structural limits to fossil fuel supply and Climate Change and have found that the emissions levels tend to align with low and medium scenarios from IPCC scenarios (Brecha, 2008; Höök and Tang, 2013; Nel and Cooper, 2009; Ward et al., 2012, 2011). Our results coincide with them; however, even these relatively “low” emission profiles imply that climate change could reach dangerous dimensions.

5.6.4. Summary and discussion on the results

Considering the assumptions in the modelling and if the depletion curve estimates of non-renewable energy resources in the literature are accurate, our results confirm the short-term lock-in of energy developments and suggest that, *the world socioeconomic system will not be able to follow any of the scenarios proposed to 2050*. Specifically:

- **Electricity generation** seems to be the least worrisome sector, especially in scenarios where electrical renewable generation is strongly promoted. In such cases, saturation in their expansion potential by 2050 is appreciable for some technologies (e.g. hydro and wind).
- **Transportation:** all the scenarios presented are unfeasible before 2020. Biofuels, alternative electric and hybrid transport, CTL&GTL, efficiency improvements and even the higher development of unconventional oil cannot reach a substitution rate able to compensate the conventional oil decline (even taking the highest estimations for oil resources). In scenarios where deglobalization is simulated, the supply-demand gap is strongly reduced due to a decrease in energy requirements. We identify this feature as a “clue” to developing sustainable scenarios.

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

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

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

On the other hand, other assumptions such as the non-modelling of technology-fuel competition (through cost and efficiency as typically done in demand-driven models), might seem as in significant weakness of the model. However, since in all scenarios the peak of all fossil fuels occurs in the range of 15-20 years, the introduction of the competition would only tend to slightly delay the first “scarcity points” while hastening the last ones. In brief, for each scenario, the points in Figure 5.11 would tend to converge in time, thus, not affecting the main conclusions of the work. However, from a societal point of view, the transition might be less challenging if the “scarcity points” are more spread in time.

The developed model, in the version presented in this chapter, is affected by the following limitations:

- Non-inclusion of EROEI: The model operates in terms of primary energy, but in reality the useful energy used by society (Net Energy) in the future may decrease at the same time as the EROEI of the non-renewable resources diminishes, due to the smaller EROEI of unconventional resources (Murphy and Hall, 2010b). Some modern renewable energies also perform low EROEI ratios (e.g. solar (Prieto and Hall, 2013)).
- Non-inclusion of material limits and other non energetic renewable sources (e.g. water availability (Postel, 2000), minerals (e.g. phosphorus (Cordell et al., 2009), copper (Harmsen et al., 2013)).
- Absence of dynamic feedback between the main subsystems. In this model version, climate impacts and energy scarcity are not fed back to the economic system. Similar studies have shown that models are biased optimistically when feedback is omitted (e.g. (Barney, 1980; Randers, 2000)). The MEA (2005)

report concluded that approximately 60% (15 out of 24) of the ecosystem services examined are currently being degraded or used unsustainably. Also, Rockström et al., (2009) identifies 3 out of 10 planetary boundaries that have already been overstepped.

- Others: intermittency of renewable energies, non-consideration of phenomenons such as the “energy trap” (see footnote 66), the rebound effect, conflicts (within and between countries, e.g. corruption, wars), unexpected events (e.g. natural disasters), etc.

The integration of these factors would introduce further constraints to the energy transition. In this sense, the current model is conservative and its results can be seen as optimistic. Thus, *the exclusion of important issues in the model could only exacerbate these trends.* Thus, the obtained results suggest that the current socioeconomic paradigm may not be sustainable and continuous economic growth may be rather more the problem than the solution. However, GDP was not designed to measure social welfare (e.g. (van den Bergh, 2009)); and research with welfare indicators show not only that, above a certain level, there is no link between higher GDP per capita and subjective wellbeing, but reductions in GDP per capita may be welfare enhancing (Kubiszewski et al., 2013). In a socioeconomic system unable of to absolute decoupling from energy use, the abandonment of the pursuit of continued exponential GDP growth emerges as a potential policy towards sustainability. Thus, alternative socio-economic paradigm scenarios can be modelled in order to explore sustainable future paths such as those proposed by Degrowth (Kallis et al., 2012), Steady-State (Daly, 1996; Kerschner, 2010) or the New Economics of Prosperity (Jackson, 2009).

We add two considerations in relation to the modelling assumptions:

- Of the fossil fuels, coal is the most abundant. However, it is also the least studied from a depletion point of view. Thus, in order to reduce the uncertainty in future global studies, we make a call to motivate further research on this topic.
- All GEA scenarios consider increasing GDP growth. However, our results suggest that the objective of *continued exponential GDP growth* in a system incapable of effective energy-material decoupling should be promptly replaced, instead, by the objective of improving *economic welfare*.

5.7. Conclusions

In this paper we introduce and apply a novel SD model, WoLiM, which aims to fill a gap found among Energy-Economy-Environment models, since few of them integrate the estimations of fossil fuel depletion and alternative energy expectations with the energy demand generated by the socio-economic system. The model is applied to a set of scenarios that replicate the habitual scenarios in GEA studies.

The results show that a significant systemic-energy scarcity risk exists: future global energy demand-driven transitions as performed in the past might be unfeasible. These critical energy constraints have the potential to provoke unexpected abrupt changes in societies and the world configuration, making all five implemented families of scenarios from the GEA studies impossible to achieve by 2050. Transportation is the most critical sector due to the stagnation of liquids fuel production and the inefficacy of all compensation policies before 2020 (as found in Chapter 4). The Electricity sector seems the least worrisome, especially in scenarios where electrical renewable generation is strongly promoted. However, CO_2 levels still have the potential to lead to a climate change of dangerous dimensions by the mid-century. Moreover, the use of unconventional fuels in a context of rising demand-supply divergence will tend to induce energy prices to grow in a context of high volatility, with very likely adverse economic impacts (Murphy and Hall, 2011; Tverberg, 2012).

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

As seen in the previous chapter 3, most of the current energy-economy-environment models tend to use (very) large resource estimates that are subject to high uncertainties and are strongly biased towards overestimation. The analysis performed in the chapters 4 and 5 including geological constraints to non-renewable fuels extraction confirms the need to integrate the analysis of resource availability and climate change to obtain consistent societal sustainable pathways.

PART II.B: Carbon leakage under fragmented policies

CHAPTER VI

6. Industrial and terrestrial carbon leakage under climate policy fragmentation[77]

Previous chapters have been focused to baseline scenarios (Chapter 3) and global-aggregated policy scenarios (Chapter 4 and 5). However, due to the heterogeneous nature of the societies along the world it is very unlikely that policies are set at global level. Thus, this chapter is dedicated to the analysis of the unintended effects of policy fragmentation in climate change control.

The objective of stabilizing climate "at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 1992) has been translated into the long-held target of keeping global average temperature rise to below 2 degrees Celsius (°C) above the pre-industrial level. According to the Intergovernmental Panel on Climate Change (IPCC, 2014a), this target will require global GHG emissions to be severely reduced by 2050 and be close to zero by the second half the century.

Global climate change constitutes one of the greatest collective action problems where a multi-national response is required. To address the risks of climate change effectively, efforts that engage most countries (at least the "major emitters") will need to be undertaken. The Kyoto Protocol (UN, 1997), effective from 2005 to 2012, was the first attempt by the international community to curb GHG emissions through a legally binding international agreement. However, it failed to achieve a decisive breakthrough in international climate policy (Prins et al., 2010; Schiermeier, 2012). One of the lessons from the Kyoto Protocol is that a fragmented climate regime, with different countries joining the coalition with different objectives and timings, may be a more realistic scenario which may pave the way for a global regime in the long run. Consequently, the UNFCCC process has shifted from a top-down legally binding climate policy architecture towards a bottom-up approach in which countries decide individually on emission reduction targets (the so-called INDC, Intended Nationally

[77] This chapter is based on a working paper (González-Eguino et al., 2016) and the deliverable 5.4 – "Global effects of EU climate policy under fragmentation" of the FP7 European Project CECILIA2050.

Determined Contributions). The Paris Agreement, which contains INDC to 2030 from, sets out a global action plan to put the world on track to avoid dangerous climate change. The agreement recognises the need to peak global GHG emissions as soon as possible and to achieve a balance between anthropogenic emissions by sources and removals by sinks of GHG in the second half of this century. Although the INDCs represent a step forward to limit global warming, they are not sufficient and to address the shortfall.

The European Union (EU) was one of the first regions to reach an internal decision on an INDC target. On 23 October 2014 it agreed on a domestic GHG reduction target of at least 40% compared to 1990 levels and a target of at least 27% for renewable energy and energy savings by 2030 (EC, 2014). A few weeks later, on 11 November 2014, China and the USA jointly announced their respective post-2020 actions on climate change. According to the Joint-Agreement (WH, 2014), the US intends to achieve an economy-wide target of reducing its emissions by 26%-28% below its 2005 level in 2025 and China intends CO_2 emissions to peak around 2030 and to increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030. Therefore, climate action is expected to remain fragmented for a long time with a variety of regional/national climate policy agendas being pursued in different parts of the world.

One of the main concerns about bottom-up or fragmented climate regimes is carbon leakage. A fragmented climate regime is characterized by different climate policies across regions and sectors and this may lead to relocation of production to regions with less stringent mitigation rules, leading to higher emissions in those regions and, therefore, to carbon leakage. Until very recently the carbon leakage literature has focused mainly on “industrial” carbon leakage (ICL). There are three main channels that may lead to ICL[78]: (1) the fossil fuel price channel, where reductions in global fossil fuel energy prices due to a fall in their energy demand in climate-constrained regions trigger higher fossil fuel demand and CO_2 emissions in non-participating regions; (2) the competitiveness channel, where carbon-constrained industrial products lose international market shares to the benefit of unconstrained competitors; and (3) the technology-dissemination channel, where carbon-saving technological innovations induced by climate policy in climate-constrained regions spill over to regions with less stringent climate policy. IAMs have focused primarily on the fossil fuel channel (Otto et al., 2015), whereas Computable General Equilibrium models (Hourcade et al., 2006) are a better tool to incorporate the other two mechanisms. In this chapter we apply an IAM and therefore we focus exclusively on the fuel price channel when measuring ICL.

But there is another type of carbon leakage that has received little attention so far: the carbon leakage triggered by land use changes, which we refer to as “terrestrial” carbon

[78] (Calvin, 2009) and (Kriegler et al., 2015) offer a thorough discussion and quantification of the different channels by which carbon price differentials lead to changes in carbon emissions outside the regions taking domestic mitigation action and (Antimiani et al., 2013) assess alternative solutions to this type of carbon leakage.

leakage (TCL). TCL can arise, for instance, when a regional carbon tax is applied not only to industrial but also to carbon emissions from land use and land use change and, as a consequence, market forces drive these regions to re-locate the production of food and/or bioenergy to regions with less stringent terrestrial carbon mitigation rules. Wise et al. (Marshall Wise et al., 2009), Calvin et al. (2009; 2014), Kuik (Kuik, 2014) and Otto et al. (Otto et al., 2015) are examples of an emerging subset of this literature focusing on the TCL associated with carbon mitigation policies. However, to the best of our knowledge, no previous study has carried out an analysis where the magnitudes of the two forms of leakage (ICL and TCL) are included. This might be related to the fact that few models can incorporate both dimensions in the same framework (see the Supplementary Materials in Otto et al., (Otto et al., 2015)). This article uses the GCAM model to fill that gap, model also applied in the Chapter 3.

The type of mitigation strategy in this study is the so-called Universal Carbon Tax (UCT) regime in which CO_2 emissions in all sectors, including land use change, are taxed equally. This is in contrast with most of the literature, which considers the Fossil Fuel and Industry Carbon Tax (FFICT) regime, in which the carbon tax is applied only to fossil fuel and industrial emissions. Wise et al. (Marshall Wise et al., 2009) show that if correcting measures are not implemented an FFICT regime leads to a large, most probably unsustainable change in land-use due to a huge increase in bio-energy[79] production. A UCT regime would constitute an “idealized implementation” scenario. Moreover, as noted by (IPCC, 2014a, chap. 6), the mitigation scenarios used in this study consider more realistic bottom-up implementations, the two most prominent of which are “fragmented action” (mitigation is not undertaken in those countries “where” it is less expensive) and “delayed participation” (mitigation is not undertaken in the time period “when” it is less expensive). Our scenarios include both of these deviations because developing and developed countries will start reducing emissions at different stages and the two groups will have different carbon prices.

The chapter is organized as follows. Section 6.1 provides a brief overview of the GCAM model with a focus on those aspects that are of particular interest for the study. Section 6.2 present the different scenarios of fragmented climate regimes considered in the chapter. Section 6.3 discusses the key findings of the study in terms of environmental effectiveness (sub-section 6.3.1), effects on energy systems (sub-section 6.3.2), effects on land use (sub-section 6.3.3), effects on the climate system and implications for the mitigation costs (sub-section 6.3.4). Finally, section 6.4 draws conclusions.

[79] In fact, bioenergy in combination with carbon capture and storage (BECCS) plays a crucial role in temperature stabilization scenarios (<2ºC) due to its capacity to contribute to negative emissions (L Clarke et al., 2009; Edenhofer et al., 2010).

6.1. Methods

6.1.1. Overview of the GCAM model

In this chapter the GCAM version 4.0 model is applied, an IAM that links the world's energy, agriculture and land use systems with a climate model (see Appendix A for a full description of the model). GCAM is a dynamic recursive economic partial equilibrium model driven by assumptions about population size and labour productivity that determines gross domestic production (GDP) in 32 geopolitical regions (see Table E.1 in the Appendix E) operating in 5-year time steps from 1990 to 2100. The model can be run with any combination of climate and non-climate policies in relation to a reference scenario and pre-set carbon price and mitigation costs. This model tracks emissions and atmospheric concentrations of GHGs, carbonaceous aerosols, sulphur dioxide, and reactive gases and provides estimates of the associated climate impacts. An important feature of the model architecture is that the terrestrial carbon cycle model is embedded within the agriculture-land-use system model. Thus, all land uses and land covers, including non-commercial land, are fully integrated into the economic modelling. This coverage makes GCAM capable of modelling policies that jointly cover carbon in all activities in energy, agriculture, forestry, and other land uses.

1.1.2. The energy and land use systems

GCAM contains detailed representations of technology options for each of its economic components with technology choice determined by market probabilistic competition (Clarke and Edmonds, 1993). The model produces outputs that include energy and agricultural prices and land use allocation. The model can track not only fossil fuel and industrial emissions but also emissions[80] associated with land use change (LUC).

The GCAM energy system includes primary energy resource production, energy transformation to final fuels, and the use of final energy forms to deliver energy services such as passenger kilometres in transport or space conditioning for buildings. GCAM distinguishes between two different types of resources: depletable and renewable. Depletable resources include fossil fuels and uranium; renewable resources include wind, geothermal energy, municipal and industrial waste (for waste-to-energy), and rooftop areas for solar photovoltaic equipment. All resources are characterized by cumulative supply curves, i.e. upward-sloping supply-cost curves that represent the idea that the marginal monetary cost of resource utilization increases with deployment. CCS technology is available for application to large, point-source emission facilities. These include electric power generation, hydrogen production, cement manufacturing and large industrial facilities. Complete documentation on all the technologies in the energy system is provided in (L Clarke et al., 2009).

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[80] GCAM covers all GHGs, but in this analysis we just report change in CO2 emissions (also from land-use change).

The agriculture and land use component[81] is fully integrated into (i.e. solved simultaneously with) the GCAM economic and energy system components. Data for the agriculture and land use parts of the model comprise 283 sub-regions in terms of land use, based on a division of the extant agro-ecological zones (AEZs). Land is allocated between the various uses based on expected profitability, which in turn depends on the productivity of the land-based product (e.g. mass of harvestable product per ha), product price, and non-land costs of production (labor, fertilizer, etc.). The productivity of land-based products is subject to change over time based on future estimates of crop productivity change. This increase in productivity is exogenously[82] set, adopted from projections from the FAO (Bruinsma, 2003). GCAM includes several different commercial and non-commercial land uses including ten crop categories[83], six animal categories[84], three bioenergy categories (see below), forests, pasture, grassland, shrubs, desert, tundra, and urban land. All agricultural crops, other land products, and animal products are globally traded within GCAM.

Bioenergy in GCAM is classified into three categories: traditional bioenergy, bioenergy from waste products, and purpose-grown bioenergy. Traditional bioenergy comprises straw, dung, fuel wood, and other energy forms that are utilized in an unrefined state in the traditional sector of an economy. Traditional bioenergy use, although significant in developing regions, is a relatively small component of global energy and, as regional incomes increase over the century, it becomes less economically competitive. Bioenergy from waste products is a by-product of another activity. The amount of potential waste that is converted to bioenergy is based on the price of bioenergy. However, the bioenergy price does not affect production of the crop from which the waste is derived. Purpose-grown third-generation bioenergy refers to crops whose primary purpose is the provision of energy. The amount produced in this category depends on profitability with respect to other land-use options. The productivity of those crops is based on region-specific climate and soil characteristics and varies by a factor of around three across the GCAM regions. GCAM considers also the possibility of using bioenergy in the production of electric power and in combination with CCS technologies.

6.2. Scenarios

In this section we present the scenarios of different fragmentation regimes. As mentioned in the introduction of the chapter, the UNFCCC process has shifted from a top-down legally binding climate policy architecture to a bottom-up approach in which

[81] A full description of the agriculture and land use module in GCAM can be found in Kyle et al. (Kyle et al., 2011) and Wise and Calvin (Wise and Calvin, 2011).

[82] GCAM assumes exogenous crop productivity improvements along the century, although the implications of different climate change scenarios have been explored recently (Kyle et al., 2014).

[83] The ten crop categories are corn, rice, wheat, other grains, sugar, root tuber, palm fruit, fiber crops, oil crops and other crops.

[84] The six animal product categories are: beef, dairy, pork, poultry, sheep, goat and others.

all Parties have been invited to decide their INDCs for the achievement of the climate stabilization objective. In this context, the EU has most clearly expressed its ambition by aiming for an emission reduction of 80% by 2050 and undertaking to respect that target even if no international agreement is reached.[85] China's long term commitment is less clear, but it has announced a commitment to "achieve the peaking of CO_2 emissions around 2030". Consequently, we consider as a plausible outcome one in which the regions from the developed world taking part in the international climate regime follow the EU's commitments (to reduce emissions by 80% in 2050) and the regions from the developing world taking part in the international climate regime follow China's commitments (emissions peaking in 2030).

With respect to long-term climate policy we assume that, despite its fragmentation, the international climate regime will be guided by the principles provided by the "common but differentiated convergence" (CDC) approach. This is interpreted by Höhne et al., (2006) to mean that per capita emissions will have to converge to an equal per-capita emissions level by 2100.[86] For a detailed representation of the implications of emission reduction in emission per capita in each scenario see Figure E.1 in the Appendix E.

Table 2.1 presents the scenarios that we use for our analysis. In the reference scenario (REF) we look at the possible evolution of GHG emissions in the absence of climate policies. The other six scenarios (scenarios FR1-FR6) consider different possibilities of engagement of regions in the international climate regime. In choosing the groups of regions that take part in these scenarios of fragmented climate action we assume that all or part of the regions in the developed world may consider engaging in climate action even if developing regions do not engage, that some regions in the developing world will engage in climate action only if developed regions also engage in climate action and that some regions, for reasons which may include poverty or high dependency of their economies on fossil fuel resources, will never engage in climate action.

As *Table 2.1* shows, if only developed regions take part in the international climate regime, the share of global carbon emissions covered by each of the fragmented scenarios in 2050 ranges from 7% (FR1) to 28% (FR3). If developing regions take part, the share ranges from 54% (FR4) to 88% (FR6).

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[85] The US announced on 12 November 2014 that would reduce its annual emission of GHGs by 26-28 percent below its 2005 level in 2025. This is not as clear as the EU's announcement but it seems to be consistent with the pledge made by the US Government in 2010 to reduce annual emissions by 83 percent by 2050 compared with 2005.

[86] The convergence level is set at 0.5 tons of CO2 per capita, the maximum per-capita emission level that would be required in GCAM to meet the 2°C stabilization target if every region in the world cooperates under a uniform climate regime. Notice, in contrast to some IAMs (see (IPCC, 2014a)), that GCAM model does not envisage negative emissions during the second half of the century for this stabilization target. The main reason is a greater estimated potential for carbon sinks as CCS is available relatively "early" (2020-2030) and there are not constraints to afforestation GCAM is not the only model that do envisage negative emissions for a 2 °C or RCP2.6 target (see (IPCC, 2014b, fig. 3.2)).

All the scenarios apply a UCT regime in the participating regions. This means that both industrial and terrestrial emissions are subject to the same tax. Also it is important to mention that along the convergence process in per capita emissions to 2100 there will be two regimes operating regarding the timing and the emission reduction objectives, one for developed countries and another for developing countries.

Table 6.1: Scenarios considered in the Chapter

Scenarios	Participating Regions	Share of global total CO2 emissions regulated by 2050
REF	None	0.0%
FR1	EU-27	7.1%
FR2	EU-27 + US	19.4%
FR3	Developed	28.4%
FR4	Developed + China	53.8%
FR5	Developed + BASIC	70.5%
FR6	All countries, except Africa + Russia + Middle East	88.0%

Notes: The BASIC (Brazil, South Africa, India, and China) group was formed by an agreement on 28 November 2009. All four committed to act jointly at the Copenhagen climate summit. The list of countries classified as developed and developing can be found in Table E.1 in the Appendix E. In FR6, South Africa is excluded from Africa.

6.3. Results

6.3.1. Carbon leakage and emissions

In this section we present the results for carbon leakage (ICL and TCL) associated with each of the fragmented climate policy scenarios. The carbon leakage rate is measured as the increase in carbon emissions outside the regions taking domestic mitigation action divided by the reduction in the emissions of those regions. Thus, if the emissions in participating and non-participating regions in each FRX fragmented climate regime are represented as E_P^{FRX} and E_{NP}^{FRX}, respectively, and the emissions in participating and non-participating regions in the reference scenario as E_P^{REF} and E_{NP}^{REF}, respectively, the leakage rate is given by the eq. *6.1*:

$$\text{Leakage Rate (\%)} = 100 * \frac{E_{NP}^{FRX} - E_{NP}^{REF}}{E_{P}^{REF} - E_{P}^{FRX}} \quad \text{eq. 6.1}$$

Note that a sufficiently long time-frame in the order of decades has to be considered if the aim is to properly account for variations in carbon emissions due to land-use change.[87] Therefore, in order to capture a meaningful measure of TCL, the results for carbon leakage are presented in cumulative terms from 2020 (when the international climate regime enters into force) up to 2050 and to 2100.

Figure 6.1: Global carbon leakage rate (%) for 2020-2050 (a) and 2020-2100 (b) by scenario

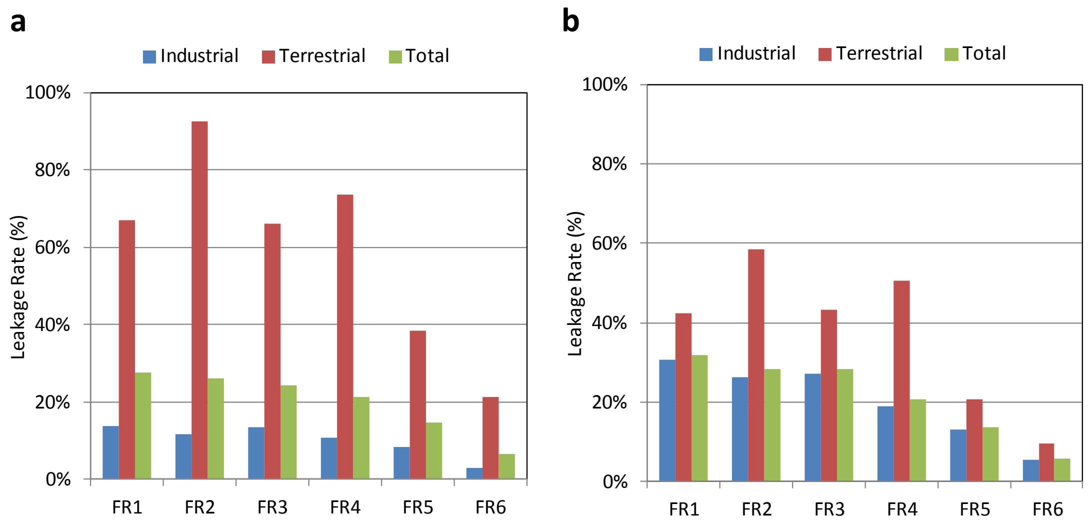

Figure 6.1 shows the cumulative carbon leakage rate for the different fragmentation scenarios from 2020 to 2050 (a) and from 2020 to 2100 (b), distinguishing between ICL and TCL. Several conclusions follow. First, the cumulative leakage rates for ICL in this study are consistent with those in the literature[88] (see (Böhringer et al., 2012)). Second, it is found that in both time periods the total carbon leakage rate decreases with the size of the coalition implementing the international climate regime. In fact, the highest total leakage rate in the period 2020-2050 is in scenario FR1 (28%) and the lowest in the scenario FR6 (6%). Third, the ICL rate is much lower than the TCL rate. In the period 2020-2050 the ICL rate ranges from 3% to 14% and the TCL rate ranges from 21% to 93%. Fourth, the ICL rate dominates in the long run, where the rates for total leakage and ICL almost coincide.

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[87] All the carbon that is stored in a forest converted to cropland is released at once, but it takes decades for afforestation to build up all the carbon storage potential in the new forests (Nilsson and Schopfhauser, 1995).

[88] Notice that the results of GCAM can only be compared with those of similar models, i.e. with partial equilibrium models.

Figure 6.2: Global carbon leakage ($GtCO_2$) for 2020-2050 (a) and 2020-2100 (b) by scenario

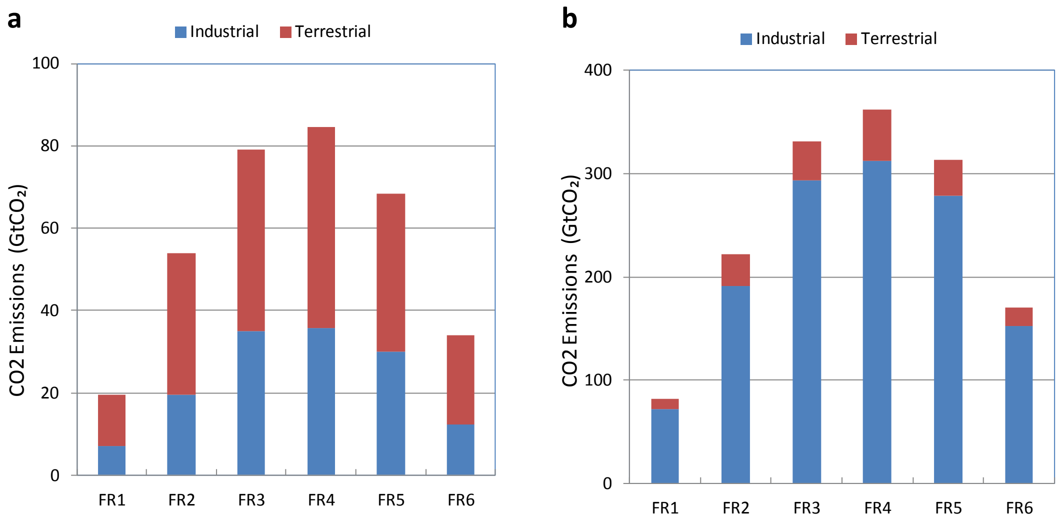


Figure 6.2 shows the cumulative carbon leakage in absolute terms associated with the different fragmentation scenarios from 2020 to 2050 (a) and from 2020 to 2100 (b). In the first period we find that cumulative carbon leakage is in the range from 22 $GtCO_2$ to 98 $GtCO_2$ and that the highest values occur in scenarios FR3, FR4 and FR5. As expected, the relationship between leakage (in absolute terms) and the size of the coalition implementing the climate regime shows an inverted-U shape: it takes low values when the size is small (FR1), the values increase as the size grows to FR2-FR3, but once the coalition reaches a certain critical level (close to that for FR4) further increases in the size of the coalition (to FR5-FR6) reduce the potential for emissions to "leak" due to the reduced size of the non-participating regions. This pattern can also be observed in the period 2020-2100, with the only difference being that the amount of leakage is much higher in this case for every scenario. Note also that when a new region joins the climate coalition it starts reducing its emissions according to its reduction target, but by contrast all the regions outside the coalition increase their emissions. This effect can be observed in Figure E.2 in the Appendix E, where regional disaggregation of carbon leakage is presented for each of the scenarios.

When comparing the TCL and the ICL effects, in absolute terms, TCL dominates during the period 2020-2050. However, if the longer period 2020-2100 is considered, the situation is inverted and the ICL effect dominates. This is due to the fact that emissions related to land-use change take place mainly between 2020 and 2030 (when mitigation policies start to be implemented in the developed and developing regions, respectively), but then start to decline. This will be examined in detail in sub-section 6.3.3.

Figure 6.3: Global emissions by scenario ($GtCO_2$): (a) energy system and (b) land-use changes

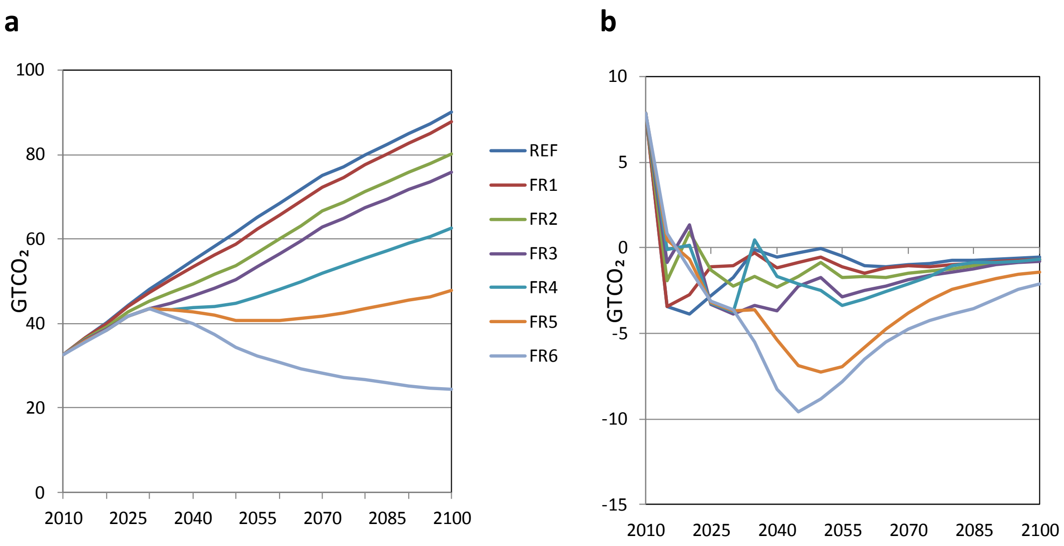


Figure 6.3 shows the trend in emissions associated with the energy and land-use systems. Figure 6.3a shows that global emissions associated with the energy system increase monotonically over time not only for the REF scenario but also for scenarios FR1, FR2 and FR3, where only developed regions take part in the international climate regime. For global emissions arising from the energy system to fall it is necessary that developing regions join the coalition (scenarios FR4, FR5 and FR6). However, global emissions from the energy system rise again around 2050 if the only developing regions joining the international climate regime are the so-called BASIC countries (scenarios FR4 and FR5). Figure 6.3b shows that in the REF scenario emissions associated with land-used change decrease from +8 $GtCO_2$ in 2010 to -0.5 $GtCO_2$ in 2100, whereas in the rest of the scenarios afforestation drives emissions associated to negative values (from -0.5 $GtCO_2$ in FR1 to -9.6 $GtCO_2$ in FR6) before 2050 and they converge to values closer to those of the REF scenario by the end of the century.

Finally, *Table 6.2* shows the mitigation rates in 2050 by scenario and regions. The shaded area represents those regions that are in the climate coalition in each of the fragmented scenarios. It can be seen that in those regions outside the grey area (non-participant regions) emissions are always higher in any fragmented scenario than in the REF scenario, due to the presence of carbon leakage. It can also be seen that the different marginal abatement cost of each country affects mitigation efforts. For example, China with an objective of a maximum increase of 140% of total CO_2 emission by 2050 (FR4) is tightened only to 103% when other developing countries enter the coalition (FR6), since China´s marginal abatement costs are higher. By contrast, the EU can relax slightly its objective by 2050 (FR1), when the US enters the coalition (FR2). Table 2 also shows that there are important differences between scenarios in terms of the global emission reduction effort. Therefore, it is best to be cautious when comparing the effect of these scenarios in terms of mitigation costs or climate change control achievement, as shown in the following sub-sections.

Table 6.2: Emission reductions (%) by 2050 (compared to 1990)

	REF	FR1	FR2	FR3	FR4	FR5	FR6
EU27	1%	-80%	-78%	-79%	-79%	-78%	-78%
USA	49%	51%	-88%	-90%	-91%	-92%	-92%
Other Developed	70%	75%	82%	-75%	-76%	-77%	-78%
China	288%	292%	298%	307%	140%	138%	103%
Brazil+ India+ S.Africa	365%	369%	383%	398%	407%	117%	101%
ROW	189%	192%	202%	214%	221%	226%	85%
Russia, ME and Africa	84%	87%	93%	100%	104%	103%	102%
Global	131%	121%	100%	86%	63%	38%	12%

6.3.2. Effects on the global energy system

This section analyses the changes in the global energy system in order to understand the driving forces behind the carbon leakage effects. Figure 6.4a shows the global primary[89] energy mix in 2050. As the size of the climate coalition increases the share of fossil fuel in total primary energy demand decreases from 82% in the REF scenario to 76% in scenario FR3. This reduction in demand for fossil fuels causes a drop in the price of fossil fuels[90] by 2050 (see Figure 6.4b). Even though the change in the fossil fuel price index is limited[91] for all scenarios, ranging from 17.5% in REF to 15.5% in FR6, the bigger the size of the coalition the lower the increase in the fossil fuel prices.

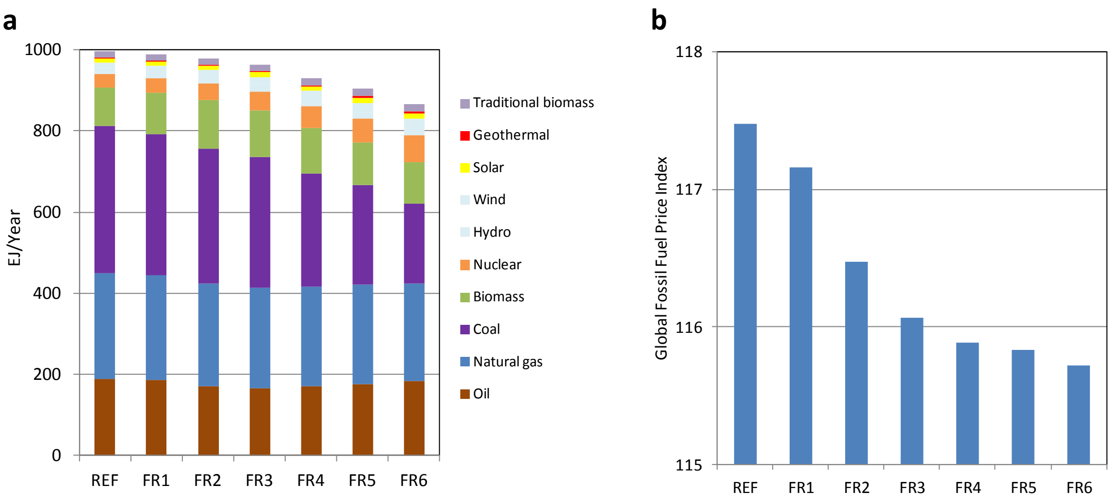
According to the results reported in Figure 6.4 it may seem that fragmentation of the international climate regime does not have a substantial impact on demand for (and therefore the price of) fossil fuels. However, one should also consider other effects in the energy system that would take place simultaneously. First, climate policies will induce improvements in energy efficiency that will be translated into reductions in global energy consumption. Thus, Figure 6a a shows a 13% reduction in the consumption of primary energy by 2050 between the REF and the FR6 scenario. Second, the inclusion in this model of CCS technologies allows for some amount of fossil fuels to be used also in the participating regions.

[89] In direct equivalent terms.

[90] The Global Fossil Fuel Price Index includes the global price variation of crude oil, natural gas and coal. Each fuel is weighted according to the proportion of energy in the primary energy mix.

[91] This is due to the supply-cost curves implemented in GCAM from Rogner (1997), characterized by large amount of resources at relatively low extraction costs (Capellán-Pérez et al., 2014a).

Figure 6.4: Energy System: (a) Global primary energy in 2050 (EJ/yr); (b) Global Fossil Fuel Price Index in 2050 (2010=100)



Source: own work.

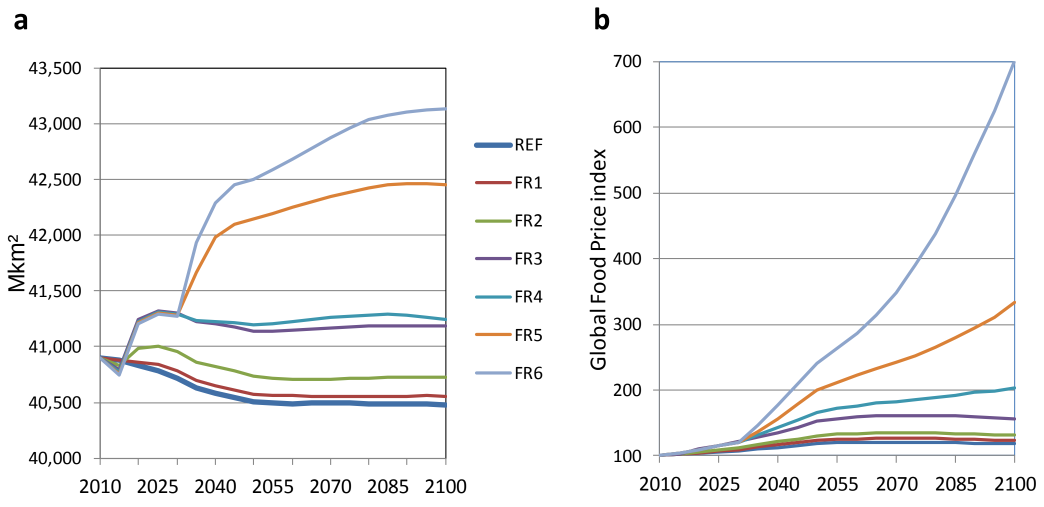
Figure E.3 in the Appendix E also shows that a substantial part of the global electricity mix in 2050 is still covered by fossil fuel with CCS technology (up to 12%). The greatest expansion due to mitigation policies is in nuclear power (up to 31%). The figure also shows that biomass does not have a prominent role in the energy system and the use of biomass with CCS is marginal in all the scenarios along the century.[92] This expansion of biomass is explored further in the next sub-section.

6.3.3. Effects on the global land-use system

The main channels for TCL are the deforestation and/or afforestation that take place in response to fragmentation of the climate regime. As stated in the introduction of the chapter, all the scenarios used in this paper are implemented following a UCT approach. When participating regions put an explicit value on terrestrial carbon emissions, they have an incentive to trade products from land with low carbon density storage (e.g. crop land) for products from land with high carbon density storage (e.g. forest). This triggers afforestation in participating countries and deforestation in non-participating countries. Clearing mature forests immediately releases many years of accumulated carbon but it will take decades for afforested areas to store that amount of carbon (Nilsson and Schopfhauser, 1995). This means there may be temporarily an increase in land-use change related emissions even if the forest area remains globally stable.

92 This is also true for all the scenarios in 2100.

Figure 6.5: Land-use System: (a) Trend in global forest area by scenario compared (Mkm²); (b) Global Food Price index by scenario (Base 2010=100)



Source: own work.

The biggest absolute variation takes place within the land given over to forests. Figure 6.5a tracks the trend in the global area given over to total forest land (managed and unmanaged). In the REF scenario there is a slight decrease in the area of forest over time due to an increasing area for food/biofuel production. However, the introduction of (fragmented) climate policy leads to an increase in the global forest area. It is even possible to see the “jumps” in afforestation in the year in which regions start their mitigation efforts (2020 for developed countries and 2030 for developing countries). Globally, the total forest area increases with the increase in the size of the coalition from +0.2% to +4.9% by 2050.

Table 6.3 shows the global land-shift under different scenarios by 2050 for crops, biomass and forest area, as the rest of the land uses remains nearly unchanged (see also Figure E.4 and Figure E.5 in the Appendix E). Afforestation in participating regions occurs at the expense of shifting food and bioenergy production to non-participating regions. By 2050 the forest area in participating regions increases between 10% and 25%, whereas in non-participating regions the land dedicated to bioenergy increases between 15% and 40% and the land dedicated to crops increases between 4% and 40% depending on the scenario.

Table 6.3: Change in the land area in 2050 for each scenario compared to the reference

	FR1	FR2	FR3	FR4	FR5	FR6
Crops						
Participating	-35.9%	-34.5%	-37.8%	-30.4%	-23.4%	-15.0%
Non-participating	4.0%	9.4%	18.4%	25.9%	38.2%	39.6%
Global	1.4%	2.3%	2.6%	4.9%	3.5%	1.3%
Bioenergy						
Participating	-38.4%	-22.8%	-23.1%	-15.4%	-21.5%	-20.9%
Non-participating	12.5%	34.3%	42.1%	41.5%	21.6%	15.6%
Global	3.1%	15.4%	9.4%	5.9%	-8.1%	-11.1%
Forest						
Participating	23.0%	17.6%	10.5%	10.2%	10.8%	8.7%
Non-participating	-0.9%	-1.9%	-2.5%	-2.9%	-2.0%	-0.6%
Global	0.2%	0.6%	1.6%	1.7%	4.0%	4.9%

Source: own work.

An important effect associated to a UCT regime is the increase in the price of food because of the pricing of terrestrial carbon emissions (see also Calvin et al. (Calvin et al., 2014)). Moreover, climate policy fragmentation forces a shift of the production of biomass/food to those regions that are outside the climate coalition, which implies that production is not undertaken in those places where productivity is highest. Thus, fragmentation will intensify the increase in the price of food globally. The impact on the global food price index[93] over the level in 2010 is shown in Figure 6.5b. The higher the mitigation target (and the level of afforestation in participating regions) the greater the increase in the price of food. In 2050 the price of food could increase by a factor of 2 in FR5 and 2.5 in FR6. By 2100, prices increase by a factor of 3 in FR5 and 7 in FR6. The greatest increases are in the prices of animal products such as beef and poultry.

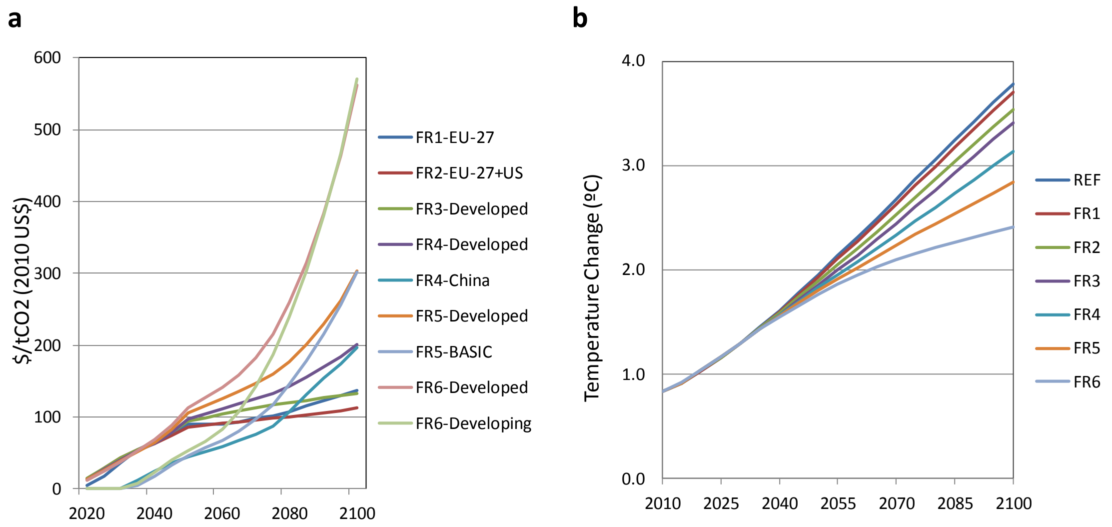
6.3.4. Effects on the climate system and mitigation costs

This section shows the implication of fragmentation for the climate system. Figure 6.6a shows the different carbon prices associated with each scenario depending on whether

[93] The Food Price Index includes the global price variation of the ten crops and six animal categories included in the GCAM model.

each region is participating or not in the international climate regime[94]. An increasing mitigation effort of participating countries means an increasing carbon price. Figure 6.6b shows the temperature change for each of the scenarios. Consistently with emission reduction targets, increases in average temperature in 2100 are very different. In the REF scenario the temperature in 2100 increases to 3.8°C above preindustrial level, whereas in FR1, FR2 and FR3, due to the fact that developing regions do not take part in the international climate regime, it is only slightly below that level (3.7, 3.5 and 3.4°C, respectively). Even in scenario FR6, where only Russia, the Middle East and Africa are outside the international climate regime, the increase in the mean global temperature (2.4°C) exceeds the threshold of 2°C.

Figure 6.6: Climate System: (a) CO2 prices by regions ($/tCO2 US$2010); (b) Global temperature change by scenario, 2010-2100 (°C)



Source: own work.

Finally, *Table 6.4* reports the mitigation costs as policy costs by 2100 in relation to the GDP of the coalition for each scenario (the absolute values in trillion 2010$ are showed in the Figure E.6 in Appendix E). The regions outside the climate coalition have no mitigation target, so the policy cost in terms of GDP is 0%. However, regions that are in the climate coalition in each of the fragmented scenarios have a policy cost. The total policy cost increases from 0.13% of global GDP in FR1 to 0.44% in FR3 and 2.49% in FR6. Also, note that the participation of the US in the coalition reduces the mitigation cost for the EU. In other situations, such as the case of China when other BASIC countries join the coalition, mitigation costs increase. This effect depends on how the mitigation options with the lowest costs are distributed among the regions, since the market will allocate more mitigation effort to these regions.

[94] Note that in FR4, FR5 and FR6 there are two “bubbles”, one for developing regions in the climate regime and the other for developed regions in the climate regime. This means that in those cases there will be two different converging prices.

Table 6.4: Policy costs by coalition and scenario in 2100 (% of GDP)

	FR1	FR2	FR3	FR4	FR5	FR6
EU27	0.90%	0.50%	0.50%	0.55%	0.70%	1.17%
USA	0.00%	1.01%	1.02%	1.21%	1.41%	1.82%
Other Developed	0.00%	0.00%	0.94%	1.14%	1.38%	1.90%
China	0.00%	0.00%	0.00%	1.73%	2.07%	3.08%
Brazil+ India+ S.Africa	0.00%	0.00%	0.00%	0.00%	3.29%	4.29%
RoW	0.00%	0.00%	0.00%	0.00%	0.00%	3.83%
Russia, ME and Africa	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Total	0.13%	0.30%	0.44%	0.82%	1.31%	2.49%

6.4. Concluding remarks

Bottom-up or fragmented climate policy regimes are prone to carbon leakage defined as the situation that may occur if, for reasons of costs related to climate policies, economies were to transfer carbon-intensive production to regions which have laxer constraints on GHG emissions. While most studies in the literature have examined the concept of industrial leakage (ICL), the phenomenon can also occur in respect of land use (TCL). Overall, the main scope of this paper is to examine the implications in terms of these two main types of leakage in the context of more realistic scenarios for current international climate regime after the Paris Agreement.

This study analyses carbon leakage implementing a UCT regime (CO_2 emissions in all sectors, including land use change, are taxed equally) under different fragmentation scenarios. For this analysis, we use the GCAM model that links the world's energy, land use and agriculture systems with the climate system. The simplifying assumption used to build the future scenarios of fragmented and delayed climate action is that developed regions taking part in the international climate regime will unilaterally commit to reduce emissions by 80% in 2050 (in line with the EU's INDC and consistent with its energy roadmap) and the emissions from developing regions taking part in the international climate regime will start later and emissions will peak in 2030 (in line with China's INDC). With respect to long-term climate policy we assume that, despite its fragmentation, the international climate regime will lead to equal per-capita emissions level by 2100. The study also includes an assessment of the effects of the fragmented climate regimes on energy systems, land use, climate and mitigation costs.

We derive four main findings from our study. First, we show that carbon leakage in absolute terms takes the highest values (between 20 and 80 cumulative $GtCO_2$ by 2050) when the biggest developing regions do not take part in the international climate regime. Second, the carbon leakage rate decreases with the size of the climate coalition (between 5% and 25% by 2050). Third, TCL turns out to be the dominant type of leakage up to 2050, due to deforestation in non-participating regions, but ICL takes over during the second half of the century. Fourth, fragmented scenarios where only developed countries take part in the international climate regime lead to a range of average estimates of temperature changes above 3.4ºC. Even in the more optimistic scenarios where only Russia, the Middle East and Africa are outside the international climate regime, coordinated climate action only has the capability of limiting the forecast temperature rise to around 2.4 ºC by 2100, exceeding the threshold of 2ºC.

Two main caveats apply to the analysis. First, this paper examines an idealized UCT regime, leaving aside the difficulties associated with its implementation. Second, the effect of climate on yields and vegetation is not included and, although it is beyond the scope of this paper, this issue is one of the improvements of the modelling approach that is currently being discussed by the IAM and GCAM communities (Kyle et al., 2014).

Finally, we point out future research directions. Even though we have already commented on some preliminary results regarding the effect of the fragmented climate regime on the price of food, more research effort should be devoted to disentangle what part of that increase is the result of the implementation of a UCT regime and what part is due to the fragmented nature of the climate regime. Another possible future research direction would be to extend the analysis to consider the introduction of biodiversity-sensitive forest preservation incentives in the international climate regime, since it has been observed that one important implication of a UCT-type instrument in a fragmented climate policy scenario is that it leads to deforestation in non-participating countries.

PART III: CONCLUSIONS. IA MODELLING TOWARDS SUSTAINABILITY

CHAPTER VII

7. Conclusions

A human-driven global environmental crisis is currently undergoing. The escalation of economic activity and population in a context of expansion of the industrial regime through the globe during the last decades is driving some of the key biophysical processes of the Biosphere near (over in some cases) the planetary boundaries (Steffen et al., 2015b). The *Anthropocene* as a distinct geological period from the *Holocene* is increasingly gaining support in the scientific community. The expression "the Great Acceleration" has become popular in the past few years[95] to refer to the accelerated trends in both the socioeconomic drivers and the environmental impacts during since 1950. In this context, a holistic framework is required to assess the urgent and radical changes that will allow human societies to achieve a sustainable future.

Environmental Integrated Assessment Models (IAMs) constitute a powerful modelling tool integrating multiple disciplines and dimensions to shed light on potential sustainability pathways. However, the consistent integration of all the physical and social processes is challenged by a combination of scientific knowledge gaps and uncertainties, as well as the inherent unpredictability about the future paths taken by societies around the planet. Among these tools, IAMs of climate change are considered as one of the best tools for the implicit evaluation of the planetary and social boundaries.

Since there is a diversity of modelling frameworks due to the different approaches used by modellers striving to capture the complex interactions and high uncertainties involved in the climate/economy/society interface, in this doctoral thesis two modelling frameworks have been applied: a state–of-the-art model (GCAM) and a new biophysical model (WoLiM). GCAM, as the majority of IAMs of climate change, is based on a standard economic approach relying on economic equilibrium that solves through optimization procedures and follow the paradigm of abundance of mineral resources. GCAM has been developed over the course of 30 years, and has been applied to produce emissions scenarios in all the Intergovernmental Panel on Climate

[95] The term "Great Acceleration" was not used until 2005 at the Dahlem Conference on the history of the human–environment relationship, which brought together many global change experts.

Change (IPCC) reports to date. On the other hand, the developed model WoLiM follows a biophysical approach focusing on basic ecological and thermodynamic principles to analyze the economic process. It also inherits from the Complex Systems approach that focuses on the dynamic interrelation between its elements.

Both models also differ in their disaggregation level: while WoLiM is a global aggregated energy-economy-climate model with a reduced set of technologies, GCAM is a highly-disaggregated IAM including subsystems such as land-use and allowing to explicitly model climate policies. Additionally, in the version presented here, WoLiM is a model to discard scenarios by physical and temporal unfeasibility whereas GCAM is an scenario planning tool. In this sense, both models have not only different structures, but different aims. This diversity has allowed approaching a variety of issues, as well as the same issue from different perspectives.

Part I comprises the Introduction of the dissertation (Chapter 1) and the overview of the IA modelling of climate change (Chapter 2). The overview of the field provides the grounds for the applications and development the IAMs across the dissertation, as well as for the outline of the proposition of modelling towards sustainability in section 7.4.2. Part II includes the development and applications of both IAMs in Chapters 3 to 6. The first three chapters investigate the energy modelling of mineral energy resources in IAMs. Chapter 3 focuses on the likelihood of climate change pathways under uncertainty on fossil fuel resources availability applying GCAM. Chapters 4 and 5 include the development of the new model WoLiM. A preliminary version of the model is applied to shed light on the physical and temporal constraints to the transition towards renewable energies focusing on the substitution of oil (Chapter 4). A full-version of the model, including all fuels and sectors, is applied in Chapter 5 to analyse the implications for socioeconomic pathways. Part II ends with Chapter 6 dedicated to the investigation of industrial and terrestrial carbon leakage under different scenarios of climate policy fragmentation with GCAM. The main findings of each chapter are summarized in section 7.1 and the main policy implications are presented in 7.2. Section 7.3 identifies different avenues for future work continuing the analyses presented in this dissertation. Section 7.4 concludes with final remarks about the contribution of the dissertation to the debate on natural resources scarcity, and about the enterprise of modelling towards sustainability.

7.1. Main findings

In relation to the implications of the uncertainty of fossil fuel resources availability and geological constraints for climate change pathways (objective A), the following conclusions for baseline scenarios (i.e. scenarios with no additional climate policy) have been obtained:

- Current fossil fuel reserve and resource estimates are subject to critical uncertainties and an emerging body of literature is providing revised estimates (remaining ultimately recoverable resources, RURRs).
- Considering the range of revised estimates, the two highest emissions pathways from the IPCC, the RCP6 and RCP8.5, where the baseline scenarios currently lie, have probabilities of being feasible of just 42% and 12% respectively by the end of the century. This is due to the likely transition to renewable energies in the second half of the century.
- In terms of temperature change, the probability of surpassing the 2°C level by 2100 remains very high (88%).
- Coal resource uncertainty emerges as the most determinant factor in future emissions uncertainty due to the poor quality of coal data globally.

The integration of flow limitations from geological constraints with the RURR revised estimates for fossil fuels in the full version of WoLiM, in combination with the simulation of the common socioeconomic scenarios considered in GEAs to 2050, sheds light on the feasibility of the energy transition pathways. Under the assumptions considered, and notably if the depletion curve estimates of non-renewable energy resources in the literature are accurate, the following can be stated:

- In the transportation sector, all of the simulated scenarios unfold as unfeasible before the year 2020. Biofuels, alternative electric and hybrid vehicles, coal-to-liquids, gas-to-liquids, efficiency improvements and even the higher development of unconventional oil cannot reach a substitution rate able to compensate the conventional oil decline. By 2030 (2050), the primary energy supply covers between 65-85% (40-65%) of the projected primary energy demand of the sector, 60-75% (35-50%) from fossil fuels.
- Electric vehicles could represent a partial solution to attenuate oil dependency, but their large scale deployment is challenged by the low performance they currently show. Biofuels are a much worse alternative from the point of view of land efficiency, since the occupation of land for an internal combustion engine vehicle is currently up to 50 times greater than the equivalent land needed by an electric vehicle powered with solar energy.
- Electricity supply, including the additional demand for electric vehicles, seems to be the least worrisome sector, especially in scenarios where the generation of electricity from renewable energy sources is strongly promoted.
- A peak pattern for the future extraction of fossil fuel resources emerges due to their combined depletion, reaching a plateau at around 500-525 EJ of primary energy supply between 2020 and 2035, depending on the scenario, which is followed by a 1-1.5% annual extraction reduction.
- The total primary energy supply (TPES) can be stabilized or even grow in some scenarios to 2050, but the past growth trends cannot be maintained, since the decrease in fossil fuels extraction can only be partially compensated by unconventional fuels extraction, alternative technologies and efficiency improvements. By 2030 (2050), the TPES covers between 80-90% (55-76%) of the projected total primary energy demand, 60-70% (30-45%) from fossil fuels.

- Flow constraints to fossil fuels extraction do not prevent from dangerous climate change despite the emission pathways are lower than high-medium emissions scenarios from the IPCC SRES (IPCC SRES, 2000a), the simulated scenarios showing a peak in CO_2 emissions in 2020-2030 at 40-45 $GtCO_2$.

In a nutshell, the obtained results indicate that a significant systemic energy-scarcity risk exists: global demand-driven evolution as performed in the past might be unfeasible. Furthermore, the application of a net energy approach instead of focusing on primary energy flows would probably generate larger discrepancies between demand and supply. From the current decade, the world socioeconomic system may progressively be forced to become independent of the cheap and abundant energy resources that were available in the past.

The results also show that the consideration of inertias and delays in the deployment of technologies are critical to assess the feasibility of transition pathways. Temporal constraints, i.e. time, emerge as an additional critical scarcity. In fact, the study of previous energy transitions shows that they are slow, in the order of decades (Smil, 2010). In this sense, the application of system dynamics (SD) demonstrates that the modelling paradigm of equilibrium can be overly optimistic in assessing the energy transition. This does not mean that other modelling approaches cannot include these features, but that while SD considers these feature intrinsically other approaches need to implement them "additionally" (see for example (Iyer et al., 2015)).

Furthermore, the WoLiM framework allows contributing to the debate about the role of energy in the economic process (e.g. (Brown et al., 2011; Stern, 2011)). The obtained results show that in the absence of a deep structural shift in the ''energy–economy'' relationship, world economic growth may be seriously limited or even negative in the future. A follow-up paper analyses which levels of GDP growth would be compatible with likely resource availability constraints in the future, and under which socioeconomic conditions (Capellán-Pérez et al., 2015). The results indicate that the larger use of coal and unconventional fossil fuel resources could sustain low economic growth maintaining the historic energy intensity at the cost of very high environmental impacts.

With regard to the implications of different international climate policy fragmentation scenarios in terms of climate change and terrestrial and industrial carbon leakage (objective B), taxing at the same price industrial and terrestrial emissions for the participating countries in a post-Paris type of Agreement (UNFCCC, 2015), the obtained results with GCAM (considering the standard fossil fuel endowments in the model) show that:

- Fragmented scenarios where only developed countries take part in the international climate regime lead to a range of average estimates of temperature changes above 3.4ºC. Even in the more optimistic scenarios where only Russia, the Middle East and Africa are outside the international climate regime, coordinated climate action only has the capability of limiting the likely temperature rise to around 2.4 ºC by 2100.

- Total carbon leakage is at its highest when the biggest developing regions do not participate, but its rate decreases with the size of the coalition.
- Terrestrial carbon leakage may be the dominant type of leakage up to 2050, due to deforestation in non-participating regions. Afforestation in participating regions occurs at the expense of shifting substantial amounts of food and bioenergy production to non-participating regions.
- The higher the mitigation target (and the level of afforestation in participating regions), the greater the increase in the global price of food. In the scenarios considered, food prices increase between 3 and 7 times by 2100 in relation to the baseline.

7.2. Policy implications

The following main policy implications can be derived from the results presented above:

- Confirmation of the fact that the scarcity of energy resources would not change the need for an urgent and globally coordinated action to avoid dangerous climate change.[96] The analysis in chapters 3-5 constitute an opportunity to revisit the likelihood controversy concerning future climate change, offering an alternative perspective that focuses on the compatibility of the proposed pathways with physical resource restrictions. Thus, the results obtained in these chapters could assist the climate policy making process in cases where the equal probability assumption may act as an obstacle. Furthermore, these findings might be considered in the development of standard sets of climate scenarios such as the SRES or RCPs in the future.
- Since current baseline scenarios do not envisage the likely depletion of fossil fuels during this century, they might be neglecting the efforts required to achieve the transition to renewable energy sources, underestimating the cost of the future energy system. In turn, current climate policy scenarios would then be overestimating the mitigation effort required to reduce emissions to safe levels.
- Energy transitions have been historically slow; anticipatory strategies to address fossil fuel depletion should be urgently implemented, such as timely and adequate R&D investments for modern renewable energies and related technologies (e.g. storage). Thus, renewable energies R&D should be prioritized in relation to other fossil-based low carbon technologies such as CCS. Additionally, anticipatory strategies in combination with a proactive

[96] Assuming the feasibility of the energy transition to renewable energy sources and thus excluding potential scenarios of collapse that may imply an unintended reduction in the use of fossil fuels.

climate policy could foster the speed-up of the learning curves of the renewable technologies, eventually contributing to reduce the overall transition costs.

- The transition to renewable energies faces its own challenges due to their low current deployment and biophysical characteristics (e.g. low power density and energy return on energy invested (EROEI)).
- Technological changes alone might not be sufficient to achieve the transformation of the energy system to overcome both energy and climate constraints. Overcoming the potential fall in fossil energy supply would thus require economic structural changes combined with social and behavioural changes.
- In a socioeconomic system unable to absolute decoupling from energy use, the abandonment of the pursuit of continued exponential GDP growth emerges as a potential policy towards sustainability.
- Effective climate policies under climate fragmentation scenarios must include emissions from land-use changes. This is of critical importance to the post-Paris Agreement scenario and the design of the Intended Nationally Determined Contributions for each country.
- Under climate fragmentation scenarios, the substantial deployment of land-based climate mitigation policies such as afforestation or bioenergy crops intensifies land-use competition, translating into the increase of food price. These circumstances may threat food security and pose problems to biodiversity conservation in some countries.

7.3. Future work

Different avenues for future work continuing the analyses presented in this dissertation are identified:

- Uncertainty and sensitivity analysis are dependent on the quality of the input distributions. Non-renewable energy resources should be continuously reassessed in the light of updated information. Especially for coal, usually seen as a vast abundant resource, there are large uncertainties related to the available resource base due to the lack of robust recoverable estimates at global level. Further work might be directed to improve the datasets' quality applied in Chapter 3. Additionally, the analysis might be extended to study the interaction with other sources of uncertainty such as socioeconomic drivers (e.g. population or economic activity) and the costs of alternative technologies for both baseline and policy scenarios.
- Integration of flow constraints to the extraction of non-renewable fuels as well as temporal constraints to the diffusion of alternative technologies in GCAM, and comparison with the obtained results with the WoLiM model.
- WoLiM was designed as a framework to be expanded in the future to include further processes and dimensions such as: dynamic feedbacks between subsystems (e.g. climate impacts on the economy, endogenise the process of economic growth taking into account the role of energy, etc.); inclusion of

mineral materials, EROEI, a higher technological disaggregation; increase the number of regions; improve the interaction between energy supply and demand; the intermittency of renewable energies (i.e. storage and overcapacities), etc. The inclusion of these features would allow to further investigate the opportunities and challenges of the energy transition from a biophysical perspective, analysing aspects such as potential materials scarcity, land availability for renewables, inequalities between regions, etc.[97]

- Chapters 4 and 5 applied a reduced number of scenarios (i.e. scenario methodology) in the WoLiM framework. Future work may be directed to design probabilistic analysis, which could also assist in the more systematic analysis of the depletion curves of non-renewable fuels existing in the literature. Similarly, a global uncertainty analysis on the most sensitive parameters of the WoLiM model might be convenient to characterize its structural uncertainty.
- The analysis in Chapter 6 used the standard fossil fuel resources in the GCAM model. However, a replication of the analysis applying the RURR estimates considered in the Chapters 3, 4 and 5 would allow evaluating the potential carbon leakage under a likely lower future availability of fossil fuel resources. Due to the higher dependence on renewable energies in general and biomass in particular of the participating regions in the climate coalitions, the levels of carbon leakage might potentially increase.

7.4. Final remarks

7.4.1. Contribution to the debate on natural resources scarcity

In this dissertation, the approaches of two different research communities are integrated: geologists and geological engineers, who have focused on estimating recoverable energy resources robustly and transparently, and the climate integrated assessment community, which has centred its efforts on exploring the technological and socioeconomic dimensions assuming the fossil energy-abundance paradigm. Since the 1990s, a greater focus has been put on the scarcity of the resource amenities provided by Nature than on the availability of particular natural resource commodities in the debate over the economic scarcity of natural resources (Krautkraemer, 2005). However, with the 21st century, interest in the future of mineral resources has substantially increased (Bardi, 2014). Recent facts such as the reach of maximum of global conventional oil production in the mid-2000s (or the continuous declining oil extraction in some traditional oil producers such as UK and Norway) and a growing literature investigating the role of energy in economic growth (e.g. (Ayres et al., 2013; Cleveland et al., 2000)) have contributed to this turnaround. In particular, the role of net energy in the functioning of our societies might be more evident in the future since energy supply in the second half of the 21st century will likely be dominated by

[97] In fact, WoLiM is a model in-development under the currently ongoing MEDEAS project H2020-LCE-2015-2 (691287) Guiding European Policy toward a low-carbon economy. Modelling Energy system Development under Environmental and Socioeconomic constraints.

fuels and technologies with low EROEI levels (Murphy and Hall, 2010a). In this context, the results of this doctoral thesis shows that the integrated analysis of resource availability and climate change is essential to obtain consistent sustainable pathways. The performed analyses suggest that the shared hypothesis on abundance of fossil fuel resources might be revisited by the IAM community, incorporating the uncertainty on their availability to the set of uncertainties more usually considered in the literature (i.e. technological, economic, political and climatic factors).

7.4.2. Modelling towards Sustainability

Modelling is a dynamic process that compares and contrasts our mental models with verifiable hypothesis in formal models to improve both in parallel. A quiet revolution is currently ongoing in the environmental IAM field with the aim to couple them with Earth System Models, progressing towards a holistic representation of the Biosphere. Preliminary results are already providing promising results qualitatively different from current frameworks. However, their development is *very slow* due to the complexities and uncertainties involved in the process. In fact, calls for further integration between disciplines have been made for decades (e.g. (Vitousek, 1994)). This slowness is especially worrying in the context of the acceleration of environmental impacts, bringing into question if these fully coupled models will be available *on time*. Moreover, there is a large discrepancy between natural scientists' understanding of ecological feedbacks and representations of environmental damages (if present at all) in IAMs (Cumming et al., 2005; Lenton and Ciscar, 2013; Pollitt et al., 2010; Weitzman, 2009). Even though the non-inclusion of feedbacks is justified by the deep related uncertainty, their omission erroneously assumes independency between the processes. Hence, the non-consideration of these impacts critically affects the consistency of the baseline scenarios. Since policy scenarios are built upon these baseline scenarios, scenarios considering environmental policies usually report net *costs*, instead of benefits. Thus, it might be argued that current models are sending a contradictory message. In the case of climate change, as explained in Chapter 2, climate costs are either not taken into account, or practically negligible in relation to the projected GDP increases along the century in most IAMs.[98]

In this context, we address the objective C stated in the Introduction by proposing four preconditions to drive the use of IAMs towards *faster* and more *effective* policy-advice towards sustainability:

1. Adoption of a Precautionary Principle (PP) approach as risk management strategy for the development and application of IAMs.
2. Emphasis on feedbacks between the processes and subsystems.

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[98] As a result, in the IPCC-AR5 review of around 300 baseline scenarios in the literature reaching 3.7-4.8°C (interquartile range) by 2100, no scenario depicts a decrease of global GDP in any region by that year in comparison with current levels despite the recognised disruption potential of climate change (IIASA, 2014; IPCC, 2014a).

3. While a full-coupled model of the Biosphere is not available, partial analyses should be complemented by an assessment of the relevant planetary and social boundaries not considered.
4. Enhancement of the credibility and legitimacy of the models by improving the documentation and transparency of the tools.

A PP approach would specially focus on extreme scenarios and uncertainty analyses, and could be complemented by cost-efficient methods. A re-focus of models towards the PP has already been proposed by some authors in the literature to assess sustainability. For example, Stern (2013) concluded that "a new generation of models is needed in all three of climate science, impact and economics with a still stronger focus on lives and livelihoods, including the risks of large-scale migration and conflicts". This would also include a more skeptical view about future technological advancements. In fact, although the window of opportunity is progressively being reduced as we use up the carbon budget to prevent dangerous climate change, this window is being artificially re-opened through modelling (e.g. (Anderson, 2015)). In this sense, applying the PP would translate into focusing on the current existing low-carbon technologies and strategies (e.g. renewables, afforestation, etc.), instead of unproven and questionable technological options such as carbon capture and storage or advanced biofuels (Fuss et al., 2014; Viebahn et al., 2007). Also, given that ecosystem services operate in highly complex ways that would be very difficult to substitute by technology, safeguarding them represents one of the wisest economic investments society could make (Daily, 1997). The emphasis on the integration of subsystems and endogenisation of the modelling structures could also be considered as an application of the PP since it has been showed that models are biased optimistically when feedbacks are omitted (e.g. (Barney, 1980; Randers, 2000)), as it is currently the case with the dominant sequential structure in IAMs of climate change.

A corollary can be derived from the preconditions 1 and 2: to properly assess the risks of environmental unsustainability, IAMs should be able to simulate potential collapse pathways of human societies ("Disaster" scenarios), especially in baseline scenarios. Thus, equilibrium should not be assumed, as it is currently the case in most economic models (Scrieciu et al., 2013); equilibrium and stability may (or may not) emerge from the interaction of the elements of the system. The main objective of the analysis should be then directed to detect the conditions to reach such equilibrium (Sterman, 2000). This was one of the cornerstones of the World3 model on which the *Limits to Growth* report was based (Meadows et al., 1972). In fact, a reappraisal of this modelling approach is ongoing after the (scientific and political) debates in the 70s and 80s (Bardi, 2011), and after the recent validation of its baseline scenario with 30 years of data (Turner, 2008).

The payoff matrix for optimistic vs. pessimistic modelling allows to visualise the related risks for adequate policy-advice (see Table 7.1): the adoption of a risk-averse PP strategy would allow to avoid "Disaster" scenarios.

Table 7.1 Payoff matrix for modelling optimism vs. pessimism

Current Policy	*Real State of the World:* Optimists Right	*Real State of the World:* Pessimists Right
Optimistic modelling policy-advice	*High*	*Disaster*
Pessimistic modelling policy-advice	*Moderate*	*Tolerable*

Source: adapted from (Costanza, 1989).

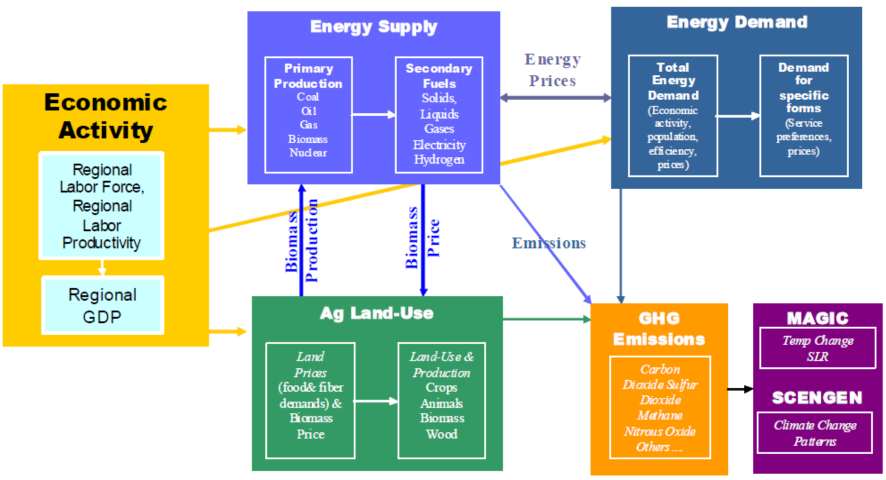
Lastly, there is a lack of transparency in the IAM field that affects the credibility and legitimacy of its results (NCC, 2015). An effort to improve the documentation and provide open source codes of the IAMs would allow for reproducibility, thus opening the possibility of learning about the model structure and being a precondition of scientific progress.

Appendixes

Appendix A. Description of the GCAM model

The Global Change Assessment Model (GCAM) is an integrated assessment model of climate change which is a descendent of the model developed by Edmonds and Reilly (1985) and the MiniCAM model (Brenkert et al., 2003; Clarke et al., 2007; Edmonds et al., 1997; Kim et al., 2006). It is developed by the *Joint Global Change Research Institute* (Pacific Northwest National Laboratory) with research affiliate status at the University of Maryland (USA).[99] It combines representations of the global economy, energy systems, agriculture and land use, with a representation of terrestrial and ocean carbon cycles, a suite of coupled gas-cycle, climate, and ice-melt models (see a schematic representation of the model in Figure A.1). In terms of the categories described in the previous section, GCAM could be categorized as a "bottom-up policy-optimization" model.

Figure A.1: Elements of the GCAM Integrated Assessment Modelling Framework



Source: Wise et al., (2009).

The GCAM is implemented within the Object-Oriented Energy, Climate, and Technology Systems (ObjECTS) framework (Kim et al., 2006). ObjECTS is a flexible, modular, integrated assessment modelling framework. The component-based structure of this model represents the global energy, land-use, and economic systems through a component hierarchy that aggregates detailed technology information up to a global macroeconomic level. Input is provided by the flexible XML standard, where data is structured in an object hierarchy that parallels the model structure. GCAM is then the result of the integration of a bottom-up module (ObjECTS) with a top-down economic module (Edmonds and Reilly, 1985).

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[99] Global Change Assessment Model official website: http://www.globalchange.umd.edu/models/gcam/

GCAM is a dynamic recursive economic partial-equilibrium model driven by assumptions about population size and labor productivity that determine potential gross domestic product in market exchange rates (GDP MER) in each of the geopolitical regions[100] at 5 year time steps. GCAM establishes market-clearing prices for all energy, agriculture and land markets such that supplies and demands for all markets balance simultaneously. Thus, GCAM has no explicit markets for labor and capital and there are no constraints such as balance of payments. The GCAM energy system includes primary energy resource production, energy transformation to final fuels, and the use of final energy forms to deliver energy services such as passenger kilometers in transport or space conditioning for buildings. GCAM contains detailed representations of technology options in all of the economic components of the system with technology choice determined by market probabilistic competition (Clarke and Edmonds, 1993). The run period goes from 1990 until 2100 (through a calibration process for the past data through to 2005).

GCAM distinguishes between two different types of resources: depletable and renewable. Depletable resources include fossil fuels and uranium; renewable resources include wind, geothermal energy, municipal and industrial waste (for waste-to-energy), and rooftop areas for solar photovoltaic equipment. All resources are characterized by cumulative supply curves, i.e. upward-sloping supply-cost curves that represent the idea that the marginal cost of resource utilization increases with deployment. Supply cost-curves for fossil fuels are based on the hydrocarbon resource assessment (Rogner, 1997) (updates have been made for unconventional resources (Calvin et al., 2011)) and on (Schneider and Sailor, 2008) for uranium.

The agriculture and land use component is fully integrated into (i.e. solved simultaneously with) the GCAM economic and energy system components. Since GCAM 3.0, the model data for the agriculture and land use parts of the model comprises 151 subregions in terms of land use, based on a division of the extant agro-ecological zones (AEZs). Land is allocated between the various uses based on expected profitability, which in turn depends on the productivity of the land-based product (e.g. mass of harvestable product per ha), product price, and non-land costs of production (labor, fertilizer, etc.). The productivity of land-based products is subject to change over time based on future estimates of crop productivity change. This increase in productivity is exogenously set, adopted from projections by (Bruinsma, 2003). Thus, it is not specifically attributed to individual components, which may include changes in management practices, increases in fertilizer or irrigation inputs or impacts of climate change. Emissions of gases related to farming, for example N_2O and CH_4, are tied to the level of production. All agricultural crops, other land products, and animal products are globally traded within GCAM. A full description of the agriculture and land use module (documentation of the data, methods used and hypotheses considered) in GCAM can be found in (Kyle et al., 2011; M. Wise et al., 2009; Wise and Calvin, 2011).

[100] GCAM 3 includes the following 14 regions: The United States of America, Canada, Latin America, Western Europe, Eastern Europe, the former Soviet Union, Middle-East, Africa, India, China and Central Planned Asia (CPA), other South and East Asia, Australia & New Zealand, Japan and Korea. GCAM 4 has been expanded to include 32 regions.

GCAM is not a trade model: Heckscher-Ohlin trade is modeled instead of bilateral trade. It is assumed that traded products are supplied to a global pool and any region can consume from that pool. Trade is allowed for all commodities in the GCAM except for electricity and CO_2 storage services, which are assumed to be produced and consumed within a given region ("GCAM wiki," 2013).

In the GCAM the physical atmosphere and climate are represented by the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC; Wigley and Raper, 1992, 2002; Raper et al., 1996). Thus, the GCAM tracks emissions and concentrations of a large number of GHG and short-lived species (including: CO_2, CH_4, N_2O, NO_x, VOCs, CO, SO_2, carbonaceous aerosols, HFCs, PFCs, NH_3, and SF_6.) from the perspective of land use change and the energy supply and supply sectors. The GCAM can be run with any combination of climate and non-climate policies in relation to a reference scenario. Policies can take a variety of forms including taxes or subsidies applied to energy markets, activity permits, e.g. cap-and-trade emissions permits, and/or technology standards, e.g. CAFE or new source performance standards. Costs are computed as the integral of a marginal abatement cost curve ("GCAM wiki," 2013). Thus the model estimates temperature increases, sea-level rise, and radiative forcing, but is unable to estimate impacts or feedbacks of climate change in the economic, energy-related and agriculture sectors due to its sequential structure (it follows the structure of Figure 2.1 with no feedback or adaptation loop). For this reason ongoing research focuses on coupling GCAM with the fully coupled Community Earth System Model (CESM) to enable it to compute bio-geophysical feedback effects of land use change (e.g. (Jones et al., 2013b, 2011)).

GCAM has been developed over the course of 30 years and regularly appears in projects for the comparison of models, such as the Energy Modelling Forum (Clarke and Weyant, 2009). It is also a member of the Steering Committee of the Integrated Assessment Modelling Consortium. Emissions scenarios produced with GCAM or one of its related models, e.g. MiniCAM, have been used extensively by the Intergovernmental Panel on Climate Change (IPCC, 2014a, 2007a, 2001b, 1995b, 1992, 1990) and for research and policy analysis by national governments and other stakeholders (Clarke et al., 2007).

Finally, GCAM is a model in constant evolution. Updates of historical data and extensions are made regularly. For example it is planned for future versions to include water markets, detailed technological options for the agricultural sector, a replacement of the MAGICC Climate model, etc.

Appendix B. Supplementary material to the Chapter 3

B.1 GCAM baseline scenario

The GCAM 3.2 baseline scenario runs for the period 2005-2100 and is characterised by a climate response at the lower bound of the range for the sample of scenarios considered in the IPCC-AR5 baseline model review (reaching a radiative forcing of 7.1 W/m^2 and a temperature change of 3.8°C by 2100) (IPCC, 2014a; Thomson et al., 2011). With the purpose of allowing comparability between the results of the present study and the IPCC-AR5 review results, the exogenous socioeconomic inputs of the GCAM 3.2 baseline were slightly modified in order to produce a climate response in the middle of the range of the IPCC-AR5 baseline model review to reach 7.5 w/m^2 and 4°C by 2100. Specifically, the applied baseline scenario is characterised by a global population that grows steadily for the next 60 years, peaking at almost 10 billion people in 2070 and then beginning to slowly decline. Global gross domestic product (market exchange rate GDP) increases almost 10 times from 2005 to 2100. Applying this socioeconomic scenario with the default energy resources of the model (see Table B.) results in a significant expansion of the global energy system over the century. Primary energy consumption (direct equivalent) increases from 450 EJ per year in 2005 to more than 1,425 EJ per year in 2100, the energy system continuing to be dominated by fossil fuels at the end of the century. Therefore, global energy and industrial CO_2 emissions continue to increase, exceeding 92 $GtCO_2$/year in 2100. Total anthropogenic CO_2 emissions are dominated by energy system emissions throughout the century.

Table B.1: Energy resources available in the GCAM baseline scenario from the year 2005

EJ	**RURR**
Conventional oil	14,960
Unconventional oil	93,635
Natural Gas	243,398
Coal	263,833
Uranium	1,707,594

B.2 Shape of the supply-cost curves

A review of the literature revealed that there is uncertainty about the shape of supply-cost curves (Aguilera, 2014; McCollum et al., 2014; MIT, 2010; NEA and IAEA, 2012; Remme et al., 2007; Rogner, 1997). Three main patterns were identified:

1. **Exponential**: extraction costs increase steadily with cumulative extraction of the first grades. We approximate this behaviour by an exponential curve:

$$\%MaxCost = a \cdot e^{b \cdot (\%MaxRURR)}$$ *eq. B.1*

The parameter *a* makes it possible to calibrate past production and costs, while *b* represents the growth rate to reach the maximum cost at RURR.

%MaxCost refers to the extraction cost in relation to the maximum cost.

%MaxRURR refers to the amount of cumulative resource in relation to the total remaining resource (the RURR).

2. **Inverse**: it is possible that large amounts of resources might be available at an extraction cost that is fairly constant and cheap (relative to higher grades). This is, for example, the case of conventional crude oil in the Middle-East, where large resources have been and are still extracted at costs in the range of $5-15 per barrel (IHS CERA, 2008). We approximate this behaviour by an inverse curve:

$$\%MaxCost = \frac{a}{URR - \%MaxRURR}$$ *eq. B.2*

Again, the parameter *a* adjusts the expression for past production and costs.

3. **Logistic**: on the other hand, it is possible that the amount of resources that are cheap (relative to the costs of higher grades) would be relatively small in relation to large quantities of significantly more expensive resources. We approximate this behaviour by an adapted logistic function.

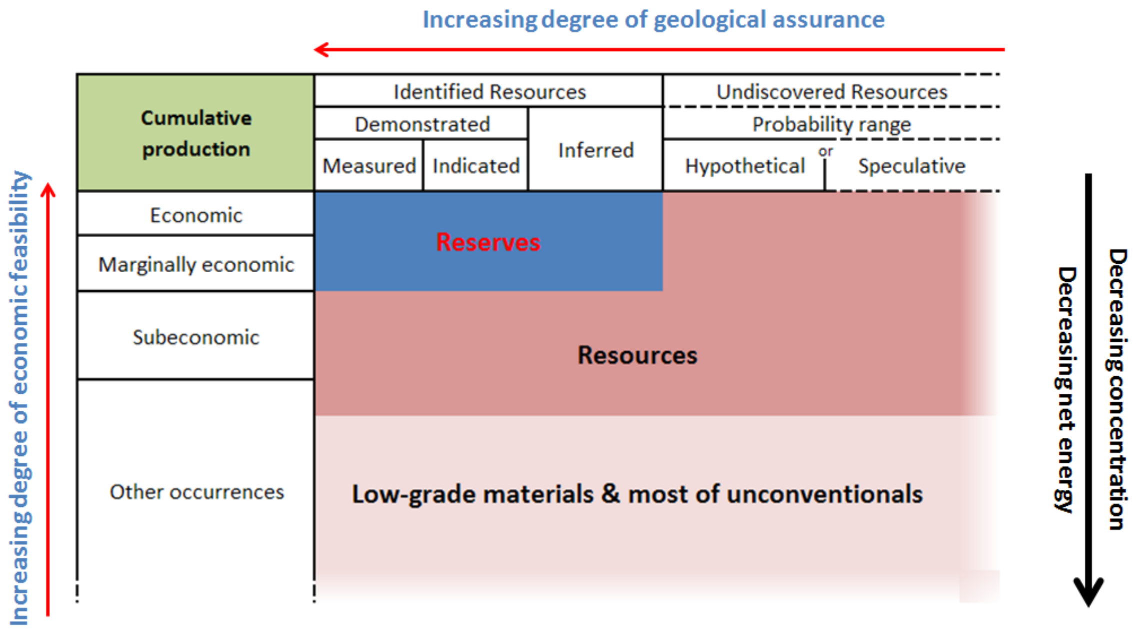
$$\%MaxRURR = \frac{RURR}{(1 + a \cdot e^{-b \cdot (\%MaxCost)})}$$ *eq. B.3*

$$\%MaxCost = \frac{1}{12}\ln\left(\frac{a \cdot b}{\frac{RURR}{\%MaxRURR} - 1}\right) + 1/2$$ *eq. B.4*

The three identified shapes are represented in Figure 3.3 as RURR and extraction cost percentage relative to maximum values.

B.3 Supplementary Figures to the Chapter 3

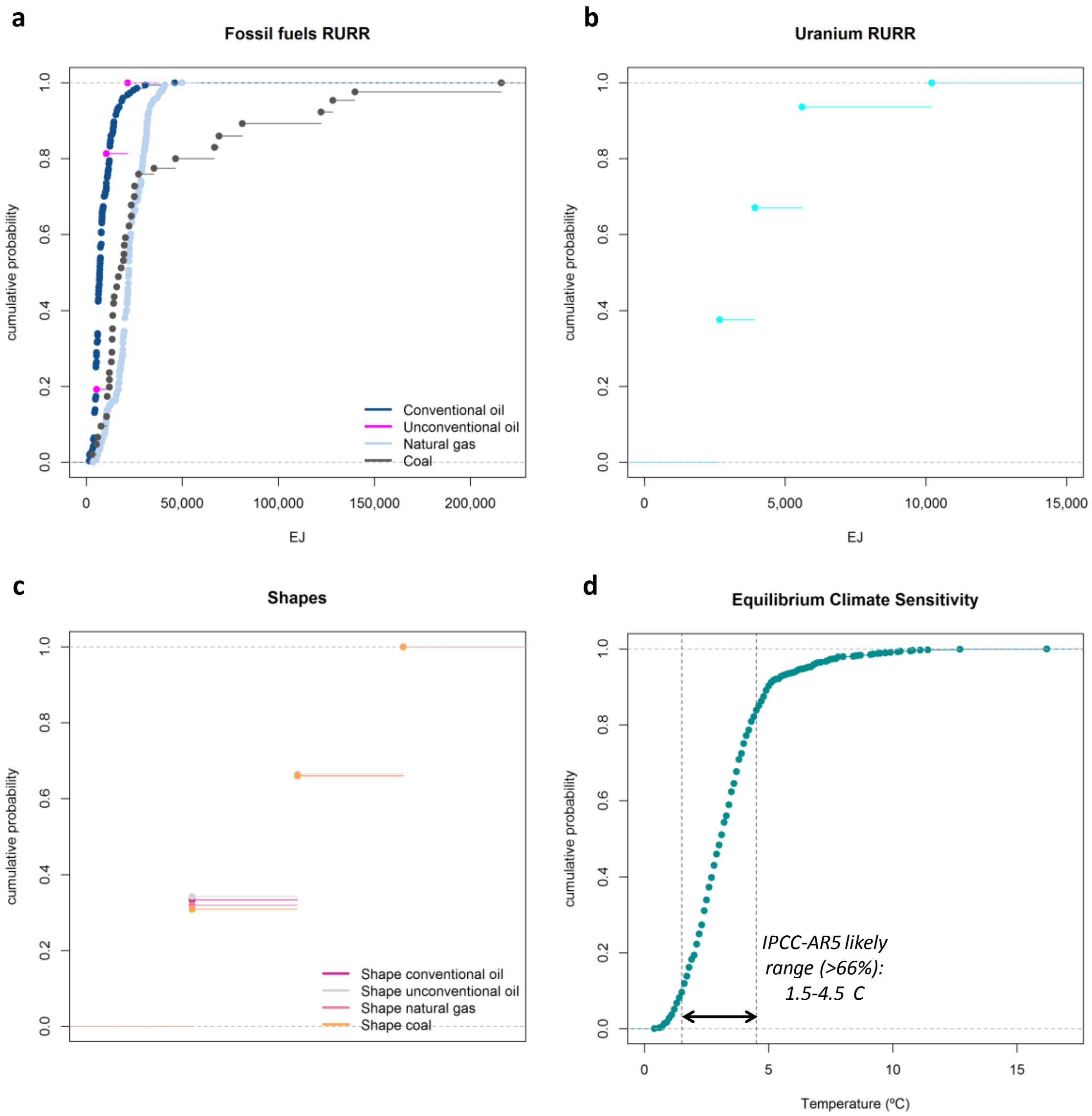
Figure B.1: Classification of reserves and resources from USGS/USBM (McKelvey Box)



Notes: Reserves are depicted in blue, resources in dark red and “low-grade materials & most of unconventionals” in light red.

Source: Adapted from references: (Hughes, 2013b; Rogner et al., 2012; USGS, 1980).

Figure B.2: Empirical cumulative distribution functions of the inputs; (a) for oil (conventional and unconventional), gas and coal RURR; (b) for uranium RURR; (c) shapes of the supply-cost curve; and (d) for equilibrium climate sensitivity



Notes: Conventional and unconventional natural gas are aggregated in accordance with GCAM modelling. For the fossil fuels, the probability assigned to each shape is 1/3. The shape for uranium is fixed to inverse.

Figure B.3: Empirical cumulative distribution function per 5-year period (2010-2100) of the outputs: (a) Total cumulative CO_2 emissions; (b) Total radiative forcing and (c) Temperature change

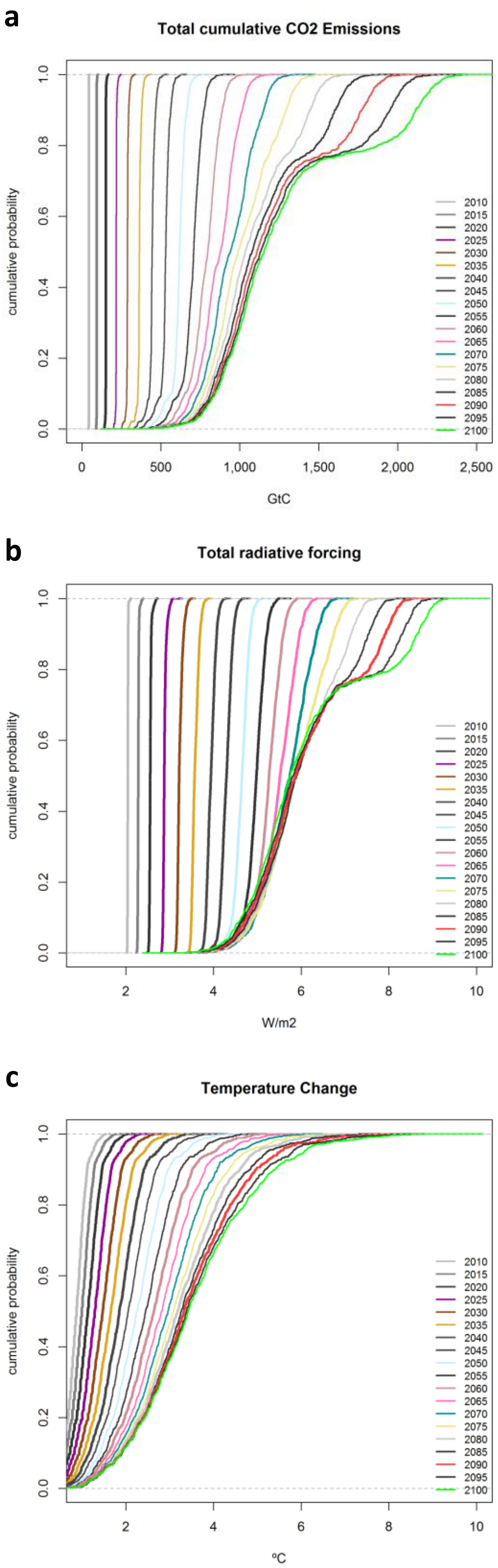
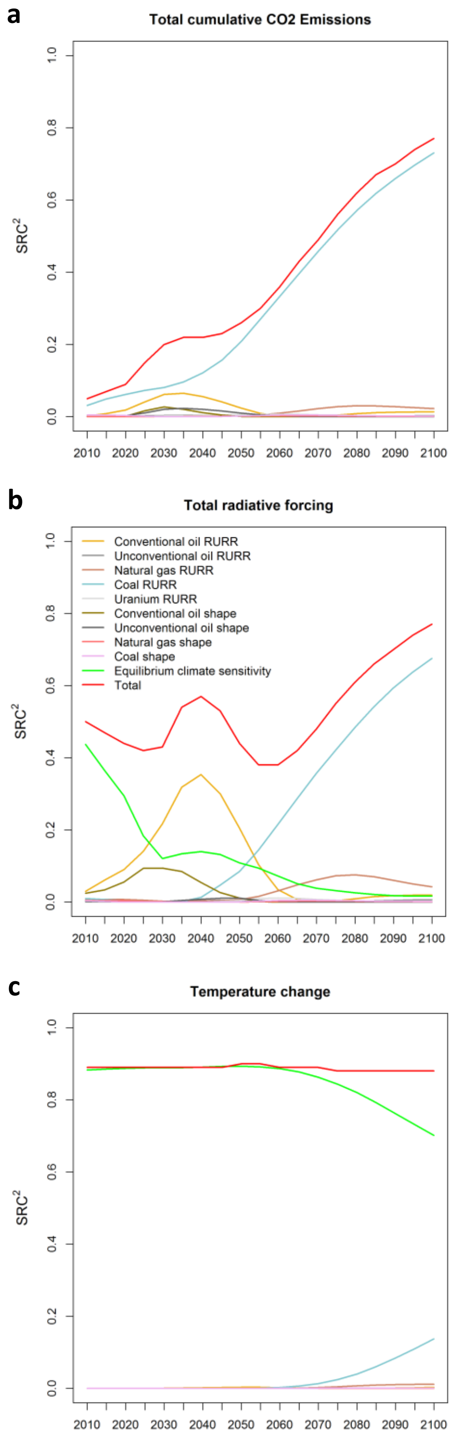
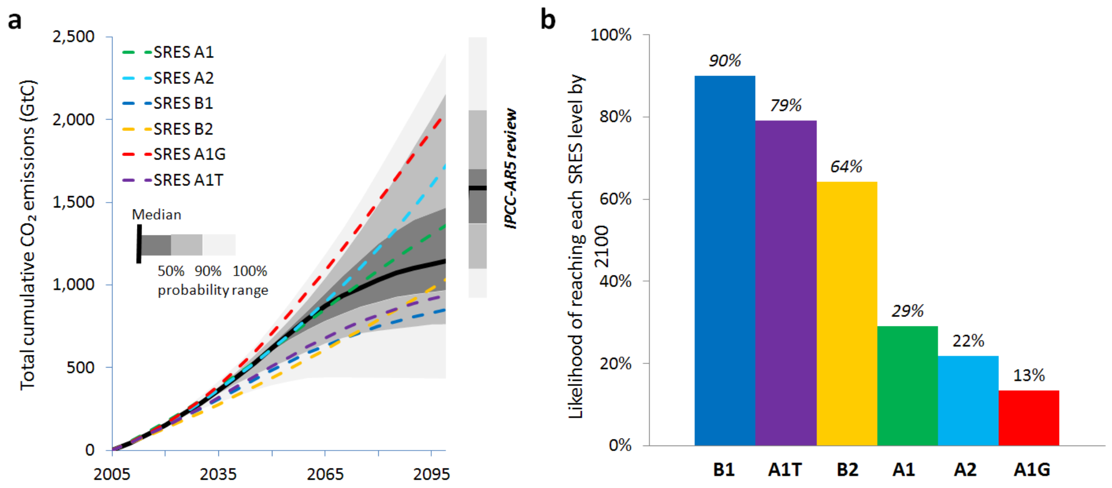


Figure B.4: Evolution of the Squared Standardized Regression Coefficients (SRC^2) over time for the three outputs: (a) Total cumulative CO_2 emissions; (b) Total radiative forcing and (c) Temperature change



Notes: SRC^2 (adimensional) approximates the contribution of the inputs to the output variance. The interpretation of each figure is as follows: the Total (red curve) represents the coefficient of determination of the total multivariate regression. The rest of curves represent the fraction of output variance (cumulative CO_2 emissions, total radiative forcing and temperature change) explained by the different inputs (namely, conventional oil RURR, unconventional oil RURR, gas RURR, etc.).

Figure B.5: Comparison of the results from the sensitivity analysis with the IPCC-AR5 review of baseline scenarios and the SRES marker scenarios: (a) Total cumulative CO_2 emission pathways 2006-2100; and (b), Likelihood of exceeding the 2100 level of each SRES scenario



Source: IPCC-AR5 review of baseline scenarios (IPCC, 2014a) and the SRES marker scenarios (IPCC SRES, 2000a).

B.4 Supplementary Tables to the Chapter 3

Table B.2: Global oil, gas and coal resource estimates from our study compared with a selection of data sources

	EJ	Conv. Oil	Unconv. Oil	Conv. Gas	Unconv. Gas	Coal
Resources + reserves	*GEA (Rogner et al.,* (2012)*)*	9,070 - 13,760	15,030 - 20,400	12,200 - 16,000	60,300 - 189,000	308,300* - 456,000*
	BGR (2013)	13,782	13,193	19,023	20,232	496,975*
Remaining recoverable resources	*IEA (WEO* (2014)	15,508	18,826	17,363	12,743	504,000*
RURR	*Mohr et al* (2015) *[Low; BG; High]*	*(8,134; 8,527; 15,053)*	*(5,297; 10,351; 15,997)*	*(8,038; 10,051; 16,470)*	*(2,689; 14,559; 18,099)*	*(7,757; 15,694; 25,524)*
	This study [Mean ± St. d.]	8,511 ± 5,333	11,977 ± 5,199	7,952 ± 4,278	14,159 ± 6,604	35,047 ± 45,060

Notes: *Coal resources that refer to the amount in-place.

Table B.3: Numeric values of the climate outcomes shown in Figure 2 (total cumulative CO_2 emissions (2006-2100), total radiative forcing and temperature change) by 2100 in comparison with the IPCC-AR5 review of baseline scenarios

	Total cumulative CO_2 emissions	**2100 Total radiative forcing**	**2100 Temperature change**
	GtC	*W/m^2*	*°C*
This study			
Median value	1,147.1	5.6	3.4
Median range (50%)	969.2 - 1,474.7	5 - 6.8	2.6 - 4.4
"Likely" range (66%)	901.2 - 1,999.0	4.8 - 8.2	2.3 - 4.9
"Very likely" range (90%)	763.3 - 2,196.9	4.3 - 8.8	1.5 - 6.1
Full range	432.9 - 2,440.5	3.2 - 9.2	0.6 - 8.8
(IPCC 2014 WGIII)			
Median value	1,584.1	7.4	-
Median range (50%)	1,369.4 - 1,700.7	7.2 - 7.6	3.7 - 4.8
"Very likely" range (90%)	1,099.4 - 2,056.5	6.2 - 8.8	2.5 - 7.8
Full range	921.5 - 2,498.2	5.3 - 9.3	-

Source: IPCC-AR5 review of baseline scenarios from (IPCC, 2014a).

Table B.4: Summary statistics of climate outcomes for the year 2100

	Mean	s.d.	c.v.
Total cumulative CO_2 emissions (GtC)	1,298 ±15	466	0.36
Total radiative forcing (W/m^2)	6.18 ±0.05	1.44	0.23
Temperature (°C)	3.57 ±0.04	1.37	0.38

Notes: Mean with standard error, standard deviation (s.d.) and coefficient of variation (c.v.).

Table B.5: Selected quantile estimates of outputs Y for the year 2100 (95% confidence interval in parentheses)

Quantile	**0.01**	**0.05**	**0.1**	**0.5**	**0.9**	**0.95**	**0.99**
Total cumulative CO_2 emissions (GtC)	599 (515 - 657)	763 (737 - 785)	837 (810 - 861)	1,147 (1,114 - 1,172)	2,110 (2,091 - 2,140)	2,197 (2,166 - 2,221)	2,292 (2,272 - 2,356)
Total radiative forcing (W/m^2)	3.88 (3.66 - 4.02)	4.38 (4.26 - 4.44)	4.62 (4.51 - 4.71)	5.74 (5.67 - 5.84)	8.65 (8.56 - 8.71)	8.87 (8.81 - 8.91)	9.11 (9.03 - 9.2)
Temperature change (°C)	1.06 (0.88 - 1.11)	1.5 (1.35 - 1.6)	1.89 (1.78 - 2.02)	3.42 (3.35 - 3.51)	5.4 (5.22 - 5.56)	6.06 (5.87 - 6.2)	7.41 (7.12 - 8.03)

Table B.6: Uranium RURR levels and associated probability derived from the Nuclear Energy Agency estimates

Levels	RURR (EJ)	Description	Prob.
1	3,023	Identified resources (RAR+IR) recoverables at a cost < USD 260/kgU	36%
2	4,212	Level 1 + Prognosticated resources recovables at a cost < USD 260/kgU	31%
3	5,829	Level 2 + Speculative resources (undiscovered resources in unknown provinces) recovables at a cost < USD 260/kgU	25%
4	10,668	Level 3 + Speculative resources and reported unconventional resources with cost unasigned	7%

Notes: RAR and IR stand for reasonable assured resources and inferred resources. Prob. refers to probability.

Source: Nuclear Energy Agency estimates from NEA and IAEA (2012).

Table B.7: Change in reserve and resource estimates compared to 1997 (1997⇔100%) by energy source from the updated IPCC range from Rogner et al. (2012) in comparison to the previous assessment by Rogner (1997)

	Reserves		Resources		Total	
	min	MAX	min	MAX	min	MAX
Oil	62%	95%	77%	104%	79%	105%
Conventional	78%	121%	69%	101%	90%	118%
Unconventional	49%	73%	80%	105%	71%	95%
Gas	180%	532%	140%	387%	152%	418%
Conventional	85%	120%	62%	76%	78%	97%
Unconventional	250%	835%	182%	551%	200%	627%
Coal	41%	50%	290%	433%	212%	312%

Notes: Minimum and maximum values refer to the ranges provided by Rogner et al. (2012).

Appendix C. Supplementary material to the Chapter 4

Figure C.1: Forrester diagram of the model with the most significant stocks and variables

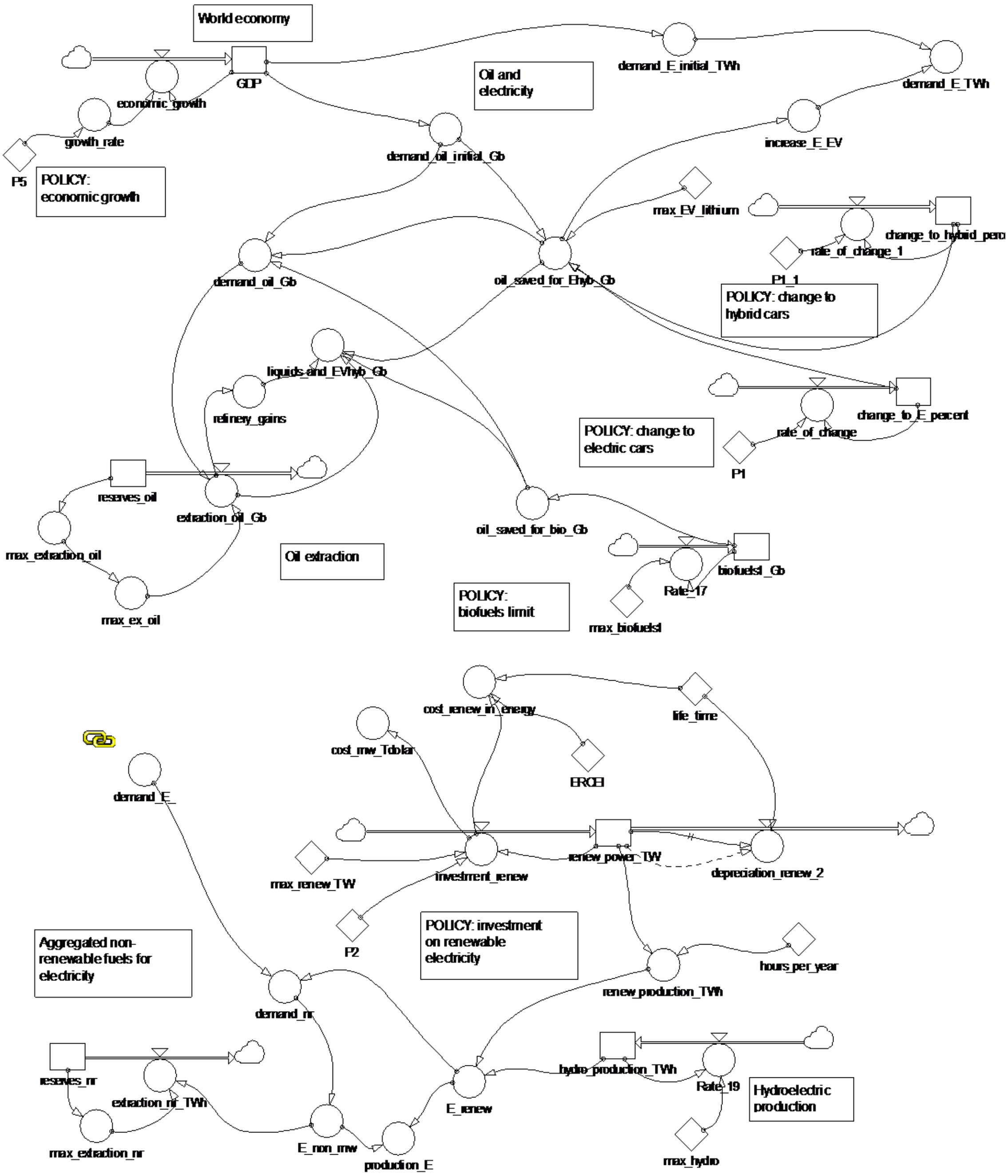
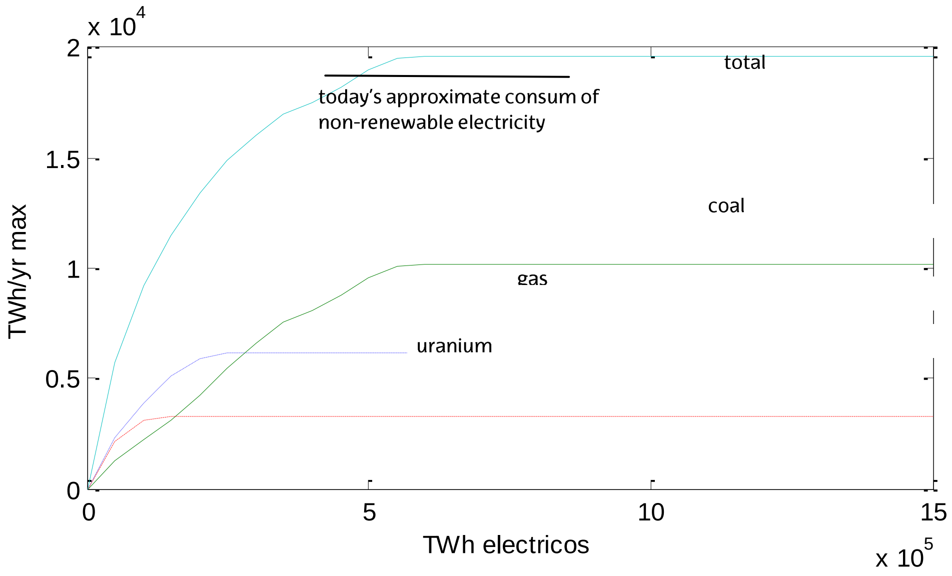


Figure C.2: Curves of maximum extraction for the non-renewable resources for electricity



Notes: The x axis represents the stock of resource left in terms of the useful final electrical energy; the y axis represents the maximum extraction rate.

Appendix D. Supplementary material to the Chapter 5

D.1 Basic structure of the WoLiM model

Figure D.1 and Figure D.2 and show an overview of the Forrester diagram of WoLiM, where the main relationships and subsystems can be seen. Demands are shown in green, non renewable resources in light blue, renewable electricity in dark blue, policies in red and emissions in orange.

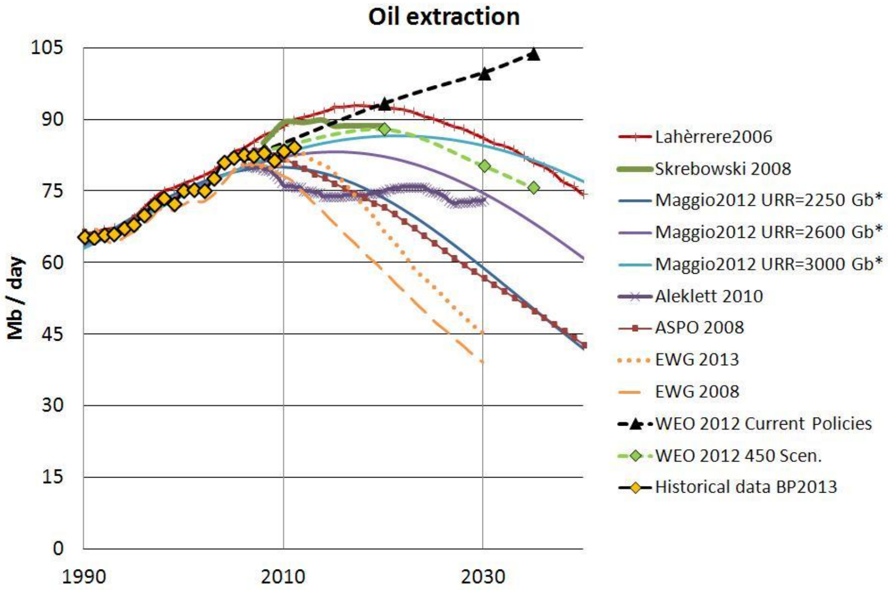
Figure D.1: Forrester diagram of WoLiM model (left side)

Figure D.2: Forrester diagram of WoLiM model (right side)

Notes: Stocks are represented as squares, flows by the arrows related to stocks, variables are represented by circles and constants by rhombus. Most of the relationships between variables are represented by lines but some are hidden for simplicity.

D.2 Updated review of fossil fuel depletion curves

Figure D.3: Estimations of oil extraction by different authors



Notes: There is a lack of standardization in the literature. For each study, "oil" refers to only crude oil (including NGLs) (Maggio and Cacciola, 2012); crude and unconventional (ASPO, 2009; EWG, 2013, 2008); crude, unconventional and refinery gains (Aleklett et al., 2010; Skrebowski, 2010; WEO, 2012); crude oil, unconventional, refinery gains and biofuels (Laherrère, 2006); finally (BP, 2013) historical data include crude oil, shale oil and oil sands. (Aleklett et al., 2010) adjust the total volume of NGL to the energy content since 1 barrel of NGL contains in reality 70% of the energy of an oil barrel.

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

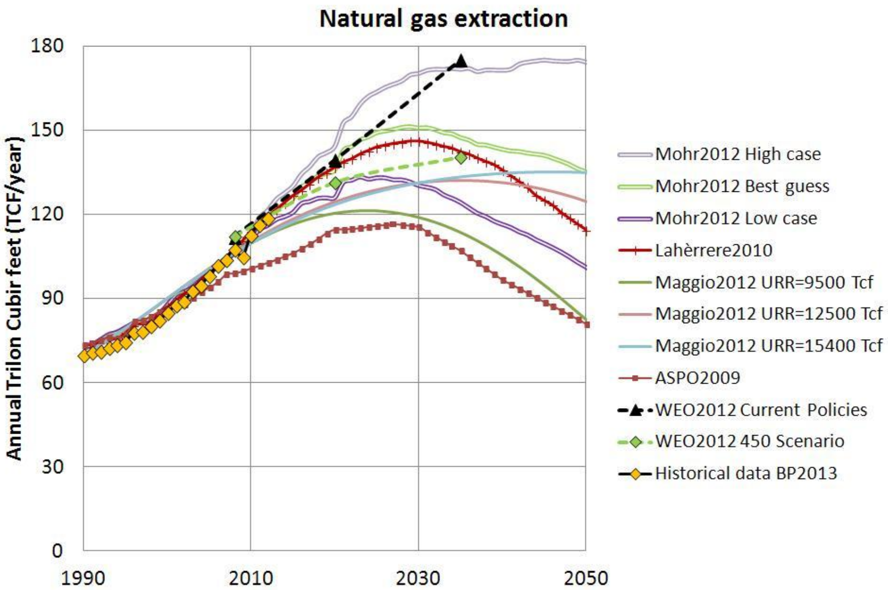
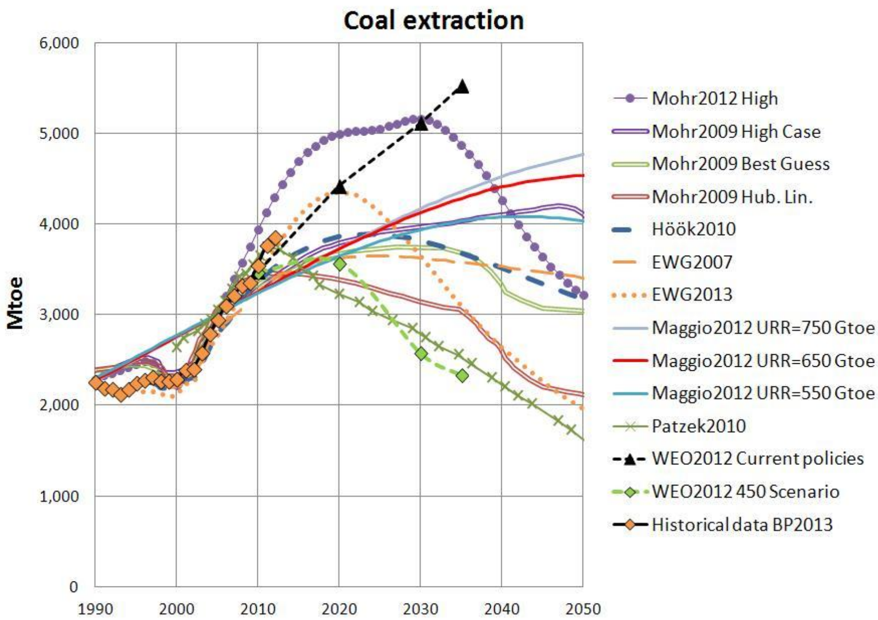
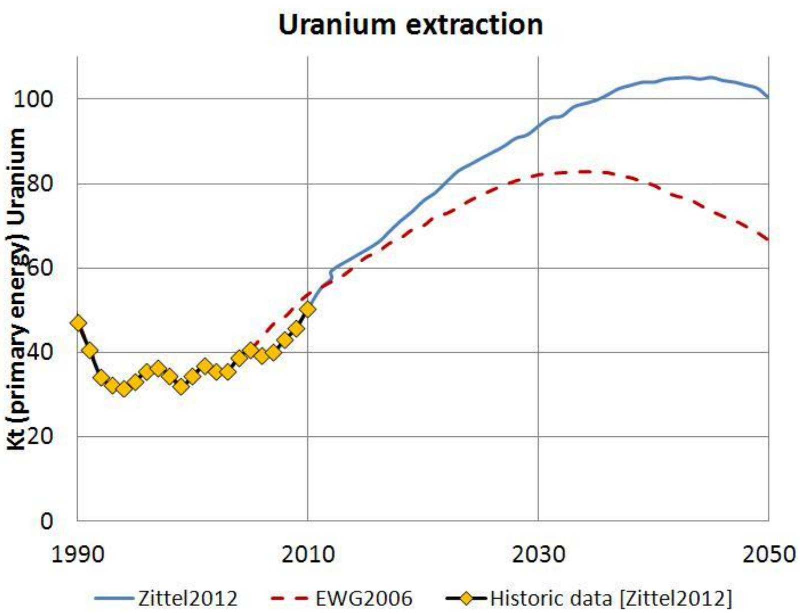


Figure D.5: Estimations of coal extraction by different authors



Notes; energy equivalence of 1 Mt = 0.482 Mtoe from Höök et al., (2010).

Figure D.6: Estimations of uranium extraction by different authors



D.3 Discussion on the techno-ecological potential of renewable energy sources in WoLiM

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

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

On the other hand, in the case of wind, (García-Olivares et al., 2012) do not take into account the wind density power as argued in (de Castro et al., 2011), which reveals more restricted constraints than the material ones.[101]

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

However, (García-Olivares et al., 2012) remains as a very valuable contribution since they demonstrate that even with very generous assumptions the societal and economical challenges to implement the required changes are very large. Thus, the

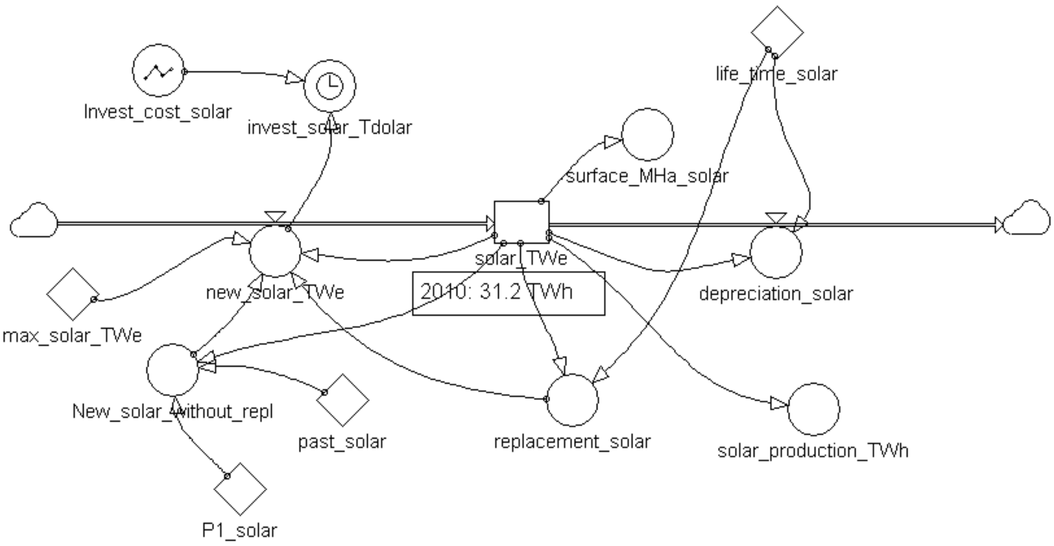
[101] Including continental shelves.

combined findings of (de Castro et al., 2011; García-Olivares et al., 2012; Trainer, 2012) allow to justify that (Jacobson and Delucchi, 2011) proposal is grossly exaggerated.

D.4 Electric renewable energies modelling

The growth of the renewable electricity production from all sources is modelled by a similar structure to the one presented in Figure D.7 for solar. The Forrester diagram shows the stock of renewable electricity infrastructure (**solar_TWe**) with its two flows: the inflow of new infrastructure determined by investments (**new_solar_TWe**), and the outflow determined by the depreciation (**depreciation_solar**) driven by the lifetime (**life_time_solar**).

Figure D.7: Structure of the renewable electric technologies (here, solar)



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

$$\frac{d(solar_{TWe})}{dt} = \text{new\_solar\_TWe} - \text{depreciation\_solar} \quad \textit{eq. D.5}$$

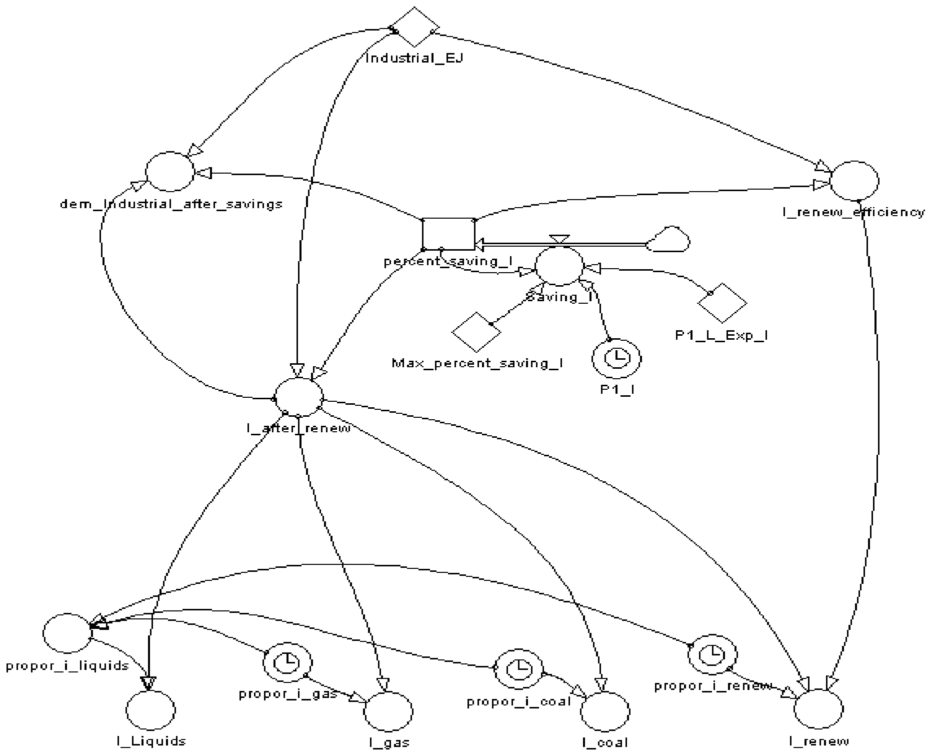
Replacement_solar just compensates for the depreciation rate, and **P1_solar** represents the annual growth considered in each scenario. However, this growth is adjusted to a function that introduces diminishing returns on the new solar power (**new_solar_TWe**) depending on the proximity to the potential (**max_solar_TWe**); creating a feedback loop that reduces the exogenous growth initially set (logistic growth). The model also accounts for the electrical production (**solar_production_TWh**), the land occupied (**surface_MHa_solar**) and the investment required (**invest_solar_Tdolar**).

D.5 Modelling of alternative technologies and saving policies

The policies that represent alternatives to oil, non-electrical renewable energies and savings (biofuels, electric and hybrid vehicle, train, savings and renewable thermal energy for buildings and industry) are described in the model with a similar structure to the one represented in Figure D.8 (savings in the industry sector in this case). The thermal uses of renewable energies are not explicit or assigned to a concrete technology (except for the 3rd generation biomass residues), but modelled as a general policy, in a similar way as done in World3 (Meadows et al., 2004).

In the example of Figure D.8, the total Industrial energy demand (**Industry_EJ**) is calculated in a different part of the model (as a function of GDP and sectoral intensities). The stock variable **percent_saving_I** represents the share to the total Industrial energy demand that is concerned with the transition policies. This variable is a stock because it is assumed that these savings accumulate as the change to better equipment is done. The variable **percent_saving_I** causes a drop in energy demand, and the variables **dem_industrial_after_savings** and **I_after_renew** account for the new demand, which is divided into the demands of individual fuels (**I_gas, I_coal, I_oil, I_renew**) according to a share consistent with the past evolution.

Figure D.8: Forrester diagram of the representation of the Industrial sector and the policies applied



D.6 Potential of bioenergy

The techno-ecological potential estimation of bioenergy depends critically on the future land availability. The foreseeable growth of land for food over the next few decades (due to population and affluence growth) is projected to be 200–750 MHa (Balmford et al., 2005; Bruinsma, 2003; Rockström et al., 2007; Schade and Pimentel, 2010), while the projected growth of new infrastructures because of population and affluence growth is more than 100 MHa. Moreover, it is estimated that current and future crop yields will be affected negatively by climate change (IPCC, 2014d), offsetting potential productivity gains from technological innovation. According to FAOSTAT (2015), there were 1,526 MHa of arable land and permanent crops in 2011. In view of the current situation, in which almost 15% of the world population is undernourished (FAO, 2012), a very large surface for bioenergy at global level is not compatible with future scenarios, such as the ones explored in this paper.

For the sake of simplicity, we decided to divide bioenergy into 3 categories for differentiated uses: traditional biomass, dedicated crops for biofuels and residues for thermal uses (Municipal Solid Waste and 3rd generation). The techno-ecological potential estimation of these categories is a sensitive and complex task: different lands (e.g. current arable vs. marginal) have different productivities, land competition issues, etc. The energy density and potentials assumed for each resource category are presented in Table D.1. These values are based on estimations from (de Castro et al., 2013a; Field et al., 2008; UNEP, 2009, p. 2009; WBGU, 2008) and our assumptions are detailed in (Capellán-Pérez et al., 2014b).

Table D.1: Bioenergy power density and potentials assumed for each resource.

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

Notes: Other potential resources, such as 4th generation biomass (algae), are not considered due to the high uncertainties of the technology and the long-term nature of its eventual commercial appearance (Janda et al., 2012).

NPP: Net Primary Production.

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

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

D.7 Potential of renewable electricity

Techno-ecological potential of renewable energies as estimated by (Capellán-Pérez et al., 2014b; de Castro et al., 2013b, 2011) are shown in **Table D.2**. These limits are lower than some other estimations found in the literature mainly because they consider aspects frequently ignored such as the prorated degradation of the cells over the entire life cycle, maintenance, self-consumption or the real land occupation of the solar parks (not only he panels).

Table D.2: Data of electric renewable in the model

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

Notes: "TW_e" represents power electric production: TWh/8760.

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

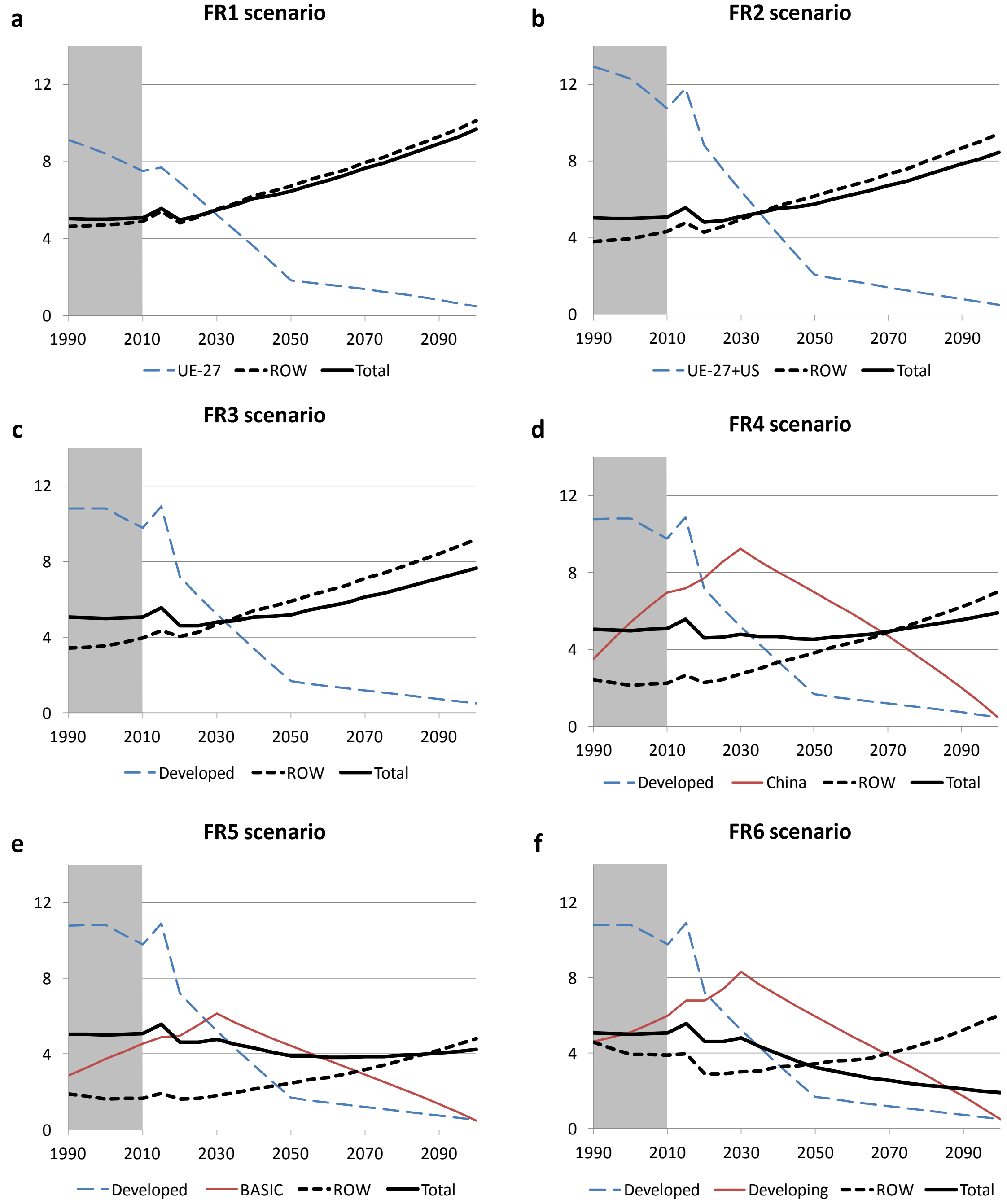
Appendix E. Supplementary material to the Chapter 6

Table E.1: Regional disaggregation of GCAM 4.0 and categorization followed in the chapter

Developed Regions	Developing Regions	Non-Participants
Argentina Australia_NZ Canada EU-12 EU-15 Europe_Non_EU European Free Trade Japan Mexico South Korea Taiwan USA	Brazil Central America and Central Asia China Colombia Europe_Eastern India Indonesia Pakistan South Africa South America_Northern South America_Southern South Asia Southeast Asia	Africa_Eastern Africa_Northern Africa_Southern Africa_Western Middle East Russia

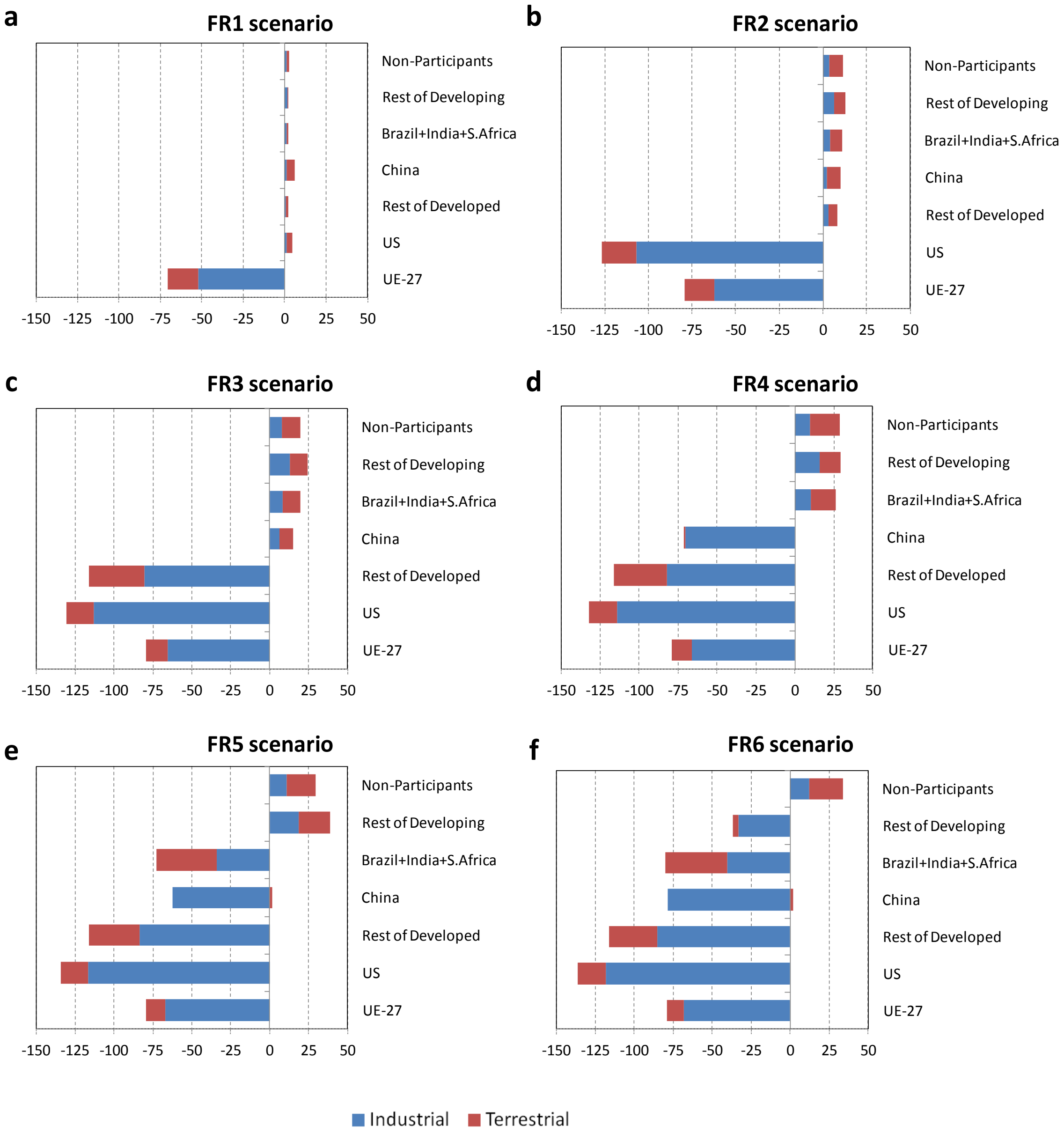
Source: Own elaboration.

Figure E.1: Emissions per capita by region and scenario, 2010-2100 (tCO_2)



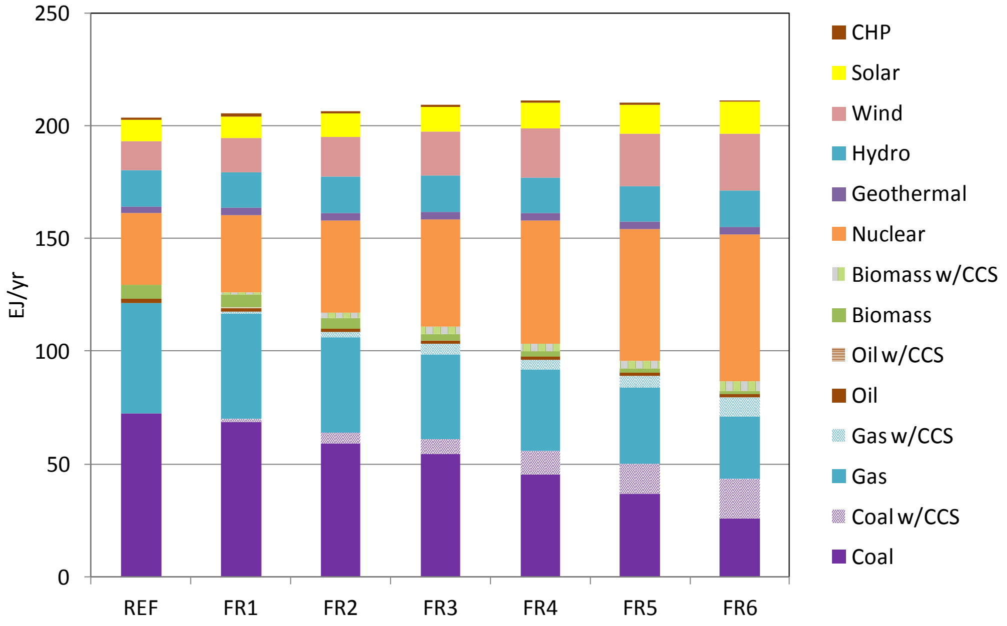
Source: Own elaboration.

Figure E.2: Carbon leakage by regions and scenarios, 2010-2050 ($GtCO_2$)



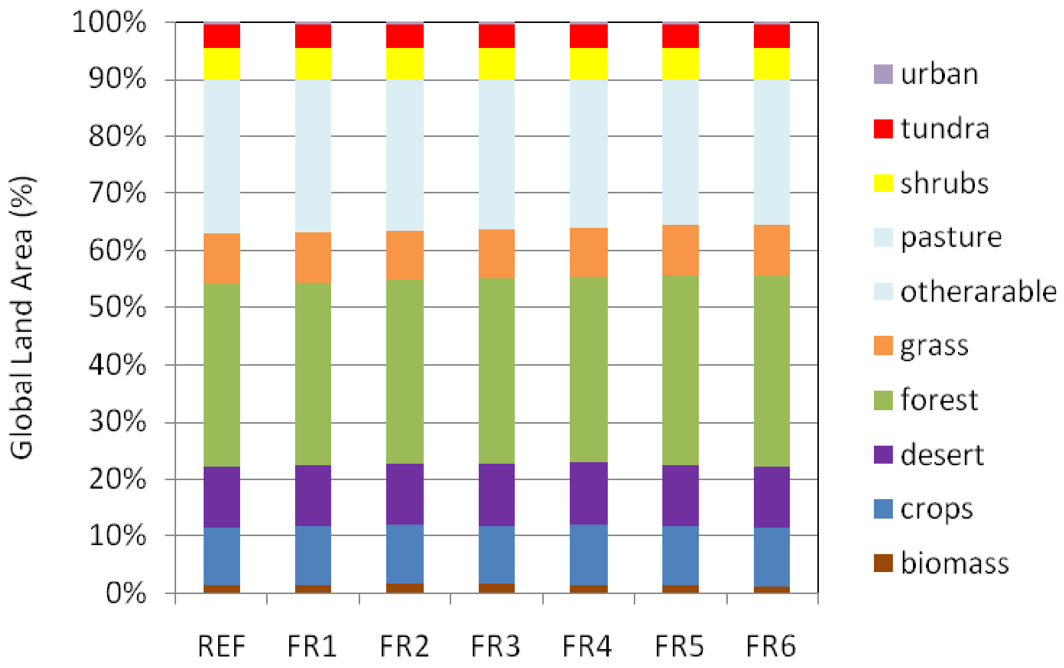
Source: Own elaboration.

Figure E.3: Global electricity consumption in 2050 by technologies (EJ/yr)



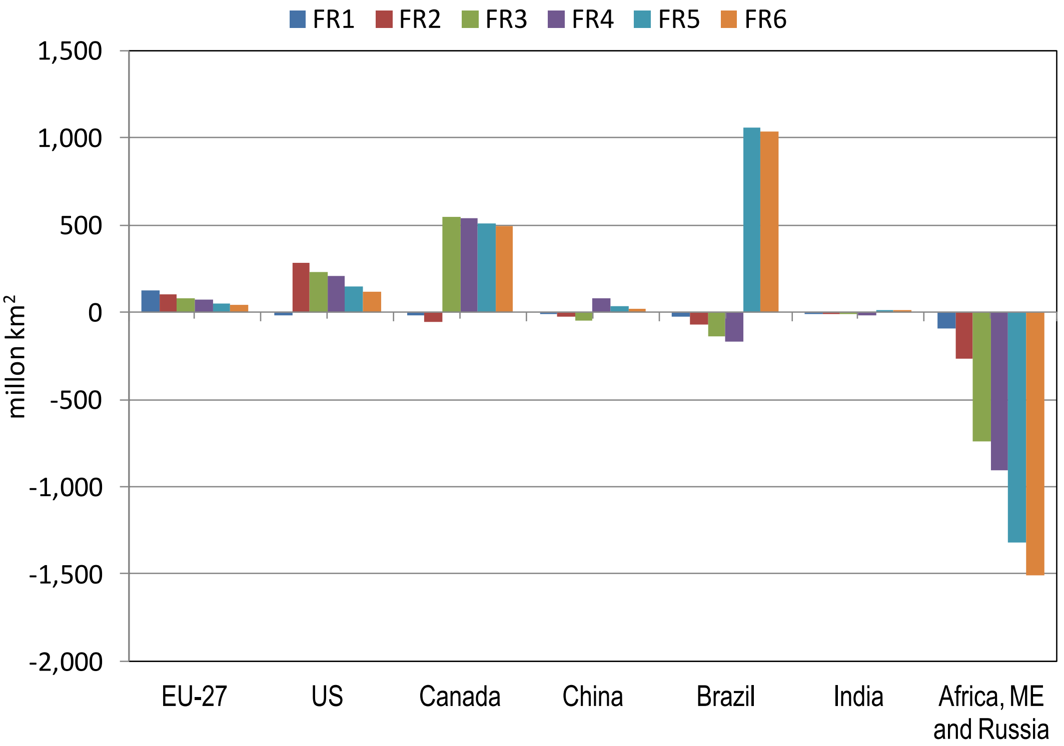
Source: Own elaboration.

Figure E.4: Global land use area in 2050 by scenario (%)



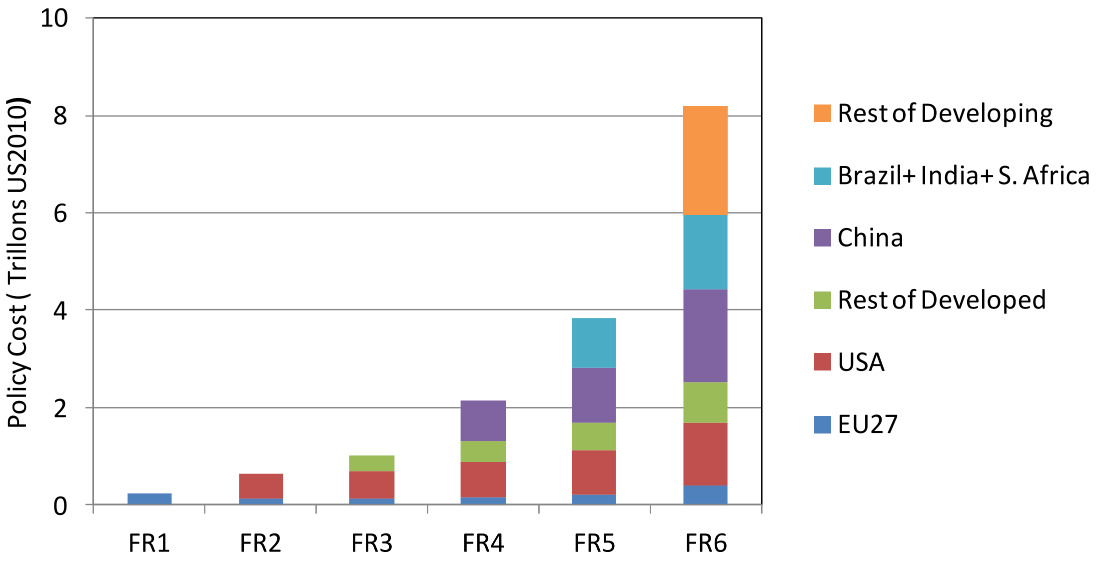
Source: Own elaboration.

Figure E.5: Change in forest area by regions for each scenario compared to REF in 2050 (in Mkm²)



Source: Own elaboration.

Figure E.6: Policy costs for the different scenarios in 2100 (Trillion 2010$)



Source: Own elaboration.

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