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New climate scenario framework implementation in the GCAM integrated assessment model

Iñigo Capellán-Pérez*[a], Mikel González-Eguino[b,c], Iñaki Arto[b], Alberto Ansuategi[a,c], Kishore Dhavala[b], Pralit Patel[d], Anil Markandya[b,e]

This report has various objectives: (i) to provide an overview of the climate Integrated Assessment approach; (ii) to describe the Global Climate Assessment Model (GCAM); (iii) to outline the new IPCC scenario framework represented by the Shared Socio-economic Pathways (SSPs) and the Representative Concentration Pathways (RCPs); and (iv) to document the implementation of the new scenario framework in version 3.1 of the GCAM. The GCAM baseline is thus calibrated to the "Middle of the Road" or SSP2 scenario using the data calculated by the OECD. The implications of this scenario are important because it will probably become a standard scenario among the research community. The exogenous variables, the implications for income convergence and the results in terms of energy mix, emissions, temperature and radiative forcing of SSP2 implementation in the GCAM are presented at both global and regional levels. These results are also compared with the GCAM-Reference baseline and the IPCC SRES representative scenarios. Then the feasibility, cost and implications of a climate policy that seeks to stabilize temperature at 2ºC (2.6 W/m^2 RCP) using a global uniform carbon tax are analyzed. The study is completed by a decomposition analysis that enables the main driving factors of CO_2 variation to be identified, including population, affluence, energy intensity, carbon intensity and fossil-fuel share of the energy mix. Finally we draw some conclusions and highlight points for further research.

Keywords: SSPs, Integrated Assessment Model, long-run projections, energy systems, climate stabilization.

JEL classification: Q4, Q47, Q54

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1. Introduction

As stated in the Cancun Agreements, the objective of stabilizing climate change *"at a level that would prevent dangerous anthropogenic interference with the climate system"* (UNFCCC, 1992) is that the global average temperature should not rise more than 2ºC above pre-industrial levels. According to the Intergovernmental Panel on Climate Change (IPCC), for this objective to be met global greenhouse gas (GHG) emissions would have to peak before 2015, and drop by 50-85% in 2050 (compared to the emission levels in the year 2000) and would need to be zero or even negative by 2100 (IPCC, 2007a, p. 39). Therefore, meeting low climate stabilization targets will require a profound, coordinated transformation of energy systems all over the world.

Analyzing the long-term implications of climate stabilization is a complex task, as it involves many uncertainties. One major source of uncertainty is the fact that climate, energy and economic policies are designed on different time scales. The relevant time scale for climate policy analysis is usually 50-100 years (IPCC, 2007a), or even longer if slow feedback effects are considered (see, e.g. (Hansen et al., 2008)). The time frame for energy policy analysis is usually closer to the lifespan of most energy infrastructures, which does not go beyond 30-50 years (WEO, 2012). In the case of economic projections, "long-term" means time-frames of up to a decade (IMF, 2013). Clearly, our ability to understand and project future trends in complex processes such as population dynamics, economic growth, technological change, climate sensitivity and human behavior is limited. Uncertainty, non-linear relationships, and cross-scale interactions make the system more complex. Scenario development is an approach to dealing with these issues that has been widely used in recent years in Global Environmental Assessments (van Vuuren et al., 2012).

The scenario framework used for long-term climate policy by many scientists and research groups over the past ten years is contained in the Special Report on Emissions Scenarios (IPCC SRES, 2000). The SRES scenarios are "baseline" (or "reference") scenarios, which means that they are not meant to represent any current or future climate policy but are used as a reference for future projections of the impact of climate change (and other) policies. The framework comprises four families of scenarios (A1, A2, B1 and B2) with 40 specific scenarios, each of which makes different assumptions about the main driving forces such as economic growth, population growth, technological development and energy and land use up to 2100.

However, in 2006 the IPCC decided to change the approach due to: (1) the need for more detailed information to run the current generation of climate models; (2) increasing interest in scenarios that explicitly explore the impact of different climate policies; and (3) the advisability of simultaneously exploring the role of mitigation and adaptation (Kriegler et al., 2012; Moss et al., 2010). It was also decided that such scenarios would not be developed as part of the IPCC process, but that new scenario development would be left up to the research community. A process of three phases was subsequently designed: first, the development of a scenario set containing emission, concentration and land-use trajectories—referred to as "Representative Concentration Pathways" (RCPs); second, a development phase with the climate model runs and development of new socio-economic scenarios ("Shared Socioeconomic Pathways", SSPs); and, finally, an integration and dissemination phase (Moss et al., 2010).

In this new process four main RCPs (2.6, 4.5, 6.0 and 8.5 W/m^2) have been developed (van Vuuren et al., 2011a) that are to be integrated with the new socio-economic scenarios (SSP1 to SSP5). Thus, climate Integrated Assessment (IA) models and RCPs can be used to conduct climate experiments and, in parallel, to explore a range of combinations of economic, technological, demographic, policy, and institutional futures and their implications in terms of radiative forcing. Recently, the research community has developed new qualitative storylines for SSPs, taking into consideration that those scenarios should guide RCP-based mitigation, adaptation and impact analyses (O'Neill, 2012; van Vuuren et al., 2012). There is also a cooperation project between three leading institutions (PIK, IIASA and OECD) which is providing the quantitative data for drivers that support SSP storylines using common assumptions (Chateau and Dellink, 2012).

This report documents the implementation of the new SSP framework in the GCAM[1] IA model to analyze climate, economic and energy-related long term implications of climate stabilization policies. The model is calibrated to the most standard storyline of SSP: the "Middle of the Road" or SSP2 scenario, using data calculated recently by the OECD (Chateau and Dellink, 2012). The implications of this scenario are important because it will probably become a standard scenario among the research community. The exogenous variables, the implications for income convergence and the results in terms of energy mix, energy prices, emissions, temperature and radiative forcing are presented and explained at global and regional levels. These results (GCAM-SSP2 baseline) are also compared with the GCAM-Reference baseline and the IPCC SRES framework. Finally, the feasibility, cost and global and regional implications of a climate policy that seeks to stabilize temperature within 2ºC (2.6 RCP) using a global uniform carbon tax is analyzed. The study is completed by a decomposition analysis that enables the main driving factors of CO_2 variation to be identified from among the following: population, affluence, energy intensity, carbon intensity and fossil-fuel share of the energy mix.

The rest of the paper is organized as follows: Sections 2 and 3 provide an overview of the climate IAM approach and of the GCAM model, respectively. Section 4 describes the new SSP framework and Sect. 5 presents the assumptions used to quantify the SSPs. The results obtained from the calibration of the GCAM model with the "Middle of the Road" scenario (SSP2) are presented in Sect. 6.1, and Sect. 6.2 analyses the implications of the 2.6 RCP climate policy. Section 7 critically discusses the results and, finally, Sect. 8 draws some conclusions and outlines paths for future work.

2. Climate integrated assessment modeling

Integrated (Environmental) Assessment Modeling (IAM) refers, in general, to any type of analysis that crosses boundaries of multiple disciplines in order to capture interactions between human and natural systems. These relationships tend to be complex, dynamic and non-linear. The central element in IAM of climate change is the climate focused economy-energy-environment (E3) IA model, although the whole IAM process should not be reduced to that model. In fact, as depicted in Fig. 1, IAM also includes the definition of the problem, the formulation of policy questions and the interpretation and communication of results (IPCC SRES, 2000; IPCC, 1995a; Kriegler et al., 2012; MEA, 2005; Schwartz, 2003; Tol, 2006). Integrated Assessment (IA) is neither new as a concept nor restricted to climate change, although the proliferation of models in the last two decades is mainly due to its application to climate research (Tol, 2006). This section offers a short overview of climate IAM.[2]

IAM and IA models started to be developed in the early 1970s with the pioneer WORLD3 model used for the "Limits to Growth" report (Meadows et al., 2004, 1972; Mesarović and Pestel, 1974), which studied the world evolution of human societies focusing on resource availability, biosphere limits and sustainability. A new discipline was born and before the end of that decade the

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[1] 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 was developed at the Joint Global Change Research Institute and has been selected by the IPCC to represent the 4.5 RCP (Thomson et al., 2011).

[2] Arigoni and Markandya, 2009; Hedenus et al., 2013; Hourcade et al., 2006; Schneider and Lane, 2005; Stanton et al., 2009; Tol, 2006 offer comprehensive surveys of this area.

first IA model linking energy conversion, emissions and atmospheric CO_2 concentration appeared (Nordhaus, 1979). In the 80s, the capacity of human societies to create ecological problems at regional and global scale became obvious (e.g. ozone depletion, chemical pollution, acid rain, etc.), stimulating concerns on the part of people, governments and, therefore, researchers: specific IA models were then applied to regional and global pollution problems, such as the RAINS model, which focused on acid rain (Alcamo et al., 1990). In the 1990s, 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. Thus, six different models[3] were developed that took part in the (IPCC SRES, 2000) scenarios: AIM (Morita et al., 1994), ASF (Lashof et al., 1989), IMAGE (Alcamo et al., 1998), MARIA (Mori and Takahashi, 1998), MESSAGE (Messner and Strubegger, 1995) and MiniCAM (Edmonds et al., 1994).

Figure 1a illustrates an idealistic, fully-integrated IAM approach for climate change analysis. The figure shows different relations and feedbacks between the four main sub-models: (1) human activities; (2) atmospheric composition; (3) climate; and (4) ecosystems. In short, human activity leads to GHG emissions, which affect atmospheric GHG concentrations and alter the climate system. Climatic change has an impact on ecosystems and also on human activities, which in turn are capable of adapting to these environmental changes.

However, in reality, until now the sequential approach (Figure 1b) has been extensively used instead of the full-scale integration models (Figure 1a). 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 climate change impacts (Arigoni and Markandya, 2009; Lenton and Ciscar, 2013), delays between the IA model calculations and the impact and adaptation assessments, dominant perceptions (e.g. idealized assumptions about the resilience of ecosystems (Cumming et al., 2005)), etc. (Hibbard et al., 2010; 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.

The diversity of climate IA models[4] is due to the different approaches used by modelers striving to capture the complex interactions and high uncertainties involved in the climate/economy/society interface. IA models 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, depending on the characteristics on which the categorization focuses. Also, 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 IA models (Arigoni and Markandya, 2009; Hourcade et al., 2006; IPCC, 2007a; Stanton et al., 2009).

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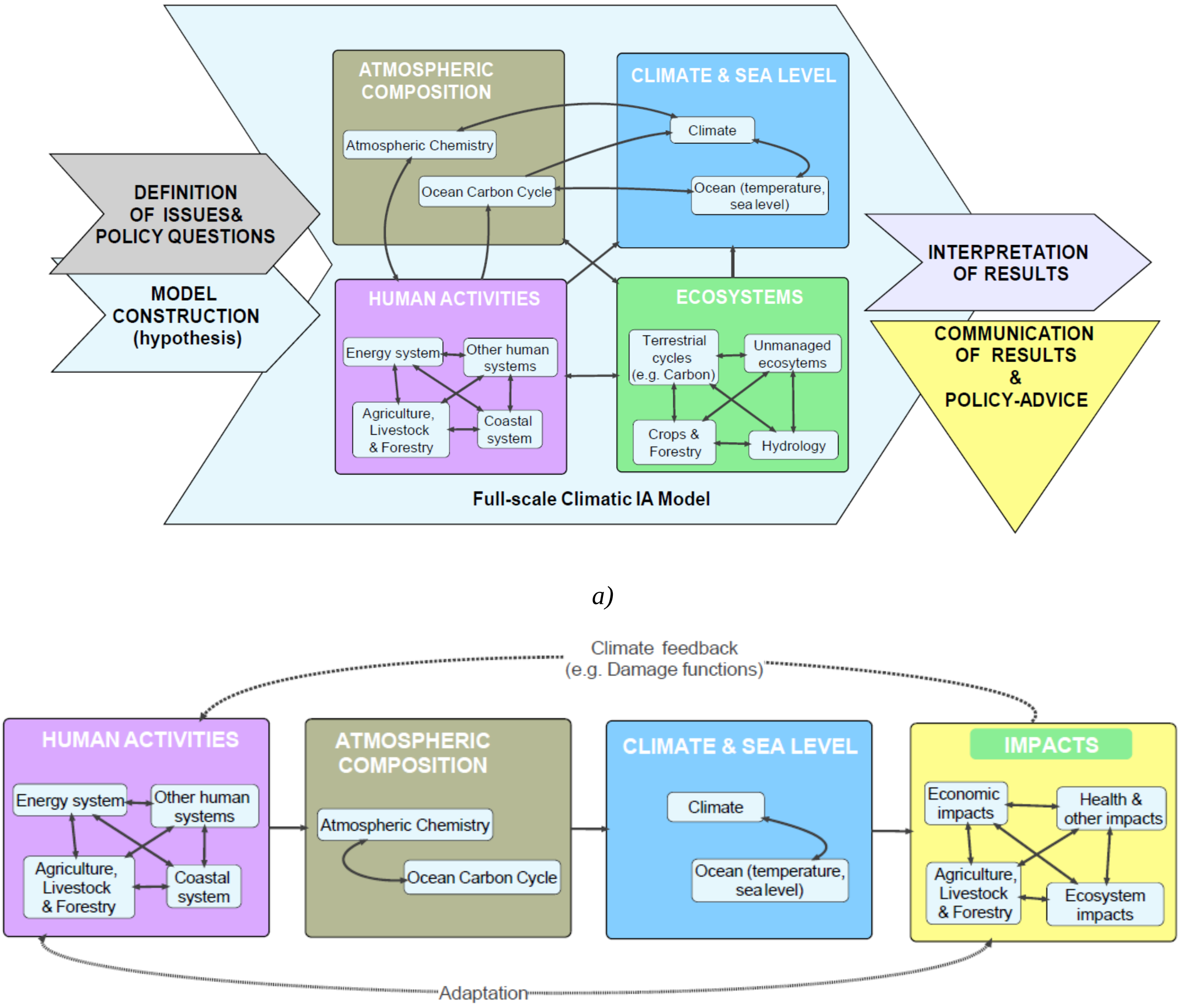
[3] Annex IV of (IPCC SRES, 2000) discusses these six modeling approaches in detail.

[4] It is difficult to estimate the exact number of climate IA models generated by the research community, since many models offer versions with slightly different characteristics. However, note that (IPCC, 1995a) overviewed more than 20 different models and a recent paper assesses 30 IAMs in terms of four key characteristics of the nexus of climate and the economy (Stanton et al., 2009).



a)

b)

Figure 1: a) Full-scale Integrated Assessment Model as an element of the IA modeling process; b) Sequential characterization of IAMs. In practice, IA models usually focus on the interactions between processes and systems within the "Human Activities" box of Error! Reference source not found.*b, including the energy system, the agriculture, livestock and forestry system, the coastal system, and the other human systems. These interactions would not be available through a purely discipline-based approach. Then the effects of human activities on the composition of the atmosphere are analyzed, as are the subsequent repercussions on climate and sea levels. Finally, the impacts of climate change on human and ecosystems and the different adaptation strategies and climate feedbacks can be assessed.*

The III Working Group of the IPCC (IPCC, 1995a) proposed 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). Policy-evaluation models take a small set of policies and assess the consequences of these policies. 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.

Another useful distinction, traditionally used to classify Economy-Energy models, refers to the degree of detail in the description of the energy system included in the models. Thus, top-down (TD) and bottom-up (BU) models are the two basic approaches to examining, the linkages between the economy and specific GHG emitting sectors, such as the energy system. TD models evaluate the system from a macroeconomic perspective, addressing the consequences of policies in terms of public finances, trade, economic competitiveness, and employment. On the other hand, BU models describe in detail the current and prospective competition of technological options and project-specific climate change mitigation policies. 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 (Tavoni et al., 2014).

Different methods have been applied to develop more hybrid model constructions in order to offset the limitations of each approach. One option is the coupling of existing bottom-up and top-down models (e.g. BU MARKAL with TD MIT-EPPA or BU MESSAGE with TD MACRO) so as to use the advantages of both approaches. However, there are many theoretical and computational difficulties associated with such coupling (see for example (Burniaux and Truong, 2002). Other options are to build a hybrid model directly (e.g. E3MG, IMACLIM models, WITCH, MIND) and to modify former conventional BU or TD models in order to "hybridize" them by *i)* coupling a BU macroeconomic model with an energy model (e.g. MIT-EPPA, MERGE); and *ii)* coupling an energy model with a partial representation of the economy (e.g. MiniCAM/GCAM, POLES). In the case of AIM, a whole family of models covering most categories has been developed (Kainuma, 2003).

In short, two things should be noted: firstly that each of these modeling approaches has its own strengths and weaknesses,[5] and secondly that different policy questions require different perspectives and, therefore, different modeling approaches. The following section starts with a description of the IA model used in our analysis: the Global Change Assessment Model (GCAM). This model, recently released with Community support,[6] regularly appears in comparisons between models (such as the Energy Modeling Forum (Clarke and Weyant, 2009)) and IPCC Assessments, and will also participate in the AR5.

3. The GCAM model

The Global Change Assessment Model (GCAM) is a climate IA model 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).[7] 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 Fig. 2). In terms of the categories described in the previous section, GCAM could be categorized as a "bottom-up policy-optimization" model.

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[5] 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. This is colloquially referred to as the "Holy Grail". The different model structures provide results that inform climate and development policy in very different ways, e.g. 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 behavior 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)

[6] Community tools include a Mailing List for GCAM users (https://listserv.umd.edu/cgi-bin/wa?A0=GCAM-COMMUNITY) and a wiki where the latest updates are documented: http://wiki.umd.edu/gcam/index.php?title=Main_Page.

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

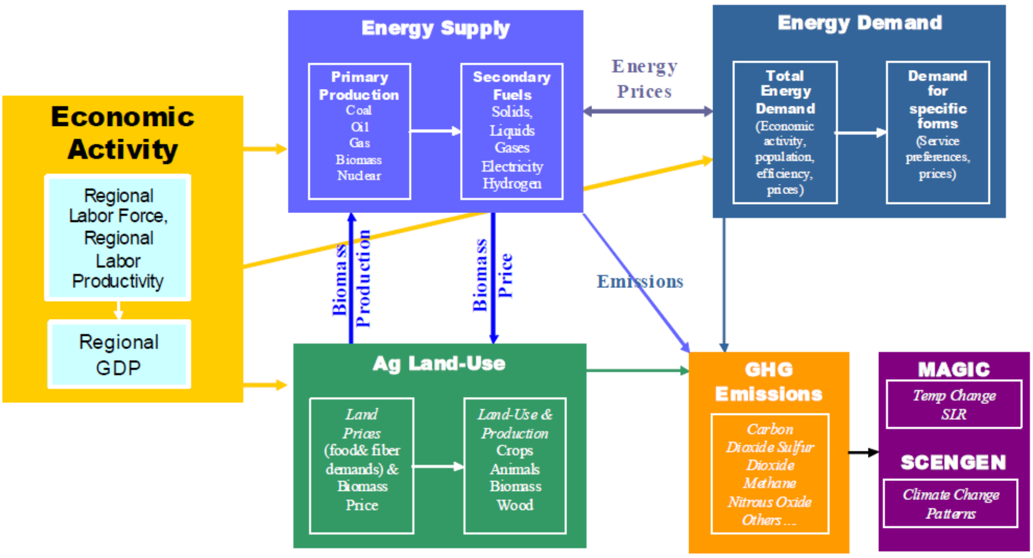

Figure 2 (Wise et al., 2009): Elements of the GCAM Integrated Assessment Modeling Framework

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 modeling 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).

GCAM is a dynamic recursive economic partial-equilibrium[8] model driven by assumptions about population size and labor productivity that determine potential gross domestic product in market exchange rates (GDP MER)[9] in each of 14 geopolitical regions[10] at 5 (or 15) 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. 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 2095 (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

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[8] Thus, GCAM has no explicit markets for labor and capital and there are no constraints such as balance of payments.

[9] Although GDP input is in market exchange rate, a procedure for converting it to purchasing power parity (PPP) values is set up, assuming that when income in currently non-developed countries reaches a threshold, markets are integrated enough for the PPP/MER differences to be small. For a detailed overview and justification of the method used see (Smith et al., 2005).

[10] The United States, 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. However, the idea is to increase the number of regions to 30: http://www.globalchange.umd.edu/data/gcam/2012/Future_Directions_in_GCAM_Development_2012-09-18.pdf.

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)[11] 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 N2O and CH4, 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; Wise and Calvin, 2011; Wise et al., 2009).

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 greenhouse gases and short-lived species[12] 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 Fig. 1b 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., 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 Modeling Forum (Clarke and Weyant, 2009). It is also a member of the Steering Committee of the Integrated Assessment Modeling Consortium

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[11] See http://wiki.umd.edu/gcam/index.php/Resource_Supply_Curves.

[12] Including: CO2, CH4, N2O, NOx, VOCs, CO, SO2, carbonaceous aerosols, HFCs, PFCs, NH3, and SF6.

(http://www.iamconsortium.org). 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, 2007b, 2001a, 1995b, 1992, 1990a) – where they will also be used in the 5th report (Moss et al., 2010) - and for research and policy analysis by national governments and other stakeholders (Clarke et al., 2007).

Finally, GCAM is a model in constant evolution. This brief presentation refers to version GCAM 3.1.[13] 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, more GCAM regions, etc.[14] This changes and updates are usually documented first in the ("GCAM wiki," 2013), which researchers are advised to consult when working with GCAM. A selected set of GCAM papers and reports is also available at http://wiki.umd.edu/gcam/index.php?title=References.

4. The new IPCC scenario framework: SSPs and RCPs

Projecting the future is not an easy task, especially for climate change, where very long-term projections are needed due to the planet's high thermal inertia. Scenario analysis offers an approach for dealing with unavoidable uncertainties,[15] at least in an internally consistent framework. Each scenario is a "storyline" that seeks to represent an archetypical vision of the future that includes the dominant driving forces: Worlds that evolve gradually, shaped by current driving forces; worlds that are influenced by a strong policy push for sustainability goals; worlds that succumb to fragmentation, environmental collapse, and institutional failure; and worlds where new human values and forms of development emerge which may be viewed positively by some people and negatively by others (IPCC SRES, 2000; MEA, 2005; Moss et al., 2010). Normally, one of these storylines is identified as a Baseline/Reference scenario, usually intended to project Business-As-Usual (BAU) behavior, and compared with a scenario that includes different policy interventions (van Vuuren et al., 2012).

Because of the complex, global nature of the climate change problem and the need for strong political intervention to promote policies for facing it, the IPCC's emission scenarios are hybrid constructs that result from extensive construction and negotiation processes between scientists and governmental agents. From the SA90 series (IPCC, 1990b) to SRES (IPCC SRES, 2000) and the new SSPs to be used for the AR5 report in 2014, there have been significant changes in some aspects while others have remained unchanged, for both scientific and political reasons (Girod et al., 2009; Tol, 2011). A brief overview of the evolution of the IPCC's emission scenarios is given in the Appendix B from (Capellán-Pérez et al., 2014).

Socioeconomic scenarios have a long history,[16] as mentioned in Sect. 2. The scenario framework used for long-term climate policy in the last decade has been mainly based on the Special Report on Emissions Scenarios (IPCC SRES, 2000). The SRES scenarios are "baseline" (or "reference") scenarios, which mean that they do not take into account any current or future climate policy. The framework comprises four main scenario groups or categories (A1, A2, B1 and B2: in terms of "global vs. regional" and "economic vs. "environmental") and 40 specific scenarios.

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[13] http://www.globalchange.umd.edu/models/gcam/download/

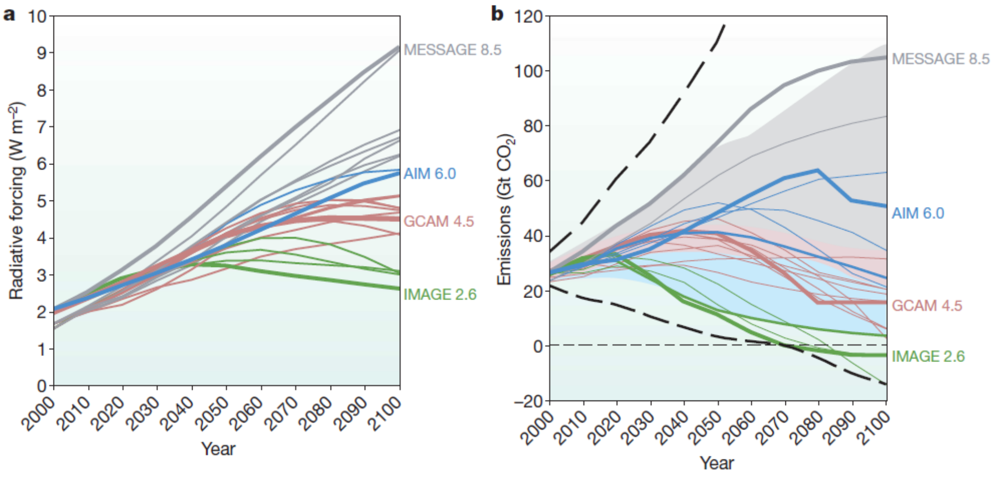
[14] http://www.globalchange.umd.edu/data/gcam/2012/Future_Directions_in_GCAM_Development_2012-09-18.pdf

[15] Raskin et al. (2002) distinguish 3 different sources of uncertainty: ignorance, "surprises" and volition (the future is subject to human choices that have not yet been made).

[16] For a more extensive discussion about socioeconomic scenarios prior to 1995, see (MEA, 2005), and for the period 2000-08 see (Van Vuuren et al., 2012).

However, unlike the previous editions and after having used the same emission scenario (IPCC SRES, 2000) for 2 consecutive reports (IPCC, 2007b, 2001b), the IPCC decided in 2006 not to commission another set of emission scenarios but to leave new scenario development up to the research community. This new framework includes such significant changes as the redesign of scenario process development from the current sequential process to a parallel approach and the consideration of intervention scenarios for exploring different approaches of mitigation and adaptation (Moss et al., 2010). Hitherto, scenarios have been developed and applied sequentially or linearly: from socioeconomic factors to greenhouse gas emissions to atmospheric and climate processes and to impacts. This process leads to inconsistency because of delays between the development of the emission scenarios, their use in climate modeling, and the availability of the resulting climate scenarios for impact research and assessment.[17] The new parallel approach makes for better collaboration between IA researchers and impact, adaptation and vulnerability assessment researchers.

With the new scenario framework the RCP -Representative Concentration Pathways- scenarios (containing emission, concentration and land-use trajectories) are not necessary linked to the SSPs -Shared Socioeconomic Pathways- (containing different technological, socio-economic and policy trajectories). Four models have been selected to represent the four main RCPs[18] (2.6, 4.5, 6.0 and 8.5 W/m^2, see Fig. 3) and it is left up to the research community to determine the SSPs and their links with RCPs. Interestingly, these concentration pathways lead to radiative forcing values that span a broader range than that of the SRES scenarios (Meinshausen et al., 2011). In this way climate models and impact, adaptation and vulnerability studies can use RCPs and, at the same time, IA models can explore the implications of different SSPs (Kriegler et al., 2012).



(a) *(b)*

Figure 3 (Moss et al., 2010): Representative concentration pathways: (a) Changes in radiative forcing relative to pre-industrial conditions. Bold colored lines show the four RCPs; thin lines show individual scenarios from approximately 30 candidate RCP scenarios that provide information on all key factors affecting radiative forcing; (b), Energy and industry CO$_2$ emissions for the RCP candidates. The range of emissions in the post-SRES literature is presented for the maximum and minimum (thick dashed curve) and 10th to 90th percentiles (shaded area). The blue shaded area shows mitigation scenarios; the grey shaded area shows baseline scenarios; the pink area shows the overlap between reference and mitigation scenarios

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[17] For example, there was a delay of 10 years between the beginning of the development of (IPCC SRES, 2000) scenarios and the first assessment of impacts in (IPCC, 2007b).

[18] The GCAM model was selected to represent the 4.5 RCP scenario. For a detailed overview of the RCP building process, see the dedicated paper by (van Vuuren et al., 2011a).

The different SSP storylines are described in (O'Neill, 2012). These storylines are constructed around two axes: challenges to mitigation and challenges to adaptation, as illustrated in Fig. 4, resulting in five different storylines that show different trends in key dimensions (such as Demographics, Economy and Lifestyles, Policies and Institutions, Technology, Environment & Natural resources). These are the storylines of each SSP scenario:

- **SSP1 (or "Sustainability''):** the challenges for adaptation and mitigation are low, as relatively rapid income growth is combined with substantially reduced reliance on natural resources. This is achieved at least in part through quick technological change and high levels of international cooperation. High levels of education induce lower fertility rates and smaller populations. Consequently, global emission levels are relatively low compared to most of the other scenarios.

- **SSP2 (or "Middle of the Road'')**: current trends continue, with moderate progress on income convergence. Some emerging economies catch up relatively quickly whereas growth is much slower in the least-developed countries, at least in the first decades. Global emissions are projected to follow business-as-usual trends. There are substantial challenges for mitigation and adaptation, but neither is particularly severe.

- **SSP3 (or "Fragmentation'')**: economic growth is assumed to be much slower due to a combination of multiple causes: lack of international cooperation, slow technological progress, low education levels and high population growth. A failure to develop clean technologies implies high global emission levels and thus severe mitigation challenges. The low income levels in developing countries, in turn, imply severe challenges to adaptation.

- **SSP4 (or "Inequality''):** high-income countries use technological advances to stimulate economic growth; leading to a high capability to mitigate. In contrast, developments in low income countries are hampered by very low education levels and international barriers to trade. These limit economic growth rates to rather low levels, implying low levels of per capita income and high challenges for adaptation.

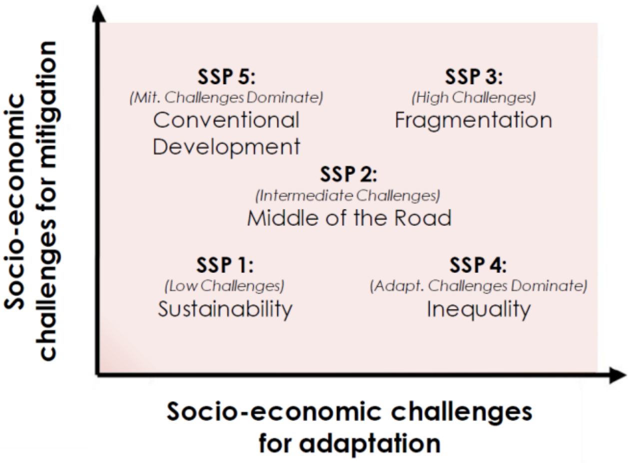

Figure 4 (O'Neill, 2012): Five SSPs for which basic narratives have been developed around two axes: challenges to mitigation and challenges to adaptation.

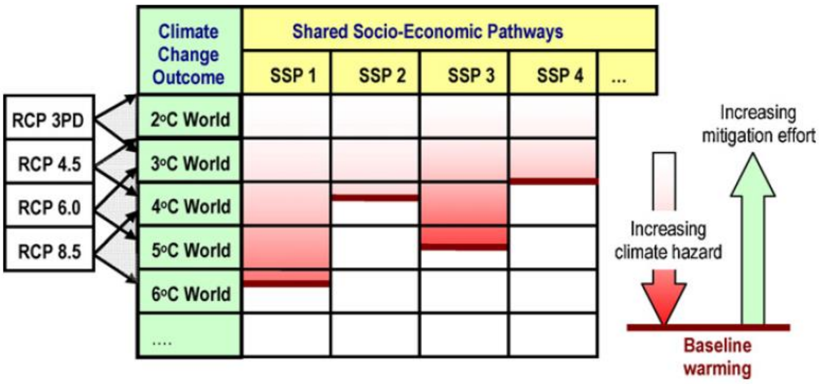

Figure 5 (Kriegler et al., 2012): Matrix of socio-economic ''reference'' developments (characterized by shared socio-economic pathways, SSPs) and climate change outcomes (determined by representative concentration pathways, RCPs). White cells indicate that not all combinations of shared socio-economic pathways and climate change outcomes may provide a consistent scenario.

- **SSP5 (or "Conventional Development'')**: countries put full focus on economic development, regardless of the environmental consequences. For the high-income countries this means an emphasis on advanced technologies, whereas many developing countries increase their demand for fossil energy sources. Although major improvements in education levels reduce fertility rates (inducing the emergence of relatively small, well-educated populations at global level), this economic development leads to high global emissions and high challenges to mitigation. On the other hand, increased income levels in the most vulnerable regions make for relatively low adaptation challenges.

One important, novel aspect of the SSP framework is that it meaningfully integrates each different scenario with the two main challenges for climate policy: mitigation and adaptation (see Fig. 5). Each cell of the matrix represents a particular combination of climate change outcomes and socio-economic assumptions, and hence it can be seen as containing the results of the associated mitigation policies. Each row of the matrix can be thought of as a summary of the implications of a given level of climate change on a range of possible future socioeconomic conditions. Each column can be thought of as describing the implications of increasing levels of climate change, or decreasing levels of mitigation effort through policy-intervention[19] for a given set of socio-economic conditions (Kriegler et al., 2012).

5. Quantification of the different SSP

The SSP framework proposed and explained in the previous section merely provides storylines of possible futures. Researchers are now producing quantitative data to interpret those qualitative scenarios. Currently, there is a common project by the Organization for Economic Cooperation and Development (OECD), the International Institute for Applied Systems Analysis (IIASA) and the Potsdam Institute for Climate Impact Research (PIK) to produce quantitative scenarios for the

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[19] As far as policy intervention is concerned (Kriegler et al. 2012) a new framework is also set up: "Shared climate Policy Assumption'' scenarios or SPAs. SPAs have three components: 1) Policy objective: RCP level or similar (e.g. temperature, GHG budget); 2) Policy instruments & measures (e.g. CO_2 and energy taxes, cap & trade, regulatory approaches); and 3) Implementation obstacles & market distortions (e.g. regional and sectoral fragmentation, trade barriers, technology failure).

world.[20] For population and urbanization, all three institutions are using the same data provided by IIASA and the National Centre for Atmospheric Research (NCAR). Even though the GDP projections are also based on harmonized assumptions (convergence speed, technological change, trade openness, etc.), they still differ at global and regional levels. The SSP database generated is publicly available.[21]

In this section we present the data provided by the OECD to compare the different SSP scenarios, because the methodology applied is very well documented. The OECD quantifies SSPs using the *ENV-Growth model (*Chateau and Dellink 2012), a neoclassical economic growth model based on the "conditional growth" hypothesis (Duval and de la Maisonneuve, 2010) that also includes energy, as both a production input and a generator of resource revenues for oil and gas producing countries. The model is based on the long-term projections of five key drivers of economic growth: (i) physical capital; (ii) employment as driven by demographic trends, labor participation rates and unemployment scenarios; (iii) human capital, as driven by education; (iv) energy demand, as driven by energy efficiency; (v) the patterns of extraction and processing of natural resources (oil and gas); and (vi) the total factor productivity (TFP) as an indicator of exogenous technical progress (for the main equations of the production function, see Annex I in (Chateau and Dellink, 2012)). The continuous improvement in *TFP* leads to more efficient production as more output can be created with the same combination of primary factors: capital and labor and, in the case of the ENV-Growth model, natural resources. Specifically, the *ENV-Growth* model features additional input-specific factor productivity for labor and energy demand. That is, human capital developments (through education) increase labor productivity, while autonomous energy efficiency increases the productivity of energy inputs (Chateau and Dellink, 2012).

Figure 6 shows a summary of the key variables for the different SSP scenarios. Population (see Fig. 6a) is developed by IIASA and is close to the "World Population Prospects" published by the United Nations (UN, 2011). SSP2 and SSP4 are quite close to the UN's "Medium Variant" scenario, SSP3 is lower than the "High Variant" and SSP1 and SSP5 are slightly higher than the "Low Variant" scenario.

The global GDP PPP level at the end of the century varies from around 2005US$ 350 trillion in scenario SSP3 to $1000 trillion in SSP5 (Fig. 6b). SSP3 projects a global GDP increase of 4 times the 2010 level by 2100 SSP5 of 15 times that level. Scenario SSP2 shows an intermediate GDP projection of over $530 trillion in 2100 (an 8-fold increase). Sustained growth in GDP per capita is necessary in order to attain these levels (see Fig. 6c). All scenarios begin in 2010 from around 3% growth[22] and stabilize at the end of the century at different rates of between around 0.5% (SSP3) and 2% (SSP5) growth.

In terms of convergence, all the SSP scenarios forecast a positive evolution at regional level. Fig. 6d illustrates the distribution of countries ranked by per capita income in 2010 and 2100. The line for 2010 indicates a high degree of income inequality, with income levels in most countries below US$7500, and less than 10% of countries with income levels above US$35,000. In all scenarios except SSP3, by 2100 per capita income levels in more than half of the countries covered by the analysis will exceed (sometimes by far) the current US income (about US$42,000). The degree of inequality in SSP4 is highlighted in the figure by the sizeable gap between the first and third quartiles (i.e. the poorest countries and the relatively rich, respectively) and by how it crosses SSP2 (indicating

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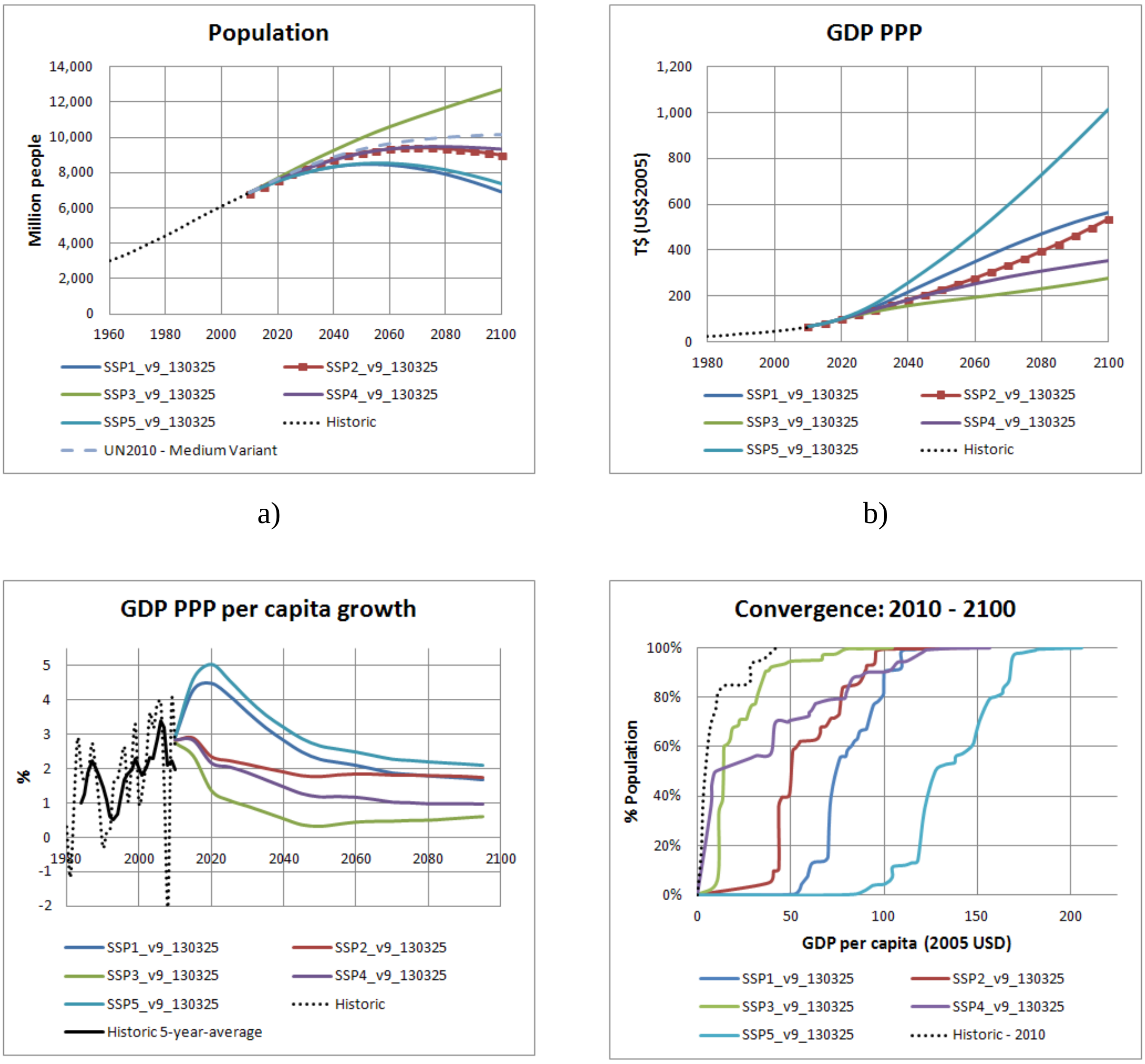
[20] At the date of this report (March 2014) this collaboration project has not yet been completed. Thus, the comparison between the three estimates cannot be conclusive. Nevertheless, the preliminary comments are at world level: IIASA starts high and ends low; PIK starts low and ends high; OECD lies in between. Also there are still differences at regional level.

[21] SSPs Database: < https://secure.iiasa.ac.at/web-apps/ene/SspDb >.

[22] According to Maddison (2001) global annual GDP per capita had a compound growth rate of 1.9% between 1900 and 2001. If the period 1950-2001 is considered, that rate drops to 1.5%.

a much smaller variation in income levels in the middle range). The other SSPs show more relative convergence in per capita income levels in 2100 across countries.

To sum up, SSP3 depicts a world which is overpopulated, where the poor regions remain poor throughout the century (although some degree of convergence is still assumed to take place). By contrast, SSP5 depicts a scenario where the population is stabilized and there is high growth and convergence. SSP2 – the Middle of the Road scenario - stays in the middle for most of the main drivers. In the next section we explore the full implications of this middle scenario.



a)

b)

c)

d)

Figure 6: (a) Population; (b) GDP PPP (US$ 2005); (c) GDP PPP per capita growth; (d) distribution of income levels – convergence in 2100. Historical data from World Bank.

6. Scenarios and results

Two scenarios are simulated in order to analyze the behavior of the GCAM model:

- Baseline scenario (GCAM-SSP2).
- Policy scenario (GCAM-SSP2-RCP2.6), where a stabilization policy is implemented in the baseline scenario GCAM-SSP2 with the objective of stabilizing the temperature below 2ºC (2.6 W/m^2 radiative forcing) by 2100.

The baseline scenario uses the SSP2 "Middle of the Road" scenario, because this scenario is been designed as the most "BAU" of all the SSPs and because using a scenario taken from the most common set of scenarios across the climate research scientific community (Tol, 2011; van Vuuren et al., 2011a) facilitates the communication of results and the comparison of different studies.[23] The technical implementation process of SSP2 in GCAM, from data provided by the OECD, is described in detail in (Capellán-Pérez et al., 2014). This data is used because the OECD methodology is well documented (Chateau and Dellink, 2012) and there are no critical differences between the 3 quantifications.

The main results of the model (energy demand and supply and technology mix, emissions and climate outputs) are first presented at global level for the Baseline scenario. To put the result in perspective, GCAM-SSP2 is compared with the GCAM Reference used by the model developers (GCAM-REF), with the high and low estimates from the IPCC SRES scenarios (IPCC, 2000, see Annex III for a brief description)[24] and with the United Nations medium fertility projection (UN, 2011) for the population. Secondly, the results are also disaggregated at regional level. The study is supplemented by a decomposition analysis of the change in carbon dioxide emissions from 7 different factors, following (Jotzo et al., 2012): (1) population; (2) per capita gross domestic product (GDP per capita); (3) the ratio of primary energy use to GDP (energy intensity); (4) the ratio of carbon dioxide emissions by unit of fossil fuel use (CO_2 intensity); (5) the ratio of fossil fuel to the primary energy use (fossil-fuel share); (6) carbon capture and storage; and (7) land use change. This method makes it possible to decompose changes in emissions (i) over time (i.e. time-decomposition); and (ii) between 2 scenarios (i.e. scenario-decomposition) into the factors influencing the variations. Thus, (i) the "Baseline" or "Policy" scenario accounts for the differences between period t and the previous period (t-1), while (ii) the "Policy-Baseline" scenario accounts for the differences between the Policy and Baseline scenarios for each period. See App. A for more information.

Finally, a similar scheme is followed to analyze the results of the Policy scenario.

6.1. GCAM-SSP2 baseline results

6.1.1.GCAM-SSP2 baseline global results

Figure 7 shows the main global results for the GCAM-SSP2 baseline scenario. The global population (see Fig. 7a) grows steadily for the next 60 years, peaking at more than 9 billion people in 2070 before beginning to decline slowly, closely following the medium fertility scenario of (UN, 2011) (and the

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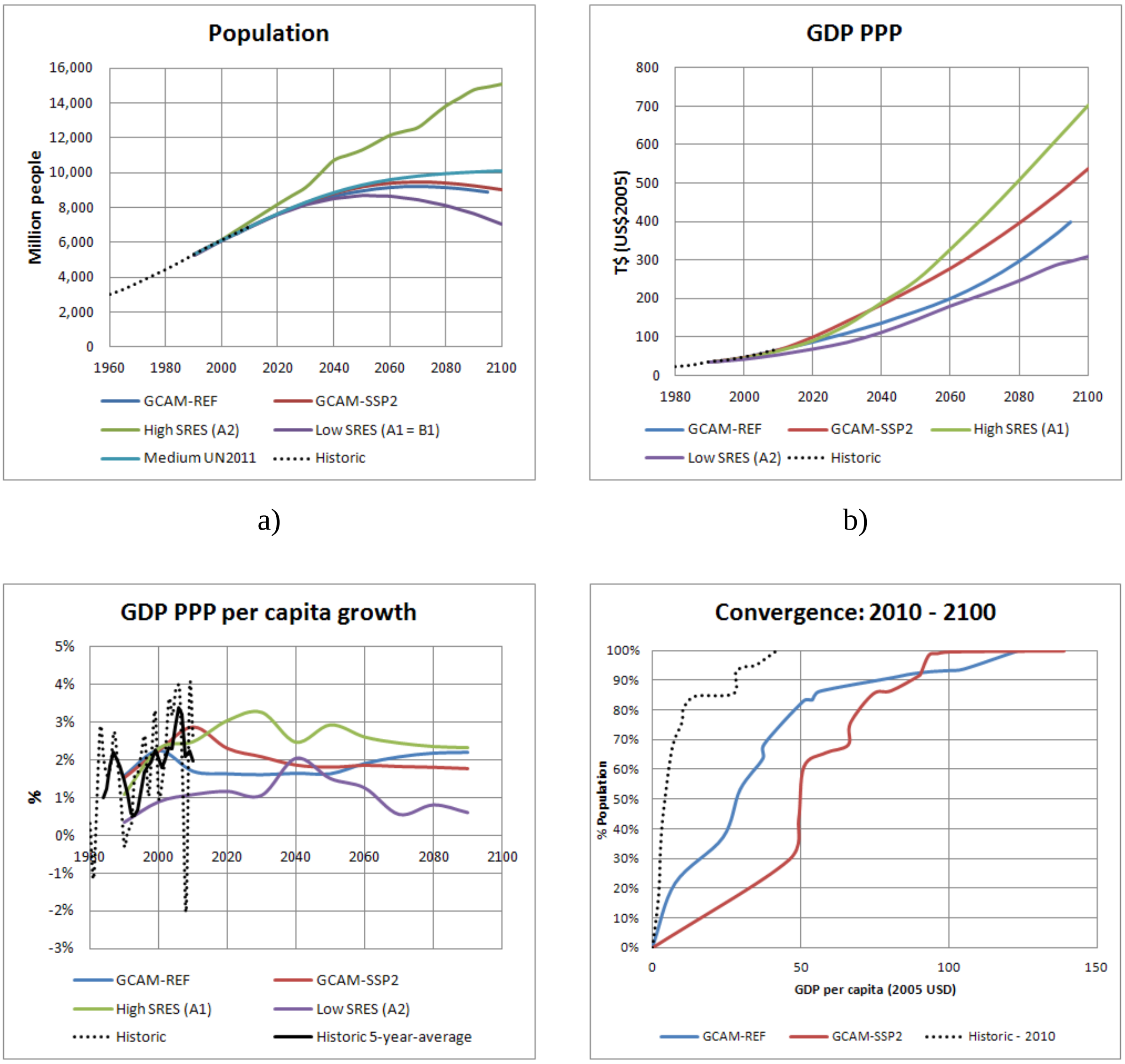
[23] In fact, this derives from the "consensus approach" applied by IPCC in international climate change research (IPCC, 1999; van der Sluijs et al., 2010): in the past, several sets of scenarios have already been used in this role (IPCC, 1990, 1992; IPCC SRES, 2000), having been extensively used in all fields.

[24] Data extracted from the SRES database < http://sres.ciesin.org/final_data.html > for the MESSAGE model (since this is the only reference model that provides GDP on both MER and PPP bases).



a)

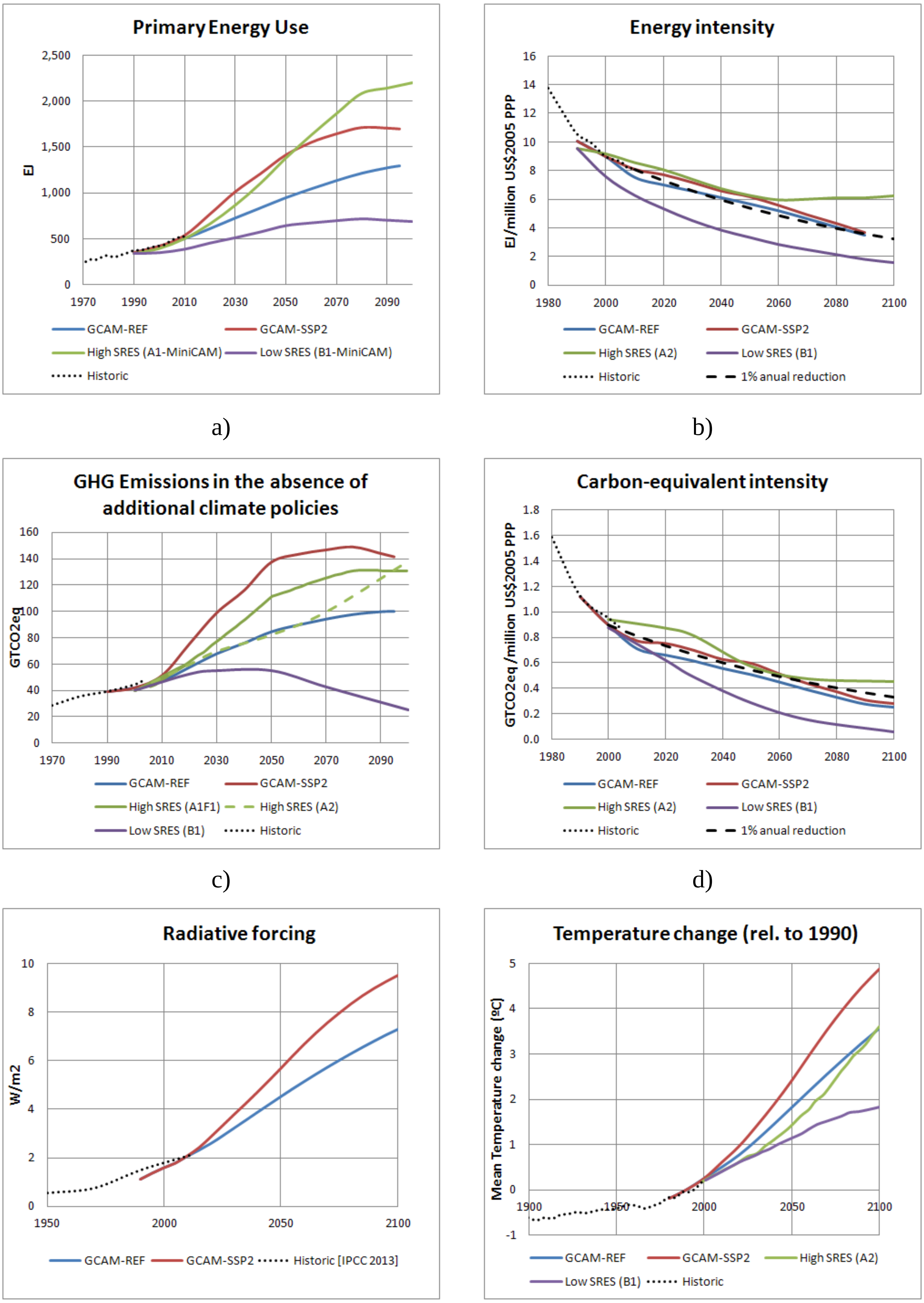
b)

c)

d)

Figure 7: Baseline: Global results (part I), socioeconomic inputs.

GCAM-REF scenario). Global GDP (see Fig. 7b) increases from 2005$ 66 trillion in 2010 to almost 500 trillion in 2095. Global GDP per capita grows at 3% per year in the first years and then slowly declines to a rate of +1.8% (see Fig. 7c). Global average GDP per capita reaches $60,000 by the end of the century, increasing 6-fold from the 2010 level with strong income increases in the current poorest regions of the planet. SSP2 is significantly more optimistic in relation to GDP growth than GCAM-REF during the first half of the 21st century. In terms of convergence/divergence of income by regions, this scenario considers absolute convergence between all the regions of the world, with high variation in convergence rates depending on the current non-developed region considered (see next section.) In 2010 only around 15% of the population lives in countries where GDP per capita is greater than $30,000, whereas in 2100 the projection is 85%.



a) b) c) d) e) f)

Figure 8: Baseline: Global results (part II).

The increase in global economic output results in a significant expansion of the global energy system. Primary energy consumption (direct equivalent)[25] increases from 570 EJ per year in 2010, to around 1750 EJ per year in 2095 (see Fig. 8a), almost 70% more than GCAM-REF. However, due to the implicit technological improvements associated with the GDP growth assumed in all regions, a decline in the primary energy use rate in the second half of the century is observed. Energy intensity declines by an annual average of 1% (see Fig. 8b), a figure fairly similar to the rate observed in the last century (Smil, 2010), which makes a six-fold increase in output compatible with just a 3-fold increase in energy demand (relative decoupling).

The baseline scenario does not include policies to limit greenhouse gas emissions and fossil fuels continue to dominate global energy consumption as in GCAM-REF, despite the substantial growth of nuclear and, to a lesser extent, renewable energy. Figure 9a shows the energy mix for primary energy consumption. Total oil production increases[26] slightly but steadily until 2095 and natural gas production increases and reaches a plateau in 2050. The source that increases most is coal, which is up from 120 EJ in 2005 (23% of total primary energy consumption) to 620 EJ in 2050 (42%) and almost 700 in 2095 (38%). Nuclear energy increases by a factor of 10 during the same period. Among renewable energy sources, the most prominent is biomass, which begins in 2005 with an estimated extraction of 20 EJ and increases to around 160 EJ by 2095 (with 3rd generation cellulosic crops accounting for more than 60% of the production).

Electricity generation increases from 65 EJ/year in 2005 to 460 EJ/year in 2095 (see Fig. 9b). This almost 7-fold increase denotes an important increase in the electrification of the economy that is independent of climate policies. Production is expected to be dominated by coal, gas and nuclear (almost 100 EJ in 2095). By the end of the century renewables can be expected to stand as follows: wind (36 EJ), solar (27 EJ) hydro (21 EJ) and biomass (20 EJ). In general, the current composition of the energy mix is expected to continue into the future.

As a consequence of the increase in primary energy consumption, based mainly on fossil fuels, emissions increase remarkably, especially in the first part of the century. GHG emissions[27] (see Fig. 8c) increase from 50 $GTCO_2eq$ in 2005 to a peak of 150 $GTCO_2eq$ in 2080, then stabilize and begin to decline a little by the end of the century. Thus, in scenario GCAM-SSP2 GHG emissions in 2095 are 42% higher than in GCAM-REF and 8% higher than in the IPCC upper range projection. Improvements in technology (See carbon intensity evolution in Fig. 8d) are not enough to outweigh the massive use of fossil fuel, and emissions thus increase by a factor of 3. GHG emissions turn into very high CO_2 concentration and radiative forcing levels in the future. According to the MAGICC sub-model, CO_2 concentrations in the atmosphere and radiative forcing are in excess of 1155 ppm and 9.5 W/m^2 respectively (Fig. 8e). In this scenario, the 2ºC threshold (relative to 1990) would be surpassed by 2040 and temperatures would continue to increase steadily up to almost 5ºC by 2095 Fig. 8f) and still more afterwards due to the high levels of radiative forcing at the end of the century.

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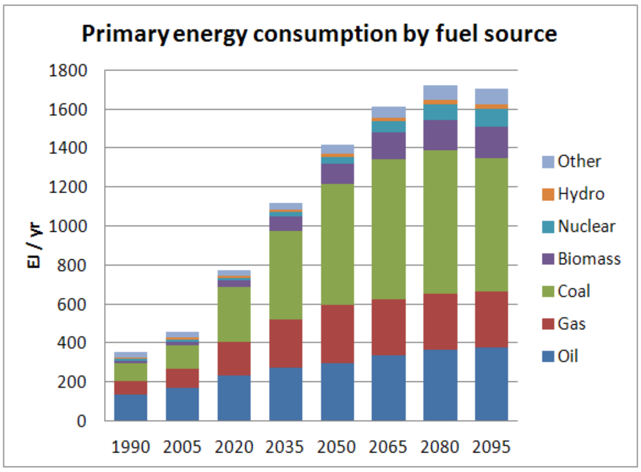
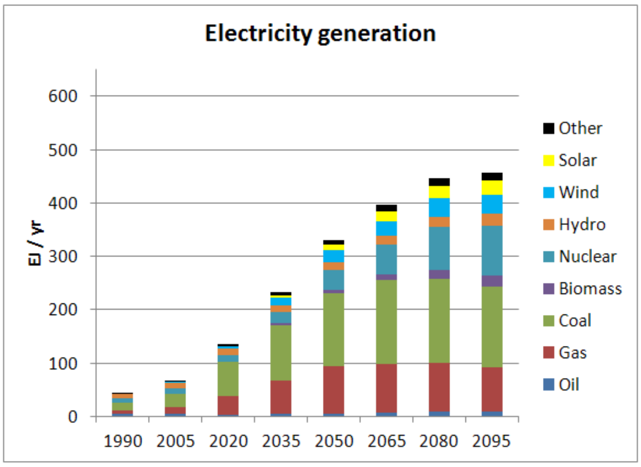
[25] There are three alternative methods predominantly used to report primary energy. While the accounting of combustible sources, including all the fossil energy forms and biomass, is unambiguous and identical across the different methods, they feature different conventions on how to calculate primary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

[26] Conventional oil extraction continues to grow and reaches a plateau in the 2030 decade (at around 125 Mb/d), while unconventional oil grows steadily at a 6.4 % per year reaching 185 Mb/d in 2080, and slowing down its trend thereafter.

[27] GHG emissions include emissions from fossil fuels, land-use changes and the equivalent CO_2 emissions from CH_4 and N_20 with GWP=25 and 298, respectively (IPCC, 2007c).



(a) *Other: wind, solar, geothermal and traditional biomass.*



(a) Other: Geothermal and Combined Heat & Power (CHP).

Figure 9: Baseline global energy mix (a) Primary energy consumption by fuel source and (b) Electricity generation.

To help provide an understanding of the behavior of the model in the Baseline scenario, Fig. 10 shows the decomposition of CO_2 emissions in relation to the previous year for different factors. The main positive contributor is the increase in GDP per capita, which is gradually offset by an increasing reduction in energy intensity, especially from 2055 onwards (see also Fig. 11). This happens because sectoral energy demand is modeled by “energy services”. Thus, while GDPpc grows, the energy service demand tends to grow at a lower rate, i.e. relative decoupling. For example, in the transport sector the per-capita passenger service demand function tends to saturate when higher GDPpc levels are reached (Kyle and Kim, 2011). It is striking to note that other factors such as population growth and CO_2 intensity have much lower impacts.

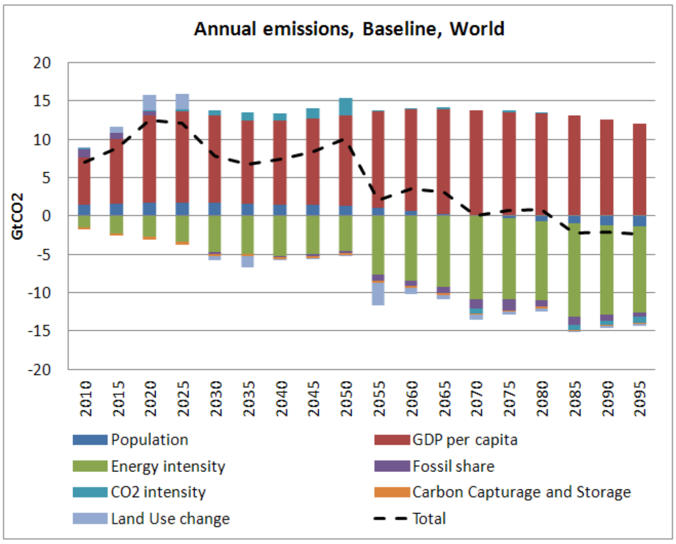


Figure 10: Contribution of each factor in relation to the previous year to total annual CO_2 emissions in the Baseline Scenario.

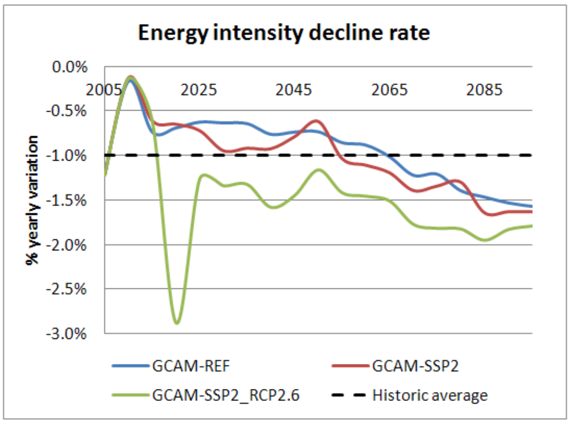
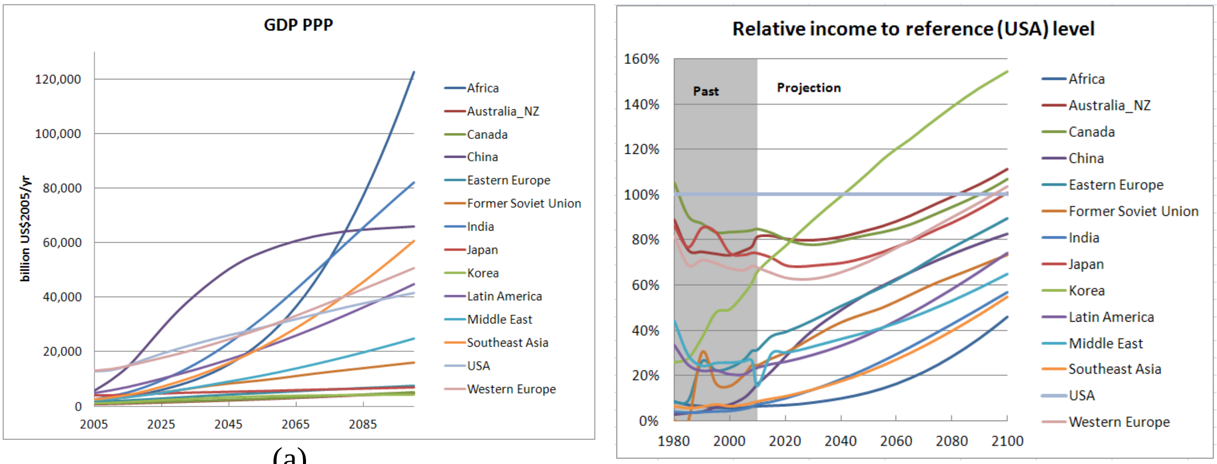


Figure 11: Changes over time in the rate of decline in energy intensity for each scenario.

The results of the GCAM-SSP2 baseline should also be put in context. If this baseline is compared with GCAM-REF or with IPCC high and low estimates, the most important difference that emerges is that the SSP2 is more optimistic in relation to GDP growth during the first half of the 21st century, especially in the poorest countries (i.e. Africa, see next section). Also, fossil fuels in GCAM are considered as relatively cheap and abundant resources (see Sect. 7 for a more detailed discussion on this point). This means that energy consumption and GHG emissions are greater in the first few decades of the century, which has a cumulative impact that increases the temperature in the second half of the century. The temperature increase projected by GCAM-SSP2 (4.8ºC) is therefore higher than the one projected by the GCAM-REF baseline (3.5ºC).

6.1.2.GCAM-SSP2 baseline regional results

Although there are some differences at regional level between GCAM-REF and GCAM-SSP2 (mostly implying higher GDP growth rates, especially for current non-developed regions), there is an important quantitative difference in the SSP2 storyline, as pointed out in the previous section. SSP2 assumes that by the end of the 21st century Africa will be the most populated region (+38% growth in

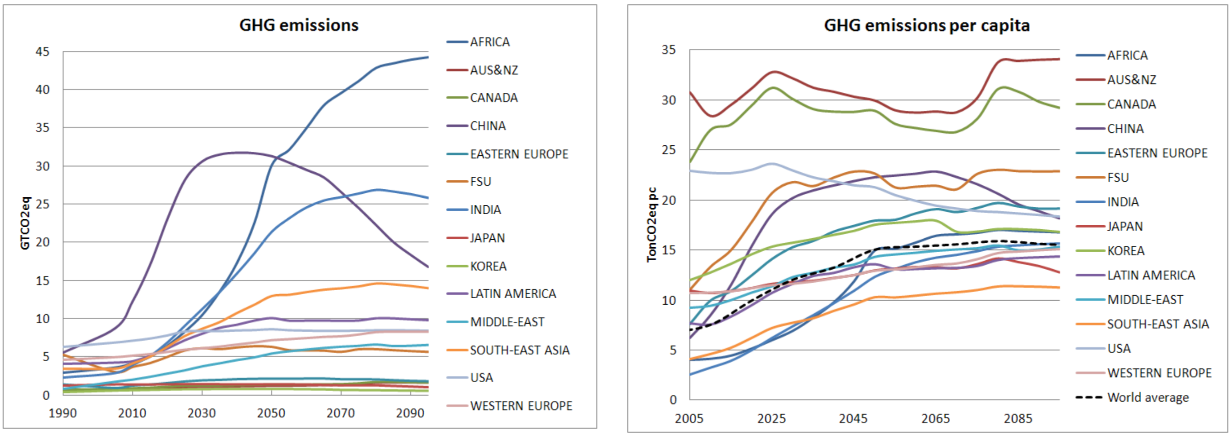


(a) (b)

Figure 12: (a) Trends over time in regional GDP PPP per region and (b) relative GDP per capita in relation to the reference in % (USA).

relation to GCAM-REF, reaching 2.8 billion in 2095), and the region that can be expected to concentrate the largest total GDP level in the world (Figure 12a). By the end of the century, African income is projected to exceed considerably the current income of developed countries (Figure 12b). Tables in App. B show the values of GDP PPP and Population inputs for each GCAM region assumed in the SSP2 scenario. Thus, during the 21st century, all current non-developed countries would be expected to significantly increase their income per capita in relation to current levels: India (x23), Africa (almost x17), South-East Asia (x14) and China (x11).

This great development means more energy consumption, with Africa also becoming the biggest consumer of primary energy in the second half of the 21st century, with a 3-fold increase on GCAM-REF. Moreover, this higher consumption is covered mainly by fossil fuels and especially by coal (more than 40% of the total), which means a huge increase in GHG emissions from 13 $GtCO_2eq$ in GCAM-REF to more than 45 in GCAM-SSP2 (Fig. 14a), i.e. more than 30% of global emissions in 2095 (compared to the current share of around 8%). A similar picture, although with much lower divergence from the GCAM-REF scenario, can be drawn for India, where a 65% increase in primary energy entails a 60% increase in GHG emissions. The regional emissions paths shown in Fig. 14a are determined by the interplay between GDP level and energy intensity improvement, as noted for the global trend: while each (currently developing) region reaches higher GDP levels, the emissions are then curved (see for example the time sequence for China – India – Africa). Figure 13 breaks down the contribution of each country to the variation in annual emissions and reveals that the world trends are largely driven by the 3 most populated regions: Africa, China and India.



(a) (b)

Figure 13: Contribution of each country in relation to the previous year to total annual CO_2 emissions in the Baseline scenario.

However, a look at the trend over time in regional emissions per capita reveals that the dispersion is reduced and most regions tend to converge to a range between 10 and 35 $TonCO_2eq$ per capita. Some highly populated regions have higher levels (e.g. USA, FSU, China), while others (e.g. South-East Asia, Japan, Latin America) are below the world average (Fig. 14a).

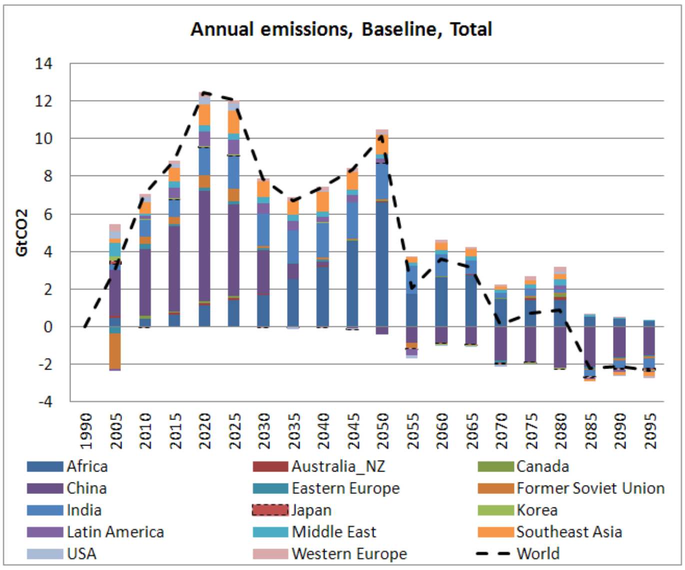


Figure 14: Regional GHG emissions (a) total and (b) per capita in the GCAM-SSP2 baseline scenario.

6.2. GCAM-SSP2-RCP2.6 results

The RCP2.6 policy is applied here to the GCAM-SSP2 Baseline scenario by imposing the 2.6 W/m^2 radiative forcing target in 2100.[28] This target is attained assuming full participation and introducing a global tax on carbon from 2020. The model provides the most cost-effective mix of technologies and fuels with the carbon price needed to reach the target. It minimizes emission mitigation costs at all points, in the sense that it allows for emissions to be mitigated when and where (region and sector) it is most cost effective. The carbon tax covers emissions from industrial activities and land-use change. The carbon price is assumed to rise at the rate of interest plus the average rate of carbon removal by oceans: the Hotelling-Peck-Wan Path (Hotelling, 1931; Peck and Wan, 1996). It is important to note that we assume here that agents that remove carbon from the atmosphere are rewarded at the same rate per ton as emitters are penalized. In other words, negative emissions receive a payment equal to the price of positive emissions.

6.2.1.GCAM-SSP2-RCP2.6 global results

This section provides the results of the policy scenario in comparison to the baseline scenario. Carbon valuation fosters a transition to low carbon technologies and fuels. Firstly, a significantly lower primary energy use is observed that never exceeds 1,200 EJ and in 2100 is 30% below the baseline scenario (Fig. 15a); energy intensity diminishes at an average rate of 1.5% per year (Fig. 11), i.e. at a 50% faster rate. GHG emissions decrease dramatically from the introduction of carbon valuation in 2020, and in fact *negative emissions* are found by the end of the century. The path followed is similar to the reference RCP2.6 scenario provided by the IMAGE model (see Fig. 3). This is achieved by the combination of the extensive use of low carbon technologies and bioenergy associated with Carbon Capture and Storage (CCS), a technology combination capable of removing CO_2 from the atmosphere in a way similar to afforestation. Thus, the large scale deployment of biomass (over 360 EJ in 2100) enables negative emissions to be achieved (Fig. 15b).

This stringent climate stabilization policy imposes an overshoot trajectory for both radiative forcing and CO_2 concentrations, which in the middle of the century show levels in excess of 3 W/m^2 and 400 ppm before ending up at 2.6 W/m^2 and 365 ppm, respectively (Fig. 15d and e), which is in line with the published GCAM RCP results.[29] Hence, the temperature is kept below 1.5ºC relative to 1990 (Fig. 15f).

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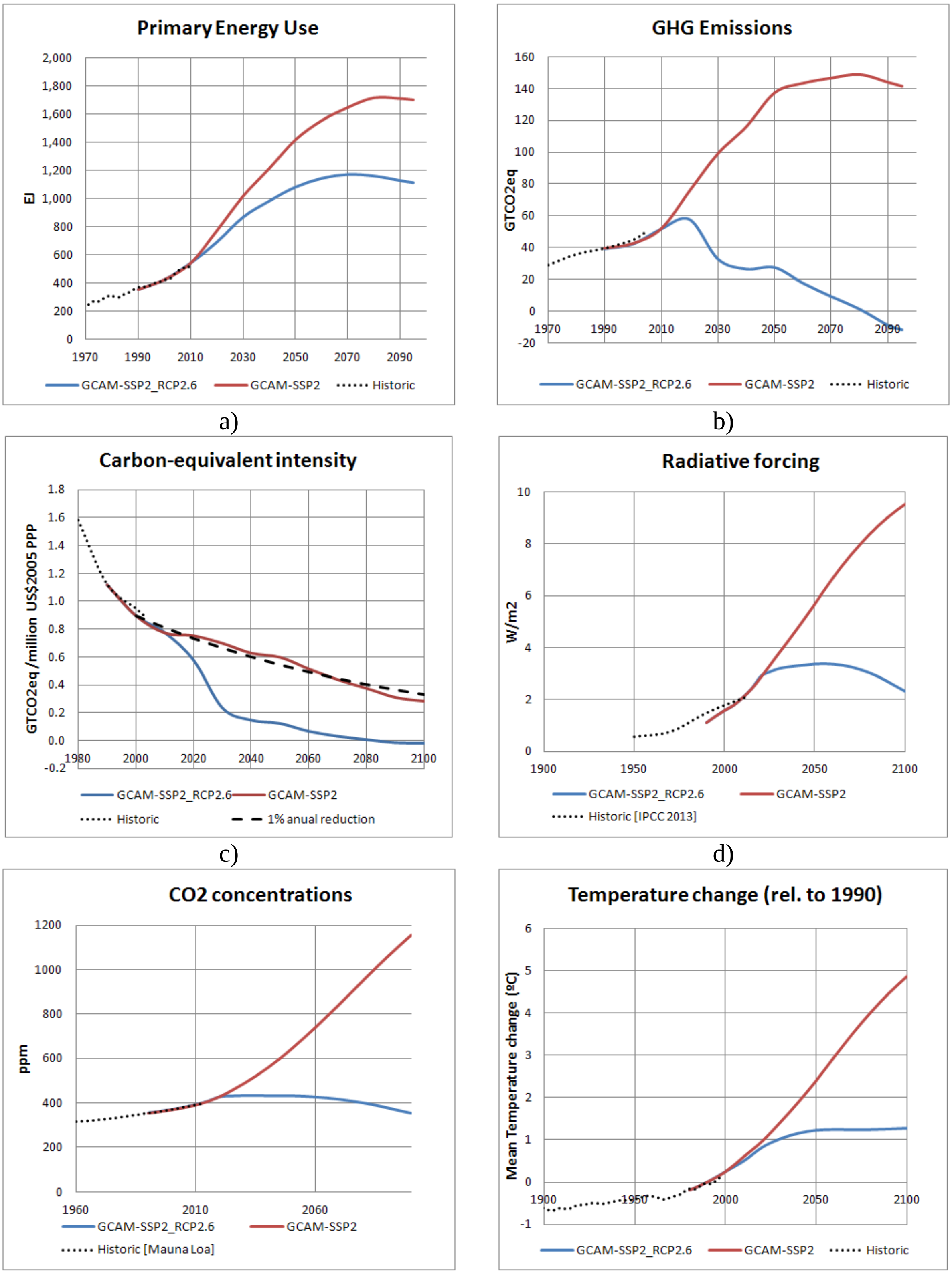
[28] Technical implementation is described in Appendix F. GCAM RCP replication data can be found at: http://www.globalchange.umd.edu/gcamrcp/.

[29] GCAM simulations of the Representative Concentration Pathway (RCP) radiative forcing targets: <http://www.globalchange.umd.edu/gcamrcp/>



a) b) c) d) e) f)

Figure 15: Comparison between the Policy and Baseline scenarios.

Renewable and nuclear energies are massively deployed over the course of the century. By 2095 their shares of total primary energy consumption are 34% (nuclear), 33% (biomass, mostly 3rd generation technologies) and 20% (other renewable energies, e.g. hydro, solar and wind), see Fig. 16a. Electricity production is largely dominated by nuclear technology (more than 50%), implying a 35-fold power increase in relation to current levels. CCS associated technologies and renewables account for roughly 25% each of the rest of the electricity generated Fig. 16b.

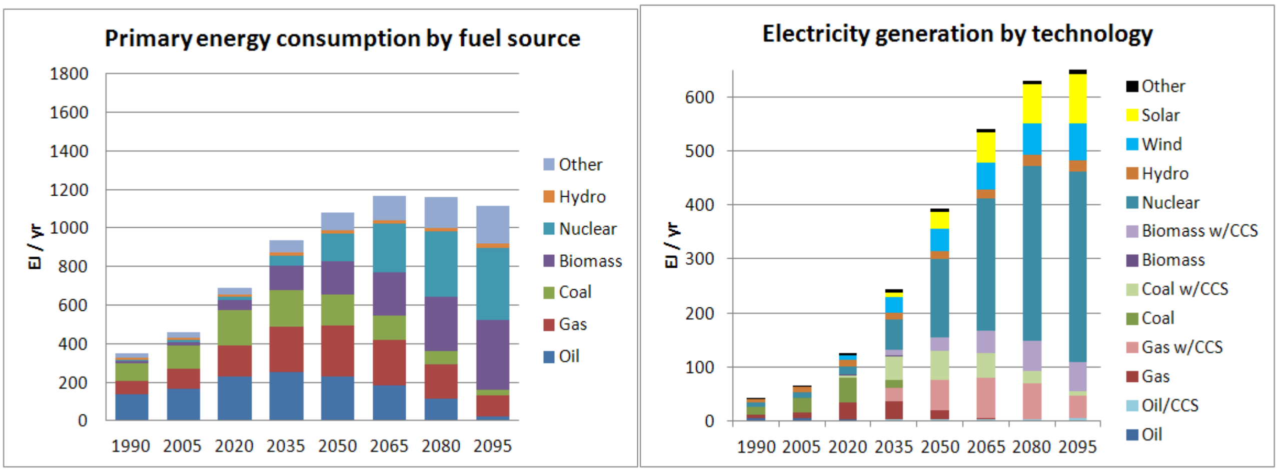
An analysis of Fig. 16 and Fig. 17 helps understand the mitigation strategy applied by GCAM-SSP2:

- Short-term: A combination of energy intensity improvements (driven by a sharp shift to more efficient end-use technologies due to the period-optimization approach of the model) and massive afforestation (almost +1,000 Mha in 2020-2025) is implemented.

- Medium-term: While nuclear and renewable grow steadily, CCS emerges as a transition technology that enables total fossil fuel extraction to be increased up to 2035, peaking at 675 EJ (i.e. almost double its current levels). In the electricity mix, fossil fuels continue to increase their share until 2065.

- Long-term: Fossil fuels are progressively driven out of the energy mix, decreasing from 2050 to 2095 at a combined average rate of 3% per year. The gap is filled mainly by nuclear in the electric sector and by biomass and other renewables elsewhere.

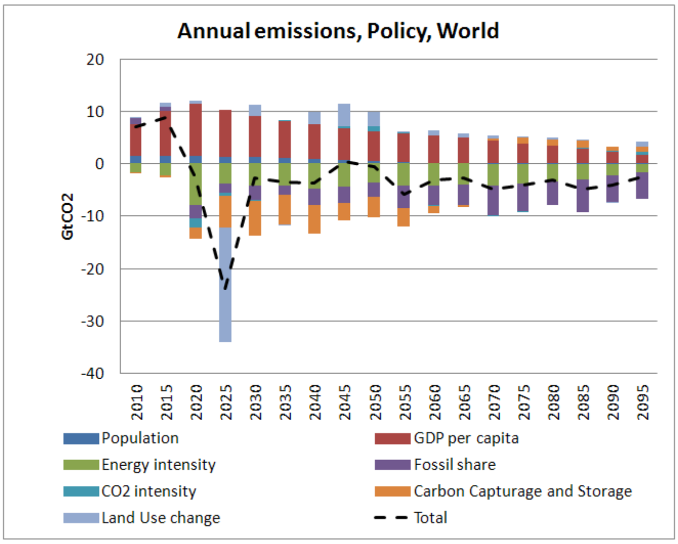
A greater electrification of the economy is observed: by the end of the century electricity demand is up 44% on the reference scenario. This is due to the transition in end-use technologies: for example, while passenger transportation is mainly covered by liquid fuels in the reference scenario, in the policy scenario more efficient technologies such as electric, hybrid and hydrogen-based modes dominate the transport sector, thus reducing the total demand for primary energy and resulting in an increase in electricity demand.



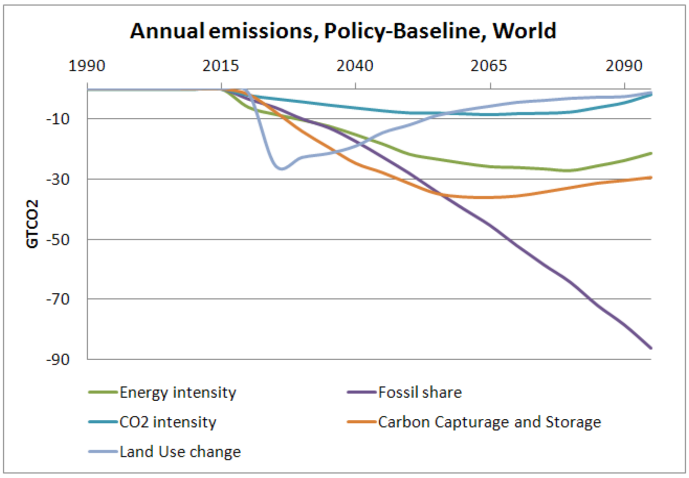
(a) Other: wind, solar, geothermal and traditional biomass

(b) Other: Geothermal and Combined Heat & Power (CHP).

Figure 16: Policy scenario GCAM-SSP2_RCP2.6 Global Energy Mix (a) Primary energy consumption per fuel source and (b) Electricity generation.



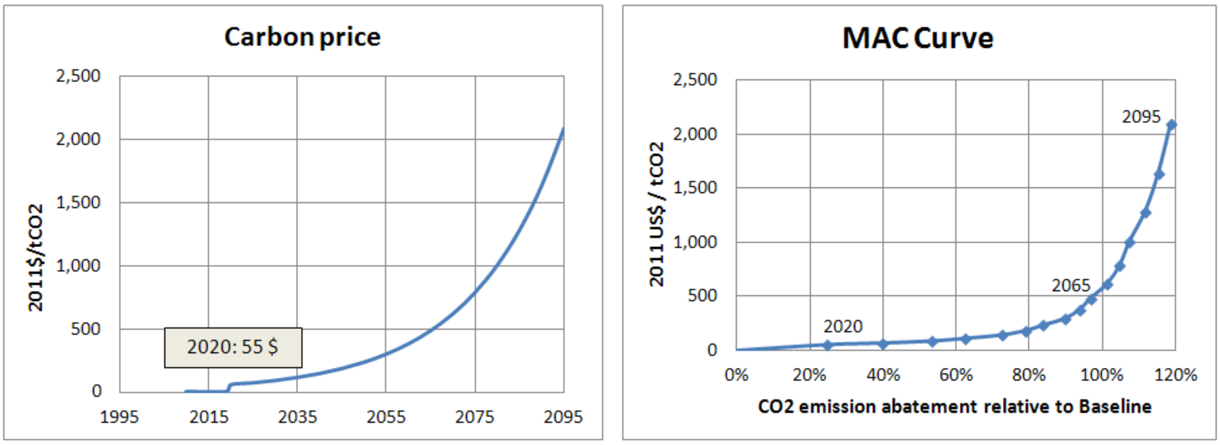
(a)



(b)

Figure 17: (a) Contribution of each factor in relation to the previous year to total annual CO_2 emissions in the Policy Scenario; (b) Difference between the Policy and Baseline scenarios in the contribution of each factor to each year's total emissions.

Figure 18 shows the carbon price path required to achieve the stabilization policy implemented. It starts with a cost of 55 2011$/t$CO_2$ in 2020 and grows exponentially, reaching around 2,100 $/t$CO_2$ in 2095. This initial price is in the low range of the results obtained for different models in the literature, which spans $20-$260, as reported by an intermodal comparison (Clarke and Weyant, 2009). Fig. 18b depicts the global Marginal Abatement Cost (MAC) curve in 2095, and shows the non-linearity of the CO_2 abatement cost: at CO_2 prices below US$500 (reached in 2065) the abatement potential is large, and from that year onwards decreasing abatement levels are achieved despite the exponential price increase. This approximately coincides with the time when *negative* CO2 *emissions* are reached at global level (note the difference in timing with Fig. 15c, where total GHG are considered).

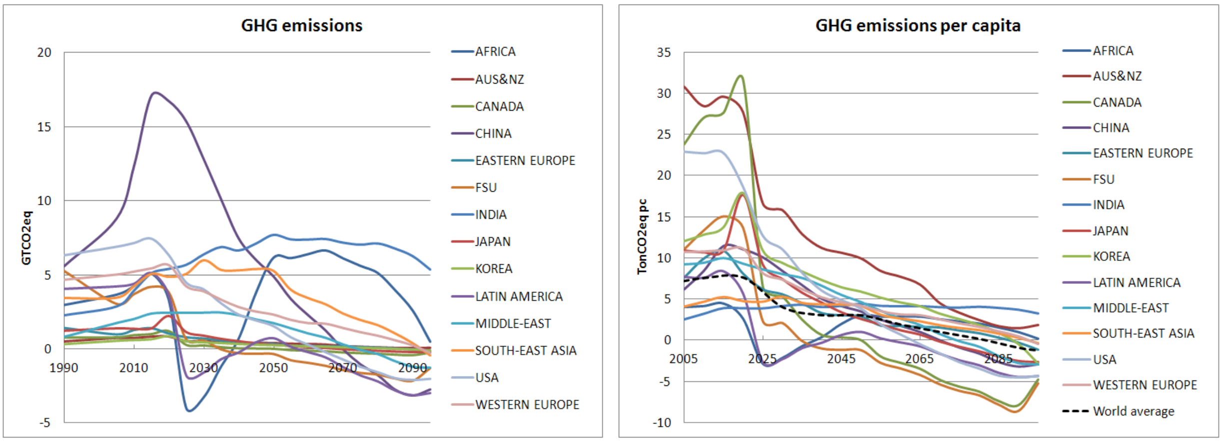


a) b)

Figure 18: Mitigation costs (2011\$/tCO$_2$): (a) carbon price path and (b) MAC Curve as emission abatement relative to Baseline (%).

6.2.2.GCAM-SSP2-RCP2.6 regional results

Most regions reach their GHG emission peak in 2020. Immediately after the introduction of the carbon tax there is also a reduction in GHG emissions per capita in all regions (Fig. 19b). There is an especially sharp reduction in Africa, the Former Soviet Union and Latin America, driven by massive afforestation (Fig. 17a, also visualized through the “Land Use Change” factor in the decomposition analysis in Fig. 20). Current developed countries show a gentler but sustained decrease. On the other hand, current in-development countries which do not have a large afforestation potential (e.g. India and South East Asia), follow a different path, maintaining or slightly increasing their emission levels in the first half of the century. Finally, from 2055 onwards all countries contribute to the annual decrease in emissions (Fig. 19a and Fig. 20) and by 2095 all country GHG emissions per capita range between -10 and 5 TCO$_2$eq (compared with the baseline in Fig. *14*).



a) b)

Figure 19: Regional GHG emissions: (a) total and (b) per capita in the GCAM-SSP2 RCP2.6 Policy scenario.

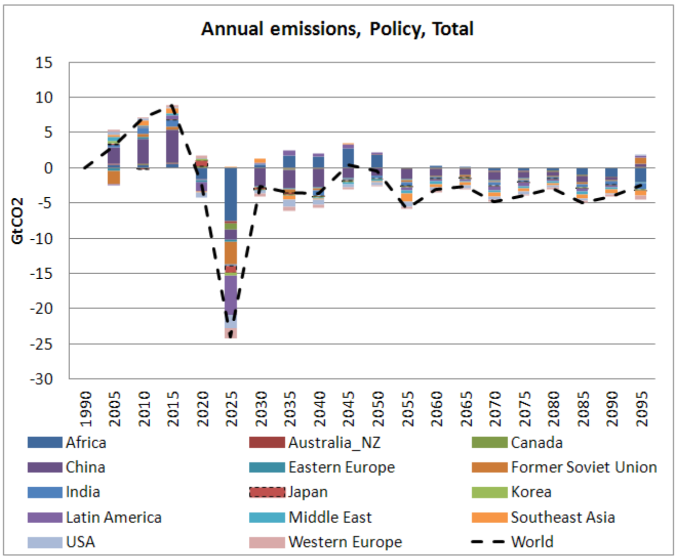
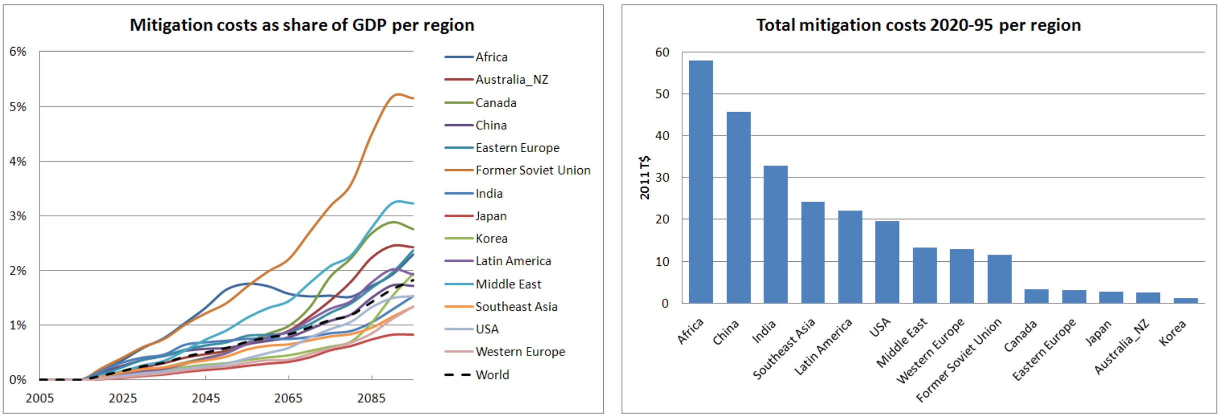


Figure 20: Contribution of each region in relation to the previous year to total annual CO_2 emissions in the Policy scenario.

Figure 21 shows regional mitigation costs. In relative terms, the share of world average mitigation costs rises steadily throughout the century to almost 2% of total GDP (Fig. 21a). This value is in the low range of commonly obtained mitigation costs, which is in accordance with the fact that GCAM is a BAU model (cf. Sect. 2). For example, the intermodal comparison performed by (Edenhofer et al., 2010) finds maximum annual rates over the course of the century of between 2 and 4.5% for the 400 ppm CO_2eq pathway. There is broad dispersion between different regions: current developed countries/regions such as Japan, Western Europe and the USA tend to be below the world average, while emergent and in-development regions such as the Former Soviet Union, the Middle-East, Africa, Latin America and China show higher figures. The Former Soviet Union and the Middle-East in particular reach figures in excess of 3% by 2095. Thus, these results highlight a tension between efficiency and equity as found by other studies (Tavoni et al., 2014).

When accounting for total mitigation costs over the century, the regions that on aggregate would need to make most effort would be Africa (almost 60 T$), China (55T$) and India (33 T$), as seen in Fig. 21b. Since the figures are regionally aggregated, they strongly depend on regional population trends (the 5 regions with the highest mitigation costs are the 5 most populated regions by 2095).



(a) (b)

Figure 21: (a) Mitigation costs as a percentage of GDP per region; (b) Total mitigation costs (not discounted) per region in 2020-2095.

7. Summary and discussion

The results are in line with those obtained by other models that simulate a very stringent climate policy. For example AIM, IMAGE, MESSAGE, GET, MERGE, REMIND, POLES, TIMER (Azar et al., 2010; 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., 2011b; Vuuren et al., 2007) have also shown that it is technically possible and economically viable to limit radiative forcing (RF) to 2.6 W/m² if all regions participate simultaneously in emission reduction with access to the full suite of technologies and effective, immediate long-term policy instruments are applied promptly (particularly carbon prices). However, a comprehensive review of these studies shows that there is no "magic bullet": mitigation strategies consist of a portfolio of measures[30] that is not homogenous for all models (Clarke and Weyant, 2009). Thus, in this section we discuss some of the specific characteristics and assumptions of the GCAM model.

7.1. Competition between electricity technologies

In both the Baseline GCAM-SSP2 and the stabilization RCP2.6 scenario nuclear and fossil fuel technologies (combined with CCS in the policy scenario) are deployed to a significantly higher level than renewable energies in the electricity sector. Also, among the renewable energies, wind energy accounts for 33% more than solar technologies by 2095 in the Baseline scenario. However, a cross-model drawn up by the *National Renewable Energy Laboratory* (NREL, 2010) concludes that the fossil and nuclear technology costs considered in GCAM-Ref are outdated:

> *"The MiniCAM data set is at the low end of the cost spectrum in 2030 – lowest, or tied for lowest – for seven* [i.e. all fossil and nuclear technologies] *of eleven technologies. This observation is likely because the MiniCAM characteristics are generally taken from the AEO 2008 publication*[31] (EIA US, 2008) *(2007 calendar year data), while the other data sets generally have characteristics based on calendar year 2008 or 2009. Although calendar year is not a direct indication of the year when the underlying data was derived, it can be used as a proxy for the vintage of the underlying data, which was not made available for MiniCAM and most other data sets. There was a significant run-up in power plant costs starting in 2007, largely due to changes in commodity prices, and these increases are likely not captured in the MiniCAM data set."*

Moreover, in recent years there has been rapid progress in the learning curves of renewable technologies, especially for solar (for which costs have dropped by more than 50% since the mid 2000's; Feldman et al., 2013; NREL, 2011) and wind power (compare EIA US, 2013, 2008).

We pay special attention to the great expansion of nuclear power since it becomes a key technology for providing electricity in both scenarios. In particular, the Policy scenario projects a 35-fold production increase by 2095, so that nuclear accounts for more than 50% of total production that year, i.e. more than 8 times the total current electricity production. Uranium resource limitations and processing costs do not put limitations on nuclear energy deployment although GCAM maintains an explicit accounting of nuclear fuel resources and processing costs. That is because fuel costs represent a relatively small fraction of nuclear electric facilities and large uranium reserves at relatively low prices are considered. Moreover, GCAM does not include the implications of limitations on nuclear

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[30] It should be noted that some of the most important technologies for achieving these scenarios are not currently available, e.g. 3rd generation bioenergy and CCS.

[31] The input GCAM data can be found in: http://wiki.umd.edu/gcam/index.php/Electricity.

waste disposal. Hence, waste disposal cannot serve as a constraint on large scale additions to the nuclear fleet (Clarke et al., 2009).

Although the bulk of the nuclear expansion is expected to take place in the medium and long term in the model, these assumptions might be too optimistic. Firstly, the nuclear industry was already in great difficulties before the Fukushima accident in 2011 (Schneider et al., 2010, 2012). That incident has in fact precipitated nuclear phase-out programs in major countries (e.g. Germany). In terms of competitiveness, the interdisciplinary study performed at MIT (Deutch et al., 2009) states that: “in deregulated markets, nuclear power is not now cost competitive with coal and natural gas”. Uncertainties exist about how capital costs will develop (they are estimated to have doubled from 2003 to 2009) and about the cost of financing, which are the main components of the cost of electricity from new nuclear plants. Thus, when accounting for the risk premium, levelized costs might increase by 30% (Deutch et al., 2009). The analysis of past trends has also shown that in fact nuclear technology exhibits an increase in costs with accumulated experience and capacity, making it a case of *negative learning by doing* (Grubler, 2010). Significant deployment programs might also be constrained by the availability of the relatively scarce metals used in the construction of reactors (Abbott, 2012) or of uranium for fuel (Dittmar, 2013).

Summarizing, the ratio of renewable/non-renewable overnight costs currently implemented in GCAM varies from 2 to 1.5 by the end of the century (NREL, 2010, fig. 19). The consideration of these issues may significantly change this ratio.

7.2. Fossil fuel resource supply curves

The model assumes large resources of both conventional and unconventional fossil fuels compared with the existing literature (Dale, 2012) (Fig. 22a), and important divergences exist between current price trends and the results given by the model. These divergences can be explained by market factors (that GCAM does not target) or by an outdated specification of the supply curves. Analysis reveals that, especially for oil, the reference used (Rogner, 1997) is outdated (cf. Brecha, 2008). Currently, the marginal price in the global oil market is determined by unconventional fuels such as shale oil whose breakeven costs are in the range of \$80-\$90 per barrel (Bernstein Research, 2012; CERA, 2008; Murray and Hansen, 2013). Thus, with the crude oil production already declining (WEO, 2012), the oil price evolution as projected by GCAM-Ref with prices below \$60 per barrel throughout the century seems highly improbable (Fig. 22b).

Unconventional gas breakeven current costs are in the range of \$4-9/MMBtU (Hughes, 2013; Medlock III, 2012; MIT, 2010; Murray and Hansen, 2013),[32] which is in the range of the long-term gas price in GCAM-Ref, which is similar for all regions. However, in contrast to oil, the total cost of delivering gas to international markets is strongly influenced by transportation costs, either via long-distance pipelines or as LNG, and by regional (structural) market specificities[33] such as oil indexation (Davoust, 2008; MIT, 2010). In fact, in recent years and after decades of similar trends, differences in gas prices between regions have significantly increased (BP, 2013) due to changes in the oil market (Fig. 22c).

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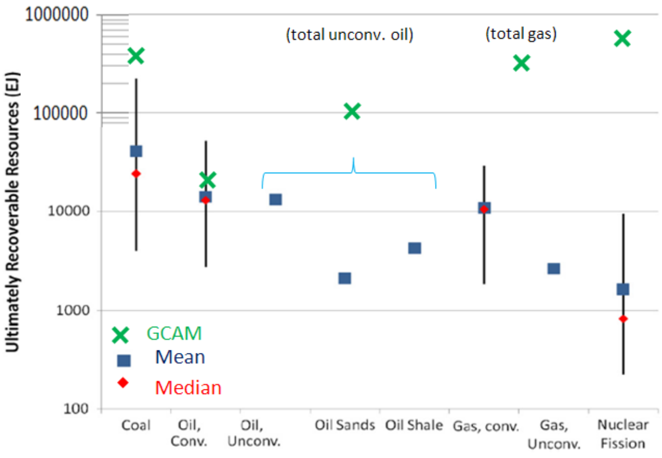
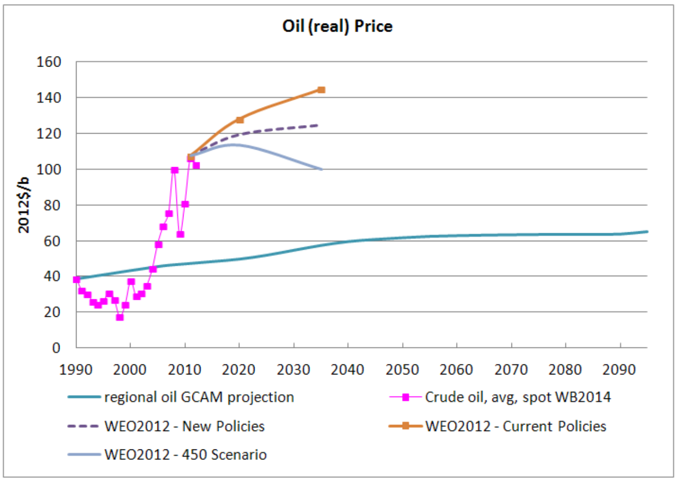
[32] In fact, this figure is expected to increase, since the average initial productivity (IP) of new wells is already declining and the heterogeneity of shale gas deposits limits the standardization of extraction techniques to create significant economies of scale (Hughes, 2013).

[33] Gas price formation varies significantly from one regional market to another depending on several structural factors (regulation, contracting practices, existence of a spot market, liquidity, share of imports, etc.) (Davoust, 2008).



(a)



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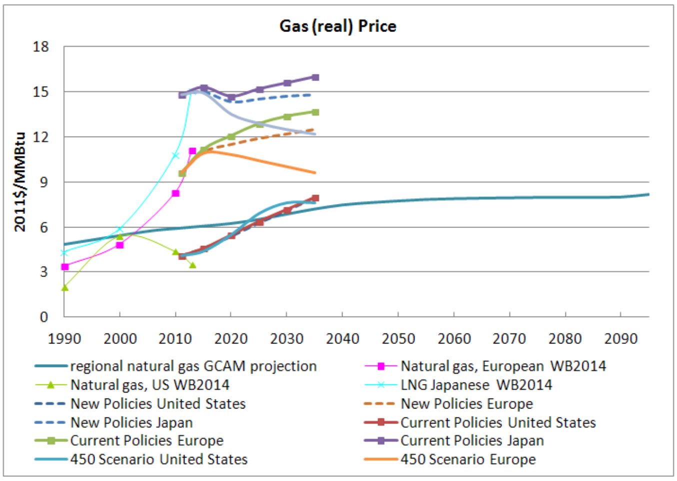


(c)

Figure 22: (a) Comparison of fossil fuels (primary energy) and uranium (ultimately producible nuclear energy) URR from the GCAM and the literature survey from (Dale, 2012); (b) oil price comparison: past trends, 3 main scenarios from (WEO, 2012) and GCAM-Ref projection; (c) gas price comparison: past trends and 3 main scenarios from (WEO, 2012) for the regional markets of Europe, United States and Japan. Although GCAM reports regional fossil fuel prices, the values for all regions are nearly the same in GCAM-Ref.

Uncertainties regarding the availability of uranium, especially grades that would enable the nuclear technology to be a net supplier of energy, are also high (see for example the discrepancies between (Dittmar, 2013; EWG, 2006) and the reference used in GCAM (Schneider and Sailor, 2008)). The current coal price is also roughly twice the price estimated in GCAM-Ref. Conventional wisdom has it that global coal reserves are ample and supply restrictions due to scarcity are not expected within the next several decades or even this century, but this is disputed by several studies (EWG, 2007; Heinberg and Fridley, 2010; Mohr and Evans, 2009; Rutledge, 2011).

Although energy consumption acts as a climatic change driver (IPCC, 2007b), few studies have focused on the effect of energy development constraints in climate scenarios. Interestingly, those few studies have found that climate uncertainty might be significantly reduced (e.g. Höök and Tang, 2013; Ward et al., 2012). Thus, a sensitivity analysis of resources and associated costs in GCAM might be relevant.

7.3 Scenario uncertainty

As shown in Sect. 6, GCAM-SSP2 results are very sensitive to the future socioeconomic evolution of Africa (Fig. 23). The SSP2 scenario assumes that by the end of the century Africa will exceed the current income of developed countries be a considerable amount (Fig. 12b). It is assumed that the structural obstacles to development recorded in this region (e.g. corruption, poverty, market failures, resource deprivation, etc.) will be progressively overcome by market forces thus enabling income convergence to take place.

A recent multi-model comparison intended to characterize the potential future energy development of Africa under different assumptions about population and income has found that population and economic growth rates will strongly influence Africa’s future energy use and emissions. Emissions from Africa could account for between 5 % and 20 % of global emissions in 2100 (Calvin et al., 2013a).

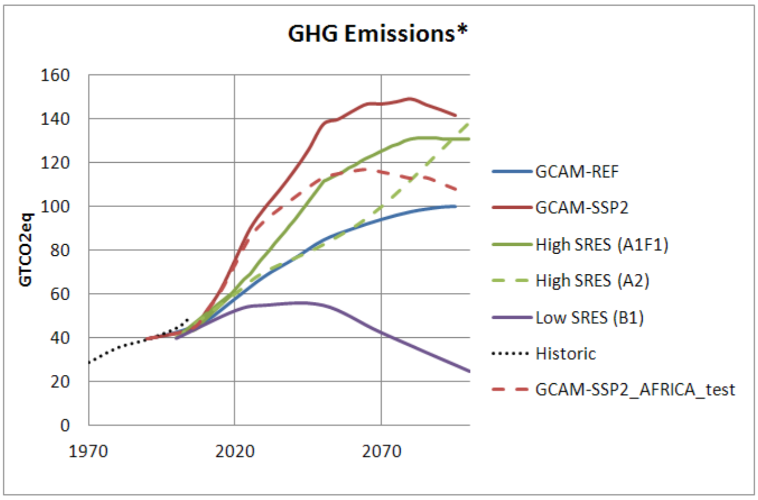
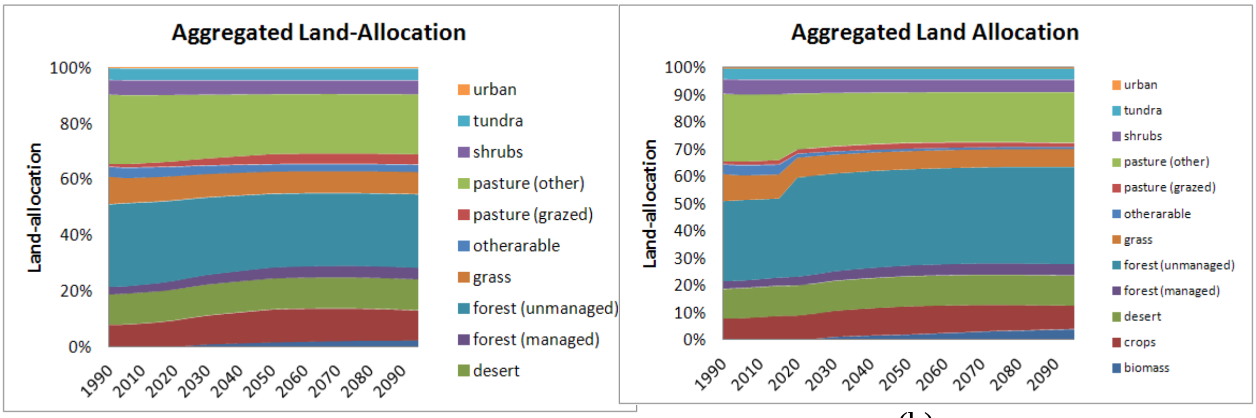


Figure 23: GHG emissions for GCAM-SSP2 (red line) and GCAM- SSP2 scenario for all regions except Africa, where GCAM-Ref data is preserved (red dashed line).

7.4 Agriculture and land-use

The Policy scenario shows major changes in global land-use allocation (Fig. 24). There is massive afforestation in the first period when carbon is valued (2020), and a change in area of almost 1000 MHa is attained by 2025. That is around 70% of the current total arable land (FAO Stats, 2013) afforested in 5 years. On the other hand, bioenergy is assumed to occupy more than 500 MHa by the end of the century. An increase in population drives an increase in the supply of food and generalized GDP growth drives a change to more land-intensive diets (i.e. more meat). This expansion in the demand for land is partially offset by an exogenous increase in the productivity of crops:[34] however, most food crop prices increase at a higher rate than income in current developing regions. Moreover, it is estimated that current and future crop yields will be affected negatively by climate change (IPCC, 2014).[35] In view of the current situation, in which almost 15% of the world population is undernourished (FAO, 2012), this might be problematic. Indeed, the sensitivity of the model to changes over time in (exogenous) crop productivity has been found to be highly significant (Wise et al., 2009). Moreover, when these climate impacts are considered important trade-offs appear and the amount of mitigation required by the energy system to reach a given climate target increases (Calvin et al., 2013b).



(a) (b)

Figure 24: Aggregated land allocation in the Baseline (a) and Policy (b) scenarios.

7.5.1 Feasibility of the GCAM-SSP2 baseline scenario and implications

The GCAM-SSP2 Baseline scenario projects a RF higher than 9 W/m^2 and CO$_2$ concentration levels largely over 1000 ppm by 2100. Temperature can be expected to rise by almost 5ºC (without accounting for the warming “in the pipeline” (Hansen et al., 2008) that would follow in the 22nd century due to the energy imbalance of the Earth). Under such circumstances, impacts from climate change would very likely reach great proportions (IPCC, 2007a; Smith et al., 2009). However, climate IA models in general and GCAM in particular have a linear structure that excludes feedbacks from climate impacts to damage[36] (economic, ecosystem disturbance, agricultural productivity, etc.) and does not consider interactions with other potential tipping points (Lenton and Ciscar, 2013). A recent

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[34] Which improves continually over time based on FAO figures until 2030 (Bruinsma, 2003) and converges to 0.25% per year thereafter.

[35] (IPCC, 2014) states that in the more extreme scenarios, heat and water stress could reduce yields by 25% between 2030 and 2049.

[36] As stated by (Stern, 2013).

article from GCAM developers highlights (i) the need to move to a more complex structure by integrating climate impact feedbacks into the modeling; and (ii) that the "analysis of climate impacts in the context of emissions stabilization is likely to yield a different understanding than undertaking either emissions mitigation analysis or climate impacts analysis independently" (Calvin et al., 2013b). In these conditions, the Baseline scenario seems clearly unfeasible: before this huge climate disturbance level is reached its high impacts would provoke radical changes in the socioeconomic system and the configuration of the world that would invalid the scenario's underlying hypothesis and its modeling structure.

Since GDP is prescribed exogenously in GCAM and scenarios are drawn up via a least-cost rather than a cost-benefit approach, mitigation costs refer to abatement costs (the costs for the transition of the energy system), not macroeconomic or welfare costs. If the costs associated with inaction (the high temperature reached in the Baseline scenario) were taken into account a very different figure would probably emerge. However, there is currently a huge gulf between natural scientists' understanding of climate tipping points and economists' representations of climate catastrophes in integrated assessment models (IAMs) (Lenton and Ciscar, 2013).[37]

8. Conclusion

This report overviews the climate Integrated Assessment approach and the new IPCC scenario framework, represented by Shared Socio-economic Pathways (SSPs) and Representative Concentration Pathways (RCPs). The GCAM model and the process of implementing the new scenario framework in the model are described. The implications of "Middle of the Road" scenario SSP2 are important because it will probably become a standard scenario among the research community.

A detailed comparative analysis of the GCAM-SSP2 Baseline and a climate stabilization scenario aiming at stabilizing the temperature below 2ºC (2.6 W/m^2 RCP) using a global uniform carbon tax has been conducted. Supplemented by a decomposition analysis, this exercise enables the behavior and main assumptions of the model to be identified and characterized, highlighting potential topics for future research. The results are along the same lines as those obtained by other models that simulate a very stringent climate policy: it is technically possible and economically viable to limit radiative forcing (RF) to 2.6 W/m^2 if all regions participate simultaneously in emission reduction with access to the full suite of technologies and effective, immediate long-term policy instruments are applied promptly (particularly carbon prices). However, the economic implications of the "low" mitigation cost obtained (below 2% of GDP for the whole period study), are imprecise due to the failure of the Baseline scenario to account for the costs of inaction.

The results of the policy mitigation scenario with full participation also highlight a tension between efficiency and equity: currently emergent or in-development countries report higher costs (as a percentage of GDP) than developed ones. This tension could be alleviated by designing an appropriate market for emissions which would also allow for financial transfers between countries.

Finally, some inconsistencies between the SSP2 storyline and the implementation conducted here have been found. In the storyline, energy resource availability and prices are reported to be "Medium", while the analysis shows that, in general, there is "large" resource availability associated with "low" prices in GCAM. Moreover, the temperature increase in GCAM-SSP2 is around 1ºC

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[37] In particular, there are multiple potential tipping points and they are not all low probability events: at least one has a significant probability of being passed this century under mid-range (2–4°C) global warming, and they cannot all be ruled out at low (<2°C) warming. By contrast, the predominant setting of climate catastrophes in IAMs is that they are associated with high (> 4°C) or very high (> 8°C) global warming (Lenton and Ciscar, 2013; Pindyck, 2013; Stern, 2013).

higher than the increase associated with the SSP2 storyline (4ºC) (Kriegler et al., 2012). Thus, further research should aim to overcome these inconsistencies and create the GCAM-BC3 version of the model. Key points in this should include: (i) an update of the fossil fuel supply curves; (ii) an update of the electricity costs; and (iii) the construction of a module for sensitivity analysis.

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Appendix A: decomposition analysis

The results of the GCAM model are very useful in understanding the implications of different scenarios on the changes over time in GHG emissions. However, from these results one cannot directly infer the extent to which changes in the different factors and countries underlying the trend in emissions (e.g. population, economic growth, technology etc.) impact changes in global emissions, which is very useful for policy making.

In order to understand better the impact of the different drivers on changes in global emissions, we apply an Index Decomposition Analysis (IDA). This method enables changes in the emissions to be decomposed over time (i.e. time-decomposition) or between 2 scenarios (i.e. scenario-decomposition) into the factors influencing the variations. There is a large body of literature on how to decompose the effects of different factors on the trends in a variable (Ang and Zhang, 2000). In this case we follow the recommendation of (Ang, 2004) and apply the Logarithmic Mean Divisia Index type I (LMDI) method, which is based on the Divisia (Divisia, 1925) and the logarithmic mean (Montgomery, 1937; Vartia, 1976).

For the sake of simplicity, we show the time-decomposition of the change in the net emissions of CO_2, although the same method could be applied to the scenario-decomposition (e.g. between the baseline and the policy scenario).

The starting point is the expression for global net emissions of CO_2 denoted by N :

$$N = \sum_r FFI_r + \sum_r U_r - \sum_r C_r \tag{1}$$

where FFI_r represents CO_2 emissions from fossil fuel and industrial uses in region r , U_r represents CO_2 emissions due to land use changes in region r and C_r represents CO_2 emissions captured and sequestered in region r .

CO_2 emissions from fossil fuel and industrial uses in region r can be expressed as the product of different components as follows:

$$FFI_r = \frac{FFI_r}{F_r}\frac{F_r}{E_r}\frac{E_r}{Y_r}\frac{Y_r}{P_r}P_r \tag{2}$$

where F_r is the primary energy use of fossil fuels, E_r is the total primary energy use, Y_r denotes GDP and P_r is the population.

Equation (2) can be rewritten as the product of a series of factors

$$FFI_r = c_r f_r e_r a_r P_r \tag{3}$$

where c_r is the gross emissions of CO_2 per unit of consumption of fossil fuel (i.e. carbon intensity), f_r is the share of total primary energy consumption accounted for by fossil fuels (i.e. fossil fuel intensity), e_r is the primary energy use per unit of GDP (i.e. energy intensity), and a_r is the GDP per capita (i.e. affluence).

Following (Ang, 2005), the changes in gross emissions of CO$_2$ in region r between t and $t+1$ can be expressed as:

$$\begin{aligned}\Delta N_r = {} & L(FFI_{rt+1},FFI_{rt})\ln\left(\frac{c_{rt+1}}{c_{rt}}\right)+L(FFI_{rt+1},FFI_{rt})\ln\left(\frac{f_{rt+1}}{f_{rt}}\right)+L(FFI_{rt+1},FFI_{rt})\ln\left(\frac{e_{rt+1}}{e_{rt}}\right)\\ & +L(FFI_{rt+1},FFI_{rt})\ln\left(\frac{a_{rt+1}}{a_{rt}}\right)+L(FFI_{rt+1},FFI_{rt})\ln\left(\frac{P_{rt+1}}{P_{rt}}\right)\end{aligned} \tag{4}$$

where

$$L(FFI_{rt+1},FFI_{rt})=\begin{cases}\dfrac{FFI_{rt+1}-FFI_{rt}}{\ln FFI_{rt+1}+\ln FFI_{rt}}, & \text{if FFI}_{rt+1}\neq FFI_{rt}\\ FFI_{rt+1} & , \text{if FFI}_{rt+1}=FFI_{rt}\end{cases} \tag{5}$$

The first term on the right hand side of (4) can be interpreted as the variation in gross CO$_2$ emissions in region r due to changes in the carbon intensity of fossil fuel use, the second as the variation due to changes in fossil fuel intensity (share of primary energy accounted for by fossil fuels), the third as the variation due to changes in energy intensity, the fourth as the variation due to changes in affluence and, finally, the fifth as the variation due to changes in population.

On the other hand, (5) and (3) lead to the expression of the change in global net emissions of CO$_2$:

$$\Delta N=\sum_r \Delta FFI_r+\sum_r \Delta U_r-\sum_r \Delta C_r \tag{6}$$

where ΔFFI_r is the change in emissions from fossil fuel and industrial uses in region r (which can be decomposed as for (4)), ΔU_r is the change in emissions in region r due to changes in land use and ΔC_r is the change in the volume of emissions captured and stored in r.

Equation (6) shows the time-decomposition for a time step (e.g. between t and $t+1$). In order to assess the change in emissions for the whole period analyzed it would be necessary to compute the cumulative sum over time for each factor/region. Moreover, **(**6**)** can also be used to decompose the difference in the emissions from 2 different scenarios for each year. Similarly to the time-decomposition, for this scenario-decomposition the results for the whole period analyzed could be computed.

APPENDIX B: Regional population and GDP inputs from SSP2.

	2005	2020	2035	2050	2065	2080	2095
Africa	909.6	1,265.6	1,651.9	2,019.4	2,313.1	2,522.5	2,641.8
Australia_NZ	24.5	30.8	36.7	42.0	46.4	49.0	49.5
Canada	32.3	37.8	43.0	47.6	51.7	54.3	54.8
China	1,419.7	1,509.7	1,506.8	1,407.6	1,250.0	1,081.7	926.4
Eastern Europe	127.8	126.8	123.7	118.6	111.9	102.6	94.0
Former Soviet Union	277.9	281.4	279.9	277.3	270.6	260.0	246.4
India	1,140.0	1,388.1	1,590.4	1,733.8	1,784.8	1,747.8	1,644.9
Japan	126.4	124.8	117.7	108.6	99.1	88.7	78.3
Korea	47.0	49.4	49.3	46.2	41.2	36.0	31.4
Latin America	551.4	643.2	709.0	741.0	739.7	717.5	682.3
Middle East	190.1	263.1	326.6	379.3	412.6	426.7	426.4
Southeast Asia	840.9	1,019.5	1,169.9	1,265.7	1,301.1	1,289.9	1,248.3
USA	300.6	339.4	375.9	405.3	432.3	451.7	459.8
Western Europe	469.3	509.3	537.9	557.2	564.1	561.0	548.9
TOTAL	6,457.6	7,588.9	8,518.8	9,149.4	9,418.5	9,389.5	9,133.4

Table B1: Regional population projection values (in millions of inhabitants) of SSP2 scenario, as adapted to GCAM regions.

	2005	2020	2035	2050	2065	2080	2095
Africa	2,144.1	4,544.0	9,673.4	19,175.6	36,591.1	65,126.4	106,239.9
Australia_NZ	799.3	1,250.1	1,784.3	2,390.9	3,099.6	3,893.8	4,660.2
Canada	1,131.8	1,531.7	2,046.7	2,647.4	3,311.9	4,123.6	4,953.8
China	5,839.1	21,422.7	40,765.6	53,821.1	60,566.5	64,074.2	65,450.9
Eastern Europe	1,650.7	2,507.0	3,568.6	4,512.8	5,424.4	6,303.1	7,088.1
Former Soviet Union	2,343.1	4,270.5	6,867.1	8,984.4	11,124.7	13,307.6	15,324.8
India	2,431.7	6,971.7	15,398.4	27,538.5	42,904.3	59,878.2	76,662.3
Japan	3,873.0	4,320.8	4,923.4	5,319.2	5,790.0	6,225.0	6,652.3
Korea	1,096.7	1,918.0	2,810.1	3,421.9	3,777.9	4,004.3	4,147.9
Latin America	4,806.6	8,505.6	13,394.2	19,164.2	25,948.0	33,579.8	41,880.1
Middle East	2,083.1	3,976.8	6,800.3	10,064.1	13,803.5	18,160.1	23,059.5
Southeast Asia	2,623.7	5,631.8	11,108.1	18,772.4	28,822.0	41,198.3	55,560.8
USA	12,692.9	17,111.4	22,787.1	27,394.6	31,902.3	36,289.7	40,254.2
Western Europe	13,026.1	16,252.0	20,825.8	26,511.4	33,180.1	40,497.8	48,054.2
TOTAL	56,541.8	100,214.2	162,752.9	229,718.4	306,246.1	396,661.8	499,989.1

Table B2: Regional GDP PPP projection values (in billions of US$2005/yr) in the SSP2 scenario, as adapted to GCAM regions.

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