RECIPE

THE ECONOMICS OF DECARBONIZATION

Description of the baseline scenario

Working Paper

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Key Messages

- **This section presents energy use and carbon emissions in the business-as-usual case for three state-of-the-art climate-economy models: IMACLIM, REMIND, and WITCH**
- **A major strength of this model comparison is that the three models embody fairly similar assumptions regarding socio-economic fundamentals, but represent very different visions of future technological developments**
- **Over the course of this century, global population is expected to peak at around 9.5 billion in 2070 and stabilize at roughly 9 billion in 2100**
- **World GDP is projected to grow at an average of 2.1% to 2.4%, resulting in income levels which are between almost 8 and 10 times their 2005 value**
- **Despite improvements in energy efficiency, total primary energy consumption is projected to increase by factors between two-and-a-half and four**
- **Without measures to decarbonise the world's energy systems, fossil fuels will remain the dominant source of energy throughout the 21st century**
- **The unabated rise of energy related carbon emission results in atmospheric concentrations between 730ppm and 840ppm CO_2**
- **These atmospheric concentrations correspond to global mean-temperature increase of 3-7°C above pre-industrial values**

1 Introduction

Energy use is a fundamental aspect of economic activity and human well-being. Households use energy for heating, cooling, cooking, and lighting; industry for the production of goods. Moreover, energy is indispensable for transport, provision of services as well as agriculture. At the current state of play, industrialised countries exhibit the by far highest levels of energy consumption per capita, on average about 3 times the world average (IEA, 2008). However, owing to robust economic growth in many parts of the world, most notably in China and India, developing countries accounted for the largest part of the increase in global energy use over the last decade. Despite growing resource scarcities, energy systems all over the world remain heavily geared toward the use of fossil fuels as a source of energy. If this trend will continue in the future, carbon emissions are bound to climb well above currently observed levels, resulting in potentially devastating effects on the Earth's climate. For this reason ambitious measures to curb energy demand or decarbonise energy production around the globe are needed to meet the goal of avoiding dangerous anthropogenic climate change. As a positive side effect, such measures can yield a number of ancillary benefits, such as improving the security of energy supply and decreasing levels of local air pollution.

In order to give recommendations regarding the optimal design of climate policies and to assess the corresponding costs and distributional consequences of GHG mitigation, it is therefore necessary to develop plausible and internally consistent scenarios describing the future evolution of energy systems and carbon emissions in a world in which no climate policy measures are adopted beyond those that are already in place. The three integrated assessment models employed in this study (IMACLIM, REMIND, and WITCH) embody fairly similar assumptions on socio-economic fundamentals, but are designed to represent different visions of future technology developments and the emergence of breakthrough technologies. We consider this feature, which will be described in more detail in section 3, a major strength of this study, as it can help to identify how underlying assumptions on technology influence possible trajectories of future energy use and carbon emissions.

This chapter describes the reference scenarios developed by the three modelling teams. It first provides an overview of the basic assumptions regarding the underlying socio-economic drivers of energy use, namely population growth and economic development. It proceeds to present the resulting energy demand and the possible responses of energy systems given different assumptions on technologies and finally assesses the impacts on the climate system. A sensitivity analysis is carried out in order to ensure that the fundamental messages derived can be upheld in the face of moderate changes in various exogenous assumptions, such as rates of technological learning and resource availability. Furthermore, the results are compared with those of two other prominent studies, namely the IEA's World Energy Outlook 2008 (IEA, 2008) and the U.S. Climate Change Science Program's Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations (CCSP, 2007). Finally, we present a short summary of this chapter together with some conclusions on what can be inferred about the way in which different assumptions regarding technological development influence our projections of energy use and carbon emissions.

2 Socio-Economic Drivers

Population Growth

Population growth is a key driver of energy consumption, carbon emissions and hence global warming. While global population has been growing at approximately 1.8% over the second half of the 20th century, population growth has started to slow down as a result of increasing incomes and onsetting demographic transitions in a large number of countries that have started to escape from poverty. However, the large majority of demographers agree in their evaluation that the world's population will keep growing until at least the middle of this century, putting additional pressures on the natural environment.

For reliable estimates regarding the development of the world population in the course of the 21st century, all three models compared in the RECIPE project employ population forecast from the UN Department of Economic and Social

Affairs, Population Division1. This scenario, depicted in Figure 1, assumes a continued upward trend in global population, albeit at steadily decreasing rates of growth, reaching 9 billion in 2050. Around this date, a significant slowdown of population growth is expected to set in, followed by a peak of world population at roughly 9.5 billion people in 2070 and a subsequent decline to roughly 9 billion at the end of the century.

On a regional basis, population in the US, Europe, and the Rest of Annex I countries stays on a flat trend, while it shows slight initial increases in China and India, with a peak and subsequent decline in 2030 and a population in 2100 which is very close to its level in 2005. The most dynamic development with respect to population is foreseen to take place in the rest of non-Annex I countries, which are expected to account for the increase of 2.5 billion people over the century, corresponding to an almost doubling of their current population. One should be aware that differences in regional population trajectories between models are due to different schemes how individual countries are aggregated into macro-regions in each model.

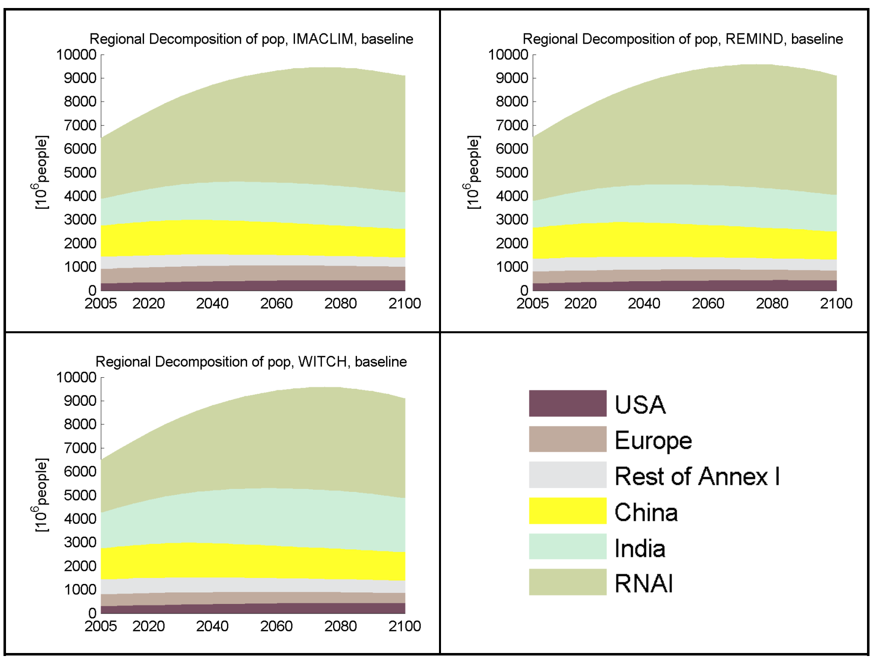

Figure 1: Population by regions

[1] The data is available from http://unstats.un.org/unsd/cdb/cdb_simple_data_extract.asp?strSearch=&srID=13660&from=simple. Population data up to 2050 are available at 5 year intervals, while for later periods, only the forecast for the year 2100 is available, but not for years between 2050 and 2100 (UN, 2004). The differences in the two datasets were thus reconciled by extrapolating levels at 5 year periods in 2050-2100 using average 2050-2100 growth rates.

Macro-Economic Development

Economic activity is a second fundamental socio-economic driver of energy use. As people become richer they consume larger amounts of goods and services and increase their demand for energy for residential use and transport. Even though technological change in the form of a more efficient use of energy and a shift in sectoral composition of production toward service based activities in industrial countries have resulted in declines in energy intensity (i.e. energy used per unit of GDP), total energy consumption has increased steadily as economic growth traditionally has outpaced technological progress.

For this report the modelling teams assumed continued economic growth close to historical values in industrial regions and more rapid catch-up growth and partial convergence in newly industrialising and most (but not all) developing and least developed countries, driven by assumptions about long-term dynamics of labour productivity and total factor productivity. For this study, we assume that the most advanced economies experience steady productivity growth at a constant long-term rate. In other regions, the dynamic behaviour is driven by a narrowing of productivity gaps. The respective parameters, calibrated on historic trajectories and 'best-guesses' on long-term trends, have been harmonized across the three models to reproduce similar GDP trajectories. The underlying vision is that the US, Europe, and Japan are expected to remain the regions with the highest incomes per capita at the end of the 21st century, with other countries, especially China and India, closing the gap. Hence, the overall picture of economic development represented by the three models is very similar in spirit, even though regional GDP trajectories show slight variations, reflecting differences in the models' internal mechanics as well as modellers' evaluations.

As can be seen in Figure 2, all three models project that world GDP (measured at market exchange rates in year 2005 US$) will have doubled by 2030 and increased more than four-fold by 2060 compared to its value in 2005. Initially, GDP grows at slightly above 3.7% per annum in all three models. Over the century, rates of GDP growth decline steadily, as nations that recently entered into the phase of industrialisation move from catch-up growth to a stage of maturity. Over the entire century, world GDP is expected to increase from US$ 44 trillion in 2005 to values ranging from US$ 338 trillion (WITCH) to US$ 440 trillion (REMIND), corresponding to average annual growth rates between 2.1% (WITCH) and 2.4% (REMIND). For average incomes per capita, shown in Figure 2, this means an increase from currently roughly US$7500 to values between US$37000 (WITCH) and US$48000 (REMIND) at the end of the century. As global population is assumed to start to decline during the last quarter of the century, per capita incomes increase more than overall GDP in this period, counterbalancing the effect of declining growth rates in world GDP to yield roughly constant rates of per capita GDP growth after 2070.

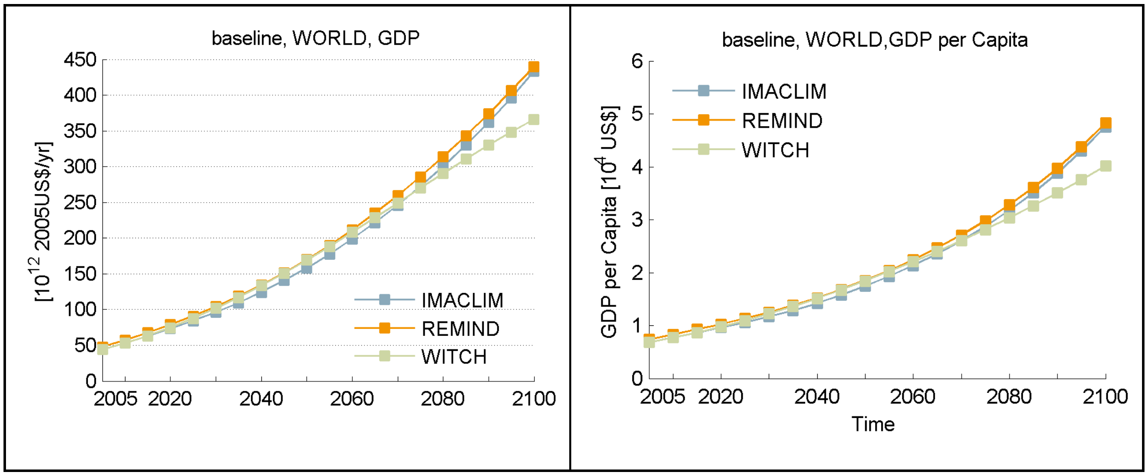

Figure 2: Global GDP and Global GDP per capita

As shown in Figure 3, in all three models the largest relative increases in national incomes occur in China and India, which are expected to continue their ascendency and turn into major economic powers. Due to large populations and dynamic economic growth in many parts of Asia, Latin America and Africa, the rest of other non-Annex I (RNAI) countries experience the largest increase in absolute terms. The US and Europe lose their current dominance but nevertheless remain key players in the international economic arena. The same applies to the rest of Annex I countries, which are projected to remain important economic actors, even though their share in world GDP declines continuously. Probably the most important difference between models can be seen in the fact that WITCH projects a higher GDP for China in 2100 than IMACLIM and REMIND, while the latter two models attribute higher importance to the rest of non-Annex I countries.

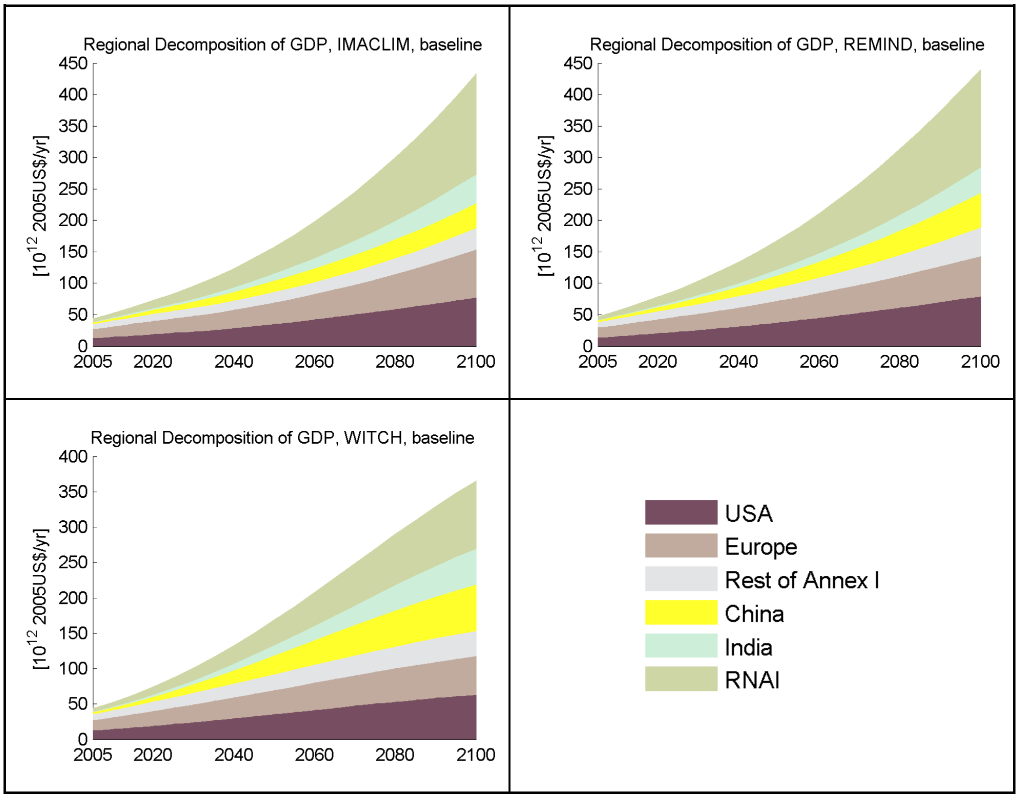

Figure 3: GDP by regions

3 Energy Use

Primary Energy Consumption

IMACLIM, REMIND, and WITCH represent different visions concerning the evolution of technology, i.e. the deployment of new technologies to the market, alternatives to substitute between different forms of energy in end use as well as parameters describing the conversion of primary to final energy and the efficiency of final energy use. For instance, IMACLIM emphasises large increases in fossil fuel demand (oil and coal through coal-to-liquid transformation) due to steadily rising demand in the transportation sector, in which relatively view possibilities for substitution exist. In REMIND carbon-free energy carriers, such as renewable energies and biomass, are expected to become competitive and be deployed to the market, even in the absence of climate policy. WITCH, in turn, focuses heavily on opportunities to counter scarcities of fossil fuels by increasing energy efficiency instead of switching to alternative sources of energy. This gives rise to three model-specific baselines exhibiting differences with regards to the total amount of energy consumed as well as the energy mix (i.e. which primary energy sources are used to generate final energy) in accordance with the respective assumptions on technology incorporated in each model. It is straightforward to see that in the absence of climate policy carbon capture and storage (CCS) is employed in none of the models.

IMACLIM paints a picture of a world in which energy consumption follows an almost linear trend and quadruples over the course of the century from roughly 400 EJ to 1600 EJ, shown in Figure 4. This corresponds to an average annual increase of 1.4%. Most demand, and the increase thereof, is met by fossil fuels, while other energy carriers, such as renewables and nuclear power, play only minor roles. An important aspect in this development is the increased use of coal in the rapidly growing transport sector by means of coal-to-liquid transformation, which explains the dominant role of fossil energy carriers in the energy mix (in which oil is increasingly being substituted by coal for transport uses). This deployment of coal-to-liquid also drives the fast increase of energy consumption in the second half of the century owing to the lower efficiency of using coal instead of oil as a source for transport fuels. Moreover, energy efficiency is of only secondary importance, as increased energy demand is largely met by the provision of abundant and cheaply available coal.

REMIND projects a strong initial growth of energy use, which slows down considerably after 2040. Total energy use increases from 400 EJ in 2005 to 1300 EJ in 2100, an annual increase of 1.2% (see Figure 4), a projected increase that is in between what is predicted by the other two models. Fossil fuels are expected to still account for the bulk of energy supply during the 30 years to come. By 2030 scarcity of fossil fuels in combination with technological progress in the renewable energy sector shift comparative advantage away from fossil fuel use (i.e. fossil fuels become more expensive compared to renewables). Hence, non-fossil sources of energy are projected to gain in importance, even in the absence of climate policy measures. Biomass becomes more and more important between

2030 and 2050 and its use remains at a high level afterwards. Nuclear power gains in significance after 2040 and remains in use until the end of the century. Due to technological learning, other renewables (such as wind and solar power) become competitive and constantly increase their share throughout the entire century.

WITCH, in turn, presents a vision of technology development that can be regarded as less optimistic when it comes to the deployment and penetration of non-fossil energy carriers, as can be seen in Figure 4. Hence, fossil fuels remain the dominant source of energy over the entire 21st century, while hydropower, biomass, other renewables, and nuclear power only account for a rather small share. However, WITCH is more optimistic in terms of energy efficiency and possibilities to substitute away from energy as an input factor in the production of final output. This becomes most notable during the second half of the century, in which the growth of energy demand slows down considerably. This results in an increase in energy use which is smaller than for IMACLIM and REMIND, to about 1000 EJ in 2100, as opposed to 1600 EJ and 1300 EJ respectively.

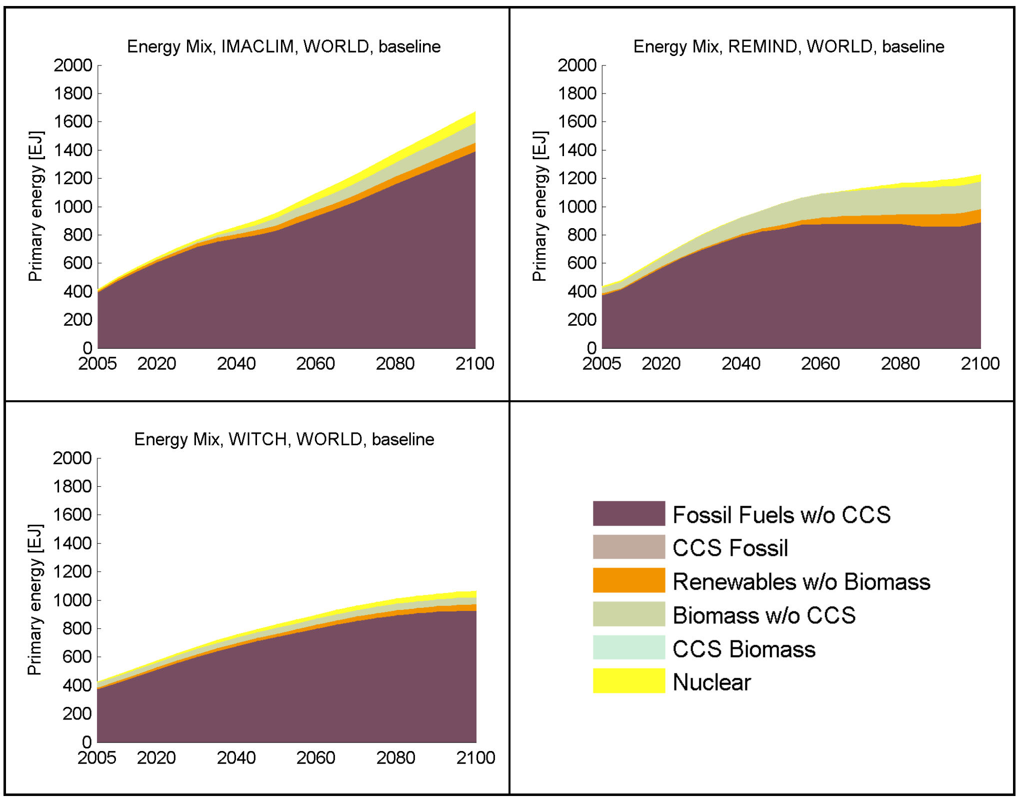

Figure 4: Global energy mix

Decomposed by regions, world energy consumption is distributed as shown in Figure 5. In all models energy use in the US, Europe, and the rest of Annex I countries, which currently account for approximately 50% of global consumption, rises steadily but at low rates. Considerable increases are predicted for the group of developing countries as a whole, with differences across models arising from different assumptions on regional growth rates as well as energy systems. For China, all models project similar increases in energy demand (roughly four-fold) as a result of different assumptions about economic growth and energy efficiency. Indeed, WITCH predicts higher economic growth than IMACLIM for China (see section 2), but is more optimistic about energy efficiency. The observed variations in total energy consumption between models are to a large extent explained by different developments in India and the rest of non-Annex I countries: For India, projections range from a seven-fold increase in REMIND to an almost eleven-fold increase in IMACLIM; for the rest of non-Annex I countries this range extends from roughly four-fold in REMIND and WITCH to an almost eight-fold rise in IMACLIM. This is again a result of the combination of energy efficiency trends and regional GDP developments, as IMACLIM combines high growth and less efficient patterns of development for those two regions.

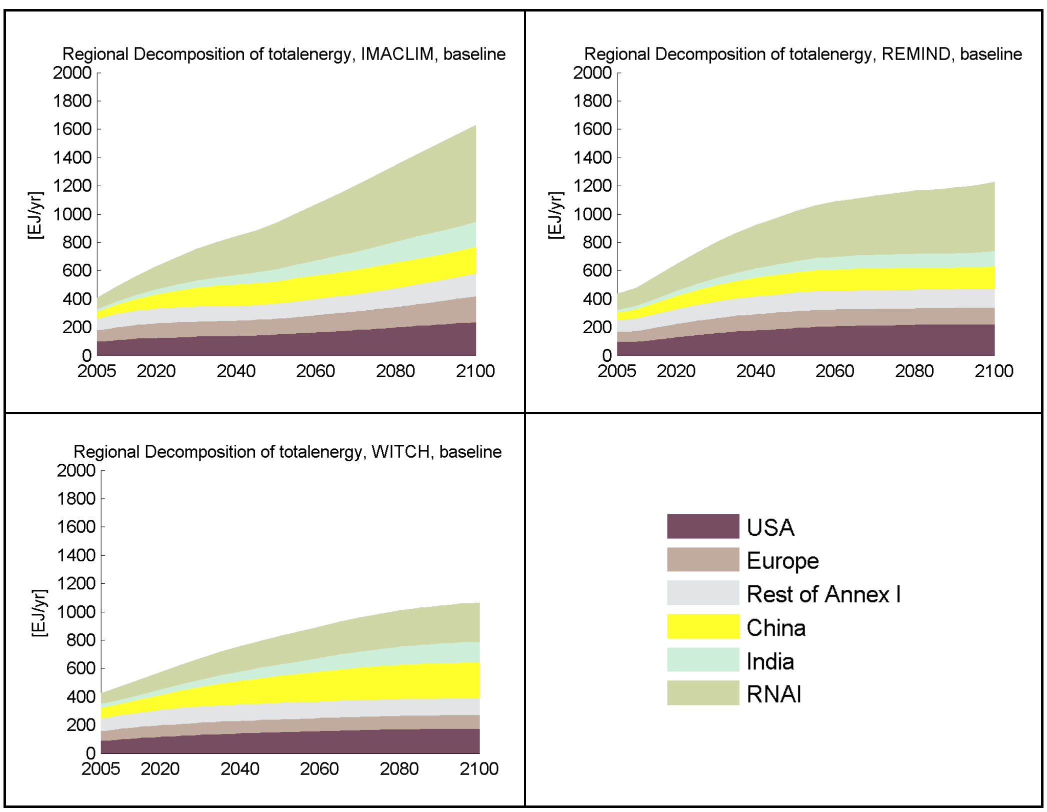

Figure 5: Primary energy consumption by regions

Energy Intensity

All three models assume continuous improvements in energy efficiency due to technological progress. This results in average annual declines in energy intensity (i.e. the ratio between primary energy and GDP) ranging from 0.9% (IMACLIM) to 1.1% (WITCH), shown in Figure 6. Therefore, at the end of the century, every US$ of final output will be produced using considerably less energy than today – a reduction of roughly two thirds in REMIND and WITCH and more than half in IMACLIM. However, it should be kept in mind that in spite of decreasing energy intensities GDP increases more than proportionally in all three models, resulting in steadily increasing levels of energy consumption2.

Differences between models are more pronounced for the short term forecasts. For instance, due to strongly increasing energy demand projected for the 2005-2030 period, improvements in energy intensity for IMACLIM and REMIND (0.6% and 0.7%, respectively) fall short of their long-run average. In IMACLIM, this reflects inertia on the renewing of technologies and equipments, which puts constraints on the improvement of global energy efficiency, while in REMIND the observed behaviour is due to especially strong increases in energy demand during the respective time period. These two models diverge in the long-run, with IMACLIM being less optimistic than REMIND for ultimate efficiency gains. This results from technical boundaries constraining long-term efficiency potentials and the deployment of coal-to-liquid, which lowers the efficiency of the fuel production process. The reference scenario for WITCH, on the other hand, turns out to be more optimistic, projecting annual improvements in energy intensity of 1.4% over the same time horizon.

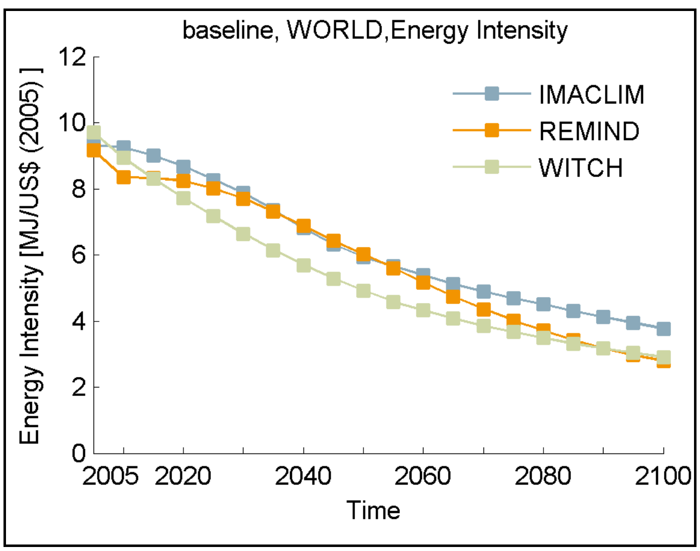

Figure 6: Global energy intensity

[2] Differences between models in the initial year 2005 are due to the fact that the models use different data sets for calibration, which show some differences with regard to primary energy consumption (especially for traditional biomass).

Fossil Fuel Prices

The different visions of technological progress described above also have impacts on fossil fuel prices. The general theme describing the availability of fossil fuels in RECIPE is one of abundant coal and relatively scarcer reserves of oil and gas. In all three models fossil fuel prices are determined by the interplay between supply and demand; hence, they are functions of parameters such as resource availability, extraction costs, substitution possibilities in final energy use, as well as technological progress and learning in the fossil and the renewable energy sectors.

As can be seen in Figure 7, the ranking of fossil fuels according to their economic value, which is determined by the relative flexibility of their use, is identical across models and does not change over time: oil is the most expensive fossil fuel, closely followed by gas, while coal remains the cheapest source of energy by far. Due to increasing scarcity of oil reserves and constraints on the temporal availability of feasible alternatives, IMACLIM and WITCH project substantial price increases for oil and gas over the course of the century. Prices rise less sharply in REMIND, owing to a higher flexibility to substitute away from final energy derived from oil and gas to other forms of energy. Coal prices stay relatively flat in IMACLIM (where coal is modelled as a backstop technology) and WITCH, but increase significantly for REMIND (due to a rising economic value arising from the universal applicability of coal in the latter model's representation of the energy system).

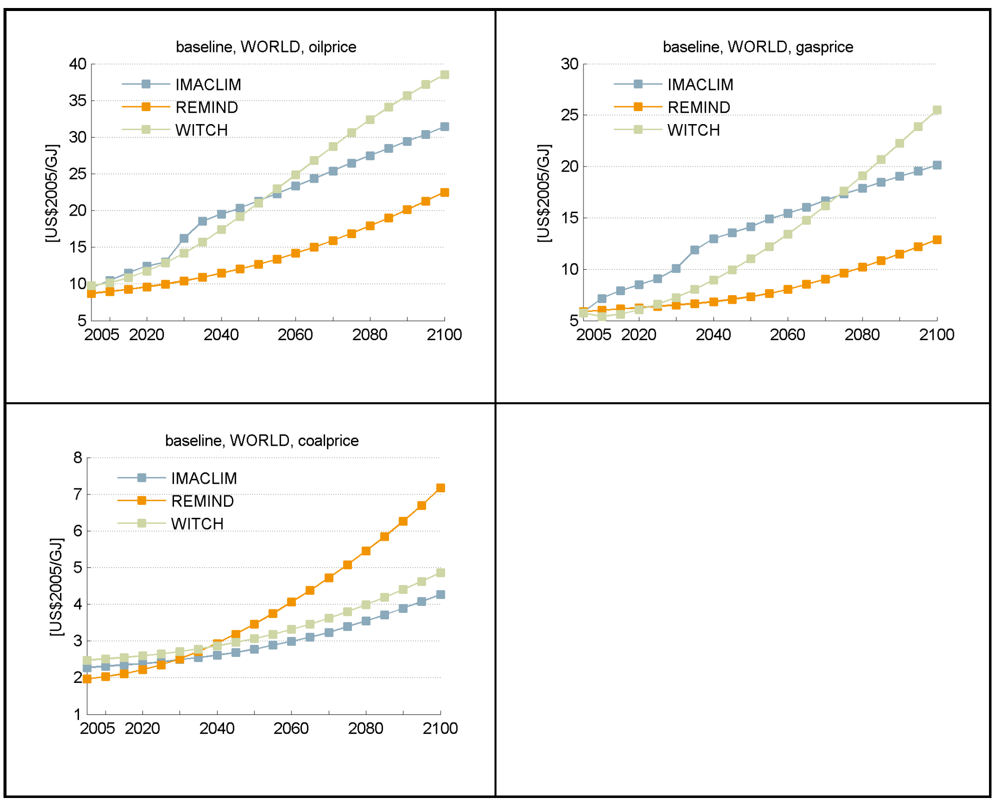

Figure 7: Fossil fuel prices

4 Carbon Emissions and Climate

Carbon Emissions

Due to the different assumptions regarding technological developments described in the previous section, the three models generate quite different emission pathways for their respective reference scenarios, as depicted in Figure 8. As energy use rises drastically and coal is modeled as a backstop technology in IMACLIM, this model projects steadily rising carbon emissions. In REMIND, novel energy technologies become competitive via learning-by-doing, so that it is optimal in this model to predominantly use fossil fuels early in the century and substitute fossil for non-fossil alternatives later on. For WITCH, improvements in energy efficiency permit maintained economic growth with ever smaller increases in energy use. Therefore, given a roughly constant energy mix, carbon emissions follow the concave trend displayed by energy consumption. In any case, the three models agree that in the absence of climate policy annual carbon emissions will continue to climb to annual rates that are a multiple of what they are today.

IMACLIM predicts the largest increase in annual carbon emissions, in line with the assumption of steadily increasing energy use without major changes in the energy mix. In the IMACLIM reference scenario energy related carbon emissions climb even more rapidly than energy use, from 27.5 GtCO2 in 2005 around 66 GtCO2 in 2050 and reach 124 GtCO2 in 2100. This fast increase of carbon emissions in the second half of the century is due to the diffusion of coal as a substitute for oil (through coal-to-liquid), which leads to a more carbon-intensive fuel production. Expressed as an annual growth rate, this almost 5-fold increase from the initial value calculates to a rise of 1.5% per year.

WITCH also predicts a steady rise in annual carbon emissions, albeit at a lower rate than IMACLIM. By 2050, annual emissions are projected to have more than doubled and stand at 62 GtCO2. Due to advances in energy efficiency and high fossil fuel prices, emissions grow less rapidly over the second half of the 21st century, almost stabilizing at 86 GtCO2 in 2100. This more than three-fold increase compared to the year 2005 equals a growth rate of 1.1% per year.

For REMIND annual carbon emissions exhibit the highest rates of growth until 2040, due to the pronounced rise in energy demand and the continued dominance of fossil fuels, amplified by the growing share of coal in the energy mix. However, rising extraction costs of fossil fuels accelerate structural changes in the energy system by the middle of the century (through which alternative energy technologies become more attractive); annual carbon emissions peak in 2055 at about 77 GtCO2 and decline modestly afterwards to an annual rate of 72 GtCO2 in 2100; over the century, the average increase is hence only 0.9% per year.

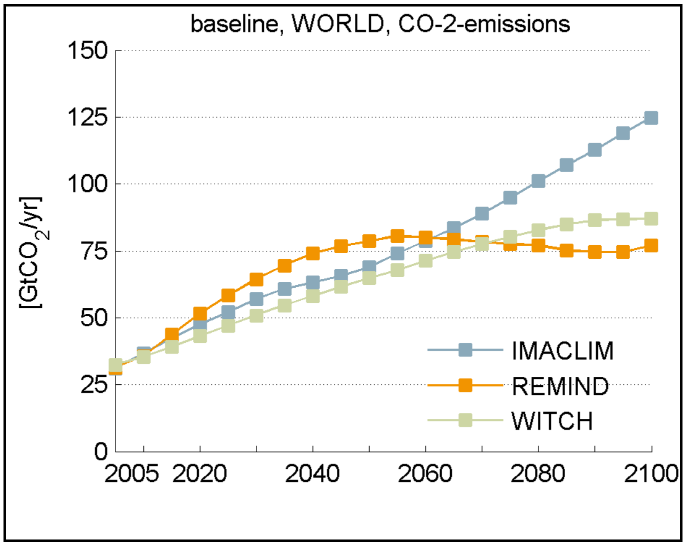

Figure 8: Global Carbon Emissions

Comparing the regional composition of carbon emissions across models (see Figure 9), we find a pattern very similar to the one that applies for energy use described in the previous section: While in 2005 industrialized countries accounted for roughly half of global carbon emissions, the by far largest future increases are expected to occur in the developing world. The models agree in their conclusion that China, India, as well as the rest of non-Annex I countries are projected to constantly increase their shares in total emissions, even though there is some variation in the regional distribution of emissions. This applies in particular to the large increase in emissions of non-Annex I countries projected by IMACLIM, corresponding to the rising demand for mobility in those developing regions, which is mainly fueled by coal-to-liquid.

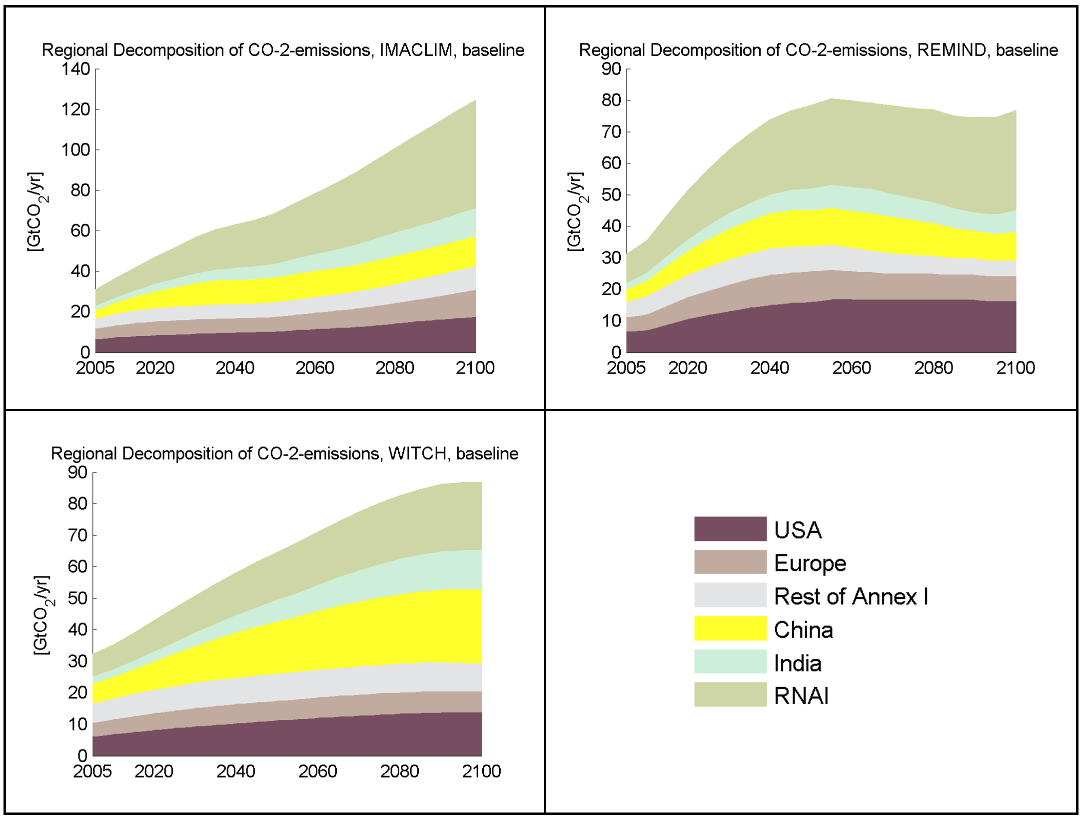

Figure 9: Carbon Emissions by regions

Carbon Intensity

The differences in model behaviors can also be analyzed by taking a closer look at carbon intensity of energy production (i.e. the amount of carbon emitted per unit of energy produced), shown in Figure 103. For IMACLIM and WITCH, carbon intensity is predicted to fluctuate around a long-term upward trend with a slight increase over the century. This is in line with the assumption that the energy mix

[3] Again, differences between models for the initial year 2005 owe to the fact that the models use different data sets for calibration

does not change considerably over time and remains heavily geared towards the use of fossil fuels in those two models. However, due to pronounced differences in energy demand and different rates of penetration of the coal-to-liquid option, emissions are considerably lower in WITCH compared to IMACLIM, especially for the second half of the century. REMIND, in turn, predicts growing use of coal and a notable increase in carbon intensity until 2030 but a decrease thereafter when renewable energies and other non-fossil energy carriers become increasingly competitive. These results again illustrate the importance of deployment of new technologies in the energy sector.

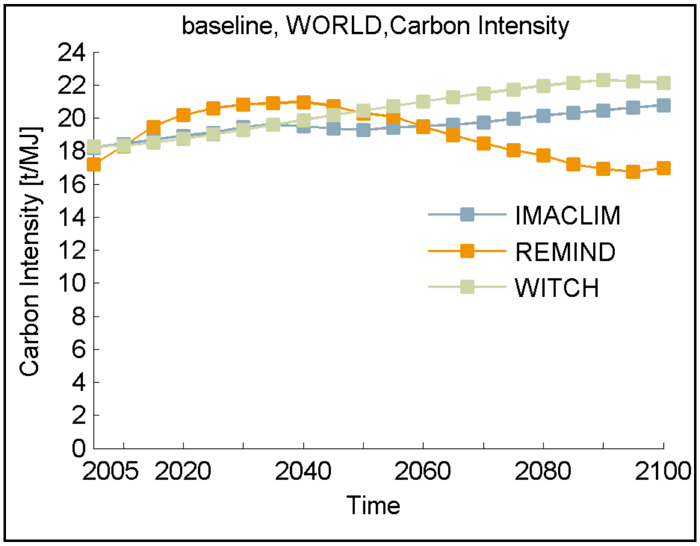

Figure 10: Global carbon intensity

Atmospheric Concentrations and Temperature

The unabated rise in energy related carbon emissions projected by all three models results in atmospheric concentrations of carbon dioxide between 730ppm CO2 (WITCH) and 840ppm (IMACLIM) in 2100, depicted in Figure 11. Increases of atmospheric CO2 concentrations of this magnitude equal an almost tripling of pre-industrial levels of roughly 280ppm. Due to the inertia of the Earth's climate system, responses to changes in atmospheric GHG concentrations occur with long time lags, making comparisons between models highly dependent on the characteristics of the particular climate module employed. For this reason, we report changes in temperatures in equilibrium values (i.e. the rise in temperatures in the very long run, when the Earth's climate system has reached its new equilibrium within a few centuries following changes in radiative forcing due to higher GHG concentrations). As can be seen from Figure 12, the respective concentrations projected by the models for the year 2100 correspond to global mean temperature increases between 3 and 7ºC. Global warming of this magnitude occurring over the time-scale of only a few centuries would be unprecedented in earth's history and entail a high likelihood of catastrophic impacts.

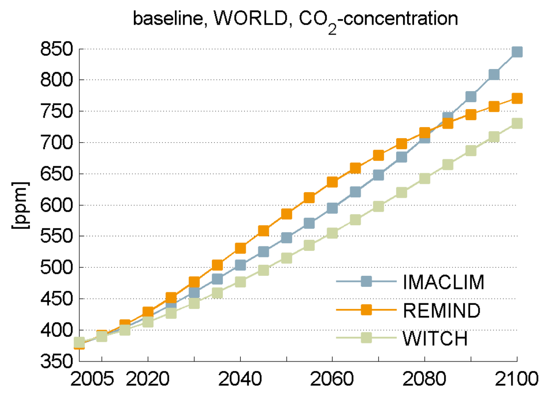

Figure 11: Atmospheric CO_2 concentrations

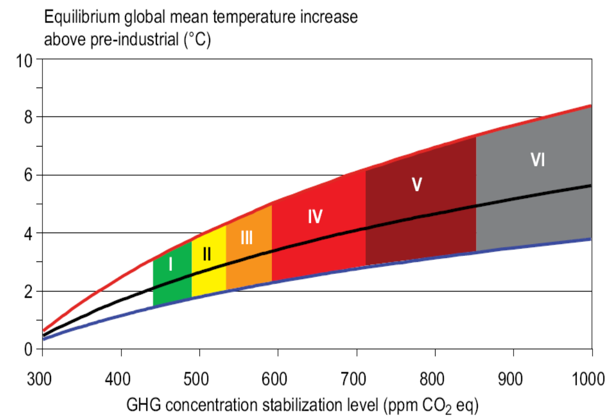

Figure 12: Equilibrium mean temperature increase. Source: IPCC (2007)

5 Sensitivity Analysis of Results

In order to evaluate the robustness of our results and to ensure that they are not driven by particular constellations of individual key parameters, two types of sensitivity checks were carried out. As model results depend on a large variety of parameters (and their possible combinations), carrying out a full sensitivity analysis on the whole range of parameters was judged to be too time-consuming, given the complexity of the models and their demand on computational resources. Therefore, the focus of the sensitivity analysis presented in this section is on assessing the impact of two parameters that were deemed crucial for the future development of the world energy system: the assumption of scarce coal reserves and expected rates of technological learning. Firstly, as coal is assumed to be in abundant supply, the reference scenario was recalculated assuming scarce coal resources by lowering reserves by 33%. Secondly the modelling teams varied their respective assumptions concerning technological learning for renewable energies by adjusting learning rates 50% down- as well as upwards and raising/lowering floor-costs by 30%. For both robustness checks, we analyse the impact of changes in parameters on each model’s energy mix and the total amount of energy consumed.

Availability of Coal

Assuming lower availability of coal results in higher extraction costs and thus higher coal prices and can be expected to result in two kinds of effects: Firstly, substitution of coal with other types of energy carriers as an energy source, and, secondly, substitutions away from energy as a production factor towards capital and labour in the production of final output. For this reason, the baseline scenario was recalculated with coal reserves lowered by 33%. As can be seen in Figure 13, none of these effects appears to be particularly pronounced in any of the three models. Total energy consumptions are basically unchanged in IMACLIM and

WITCH. The same is true for the energy mix in WITCH, while in IMACLIM some energy from fossil fuels is replaced by biomass, most likely in transportation, where biofuels are increasingly used to make up for the reduced availability of transports fuel from coal-to-liquid. In REMIND, total energy consumption drops slightly, and non-fossil energy carriers, especially renewables and biomass, gain in importance. In any case these changes are rather small and do not alter the general picture that emerged from the discussion in preceding sections.

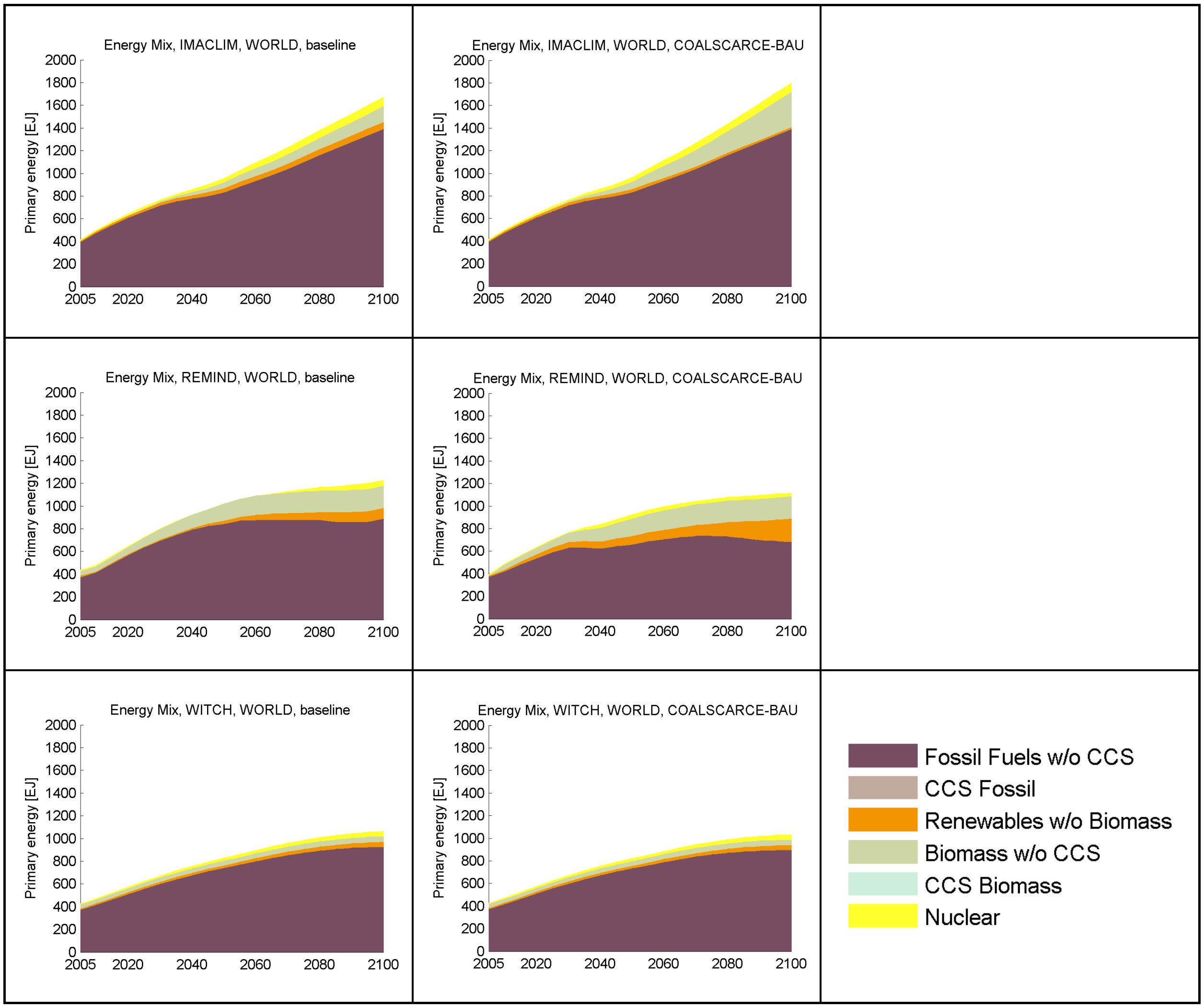

Figure 13: Sensitivity of the energy mix with respect to changes coal availability

Learning Rates

As a second robustness check, rates of technological learning (affecting investment costs and the efficiency of renewable energies) were adjusted 50% down- as well as upwards compared to the standard reference scenario. In addition, floor-costs (i.e. minimum investment costs) were raised or lowered by 30% in the high- and low-learning scenarios, respectively. The results are shown in Figure 14. We do not observe significant changes in total energy consumption in any of the three models. IMACLIM's energy mix remains practically unchanged. In REMIND, higher (lower) learning rates increase (decrease) the share of renewable energies, most notably at the end of the century. The same is true for WITCH; however, these changes are again of comparatively small magnitude.

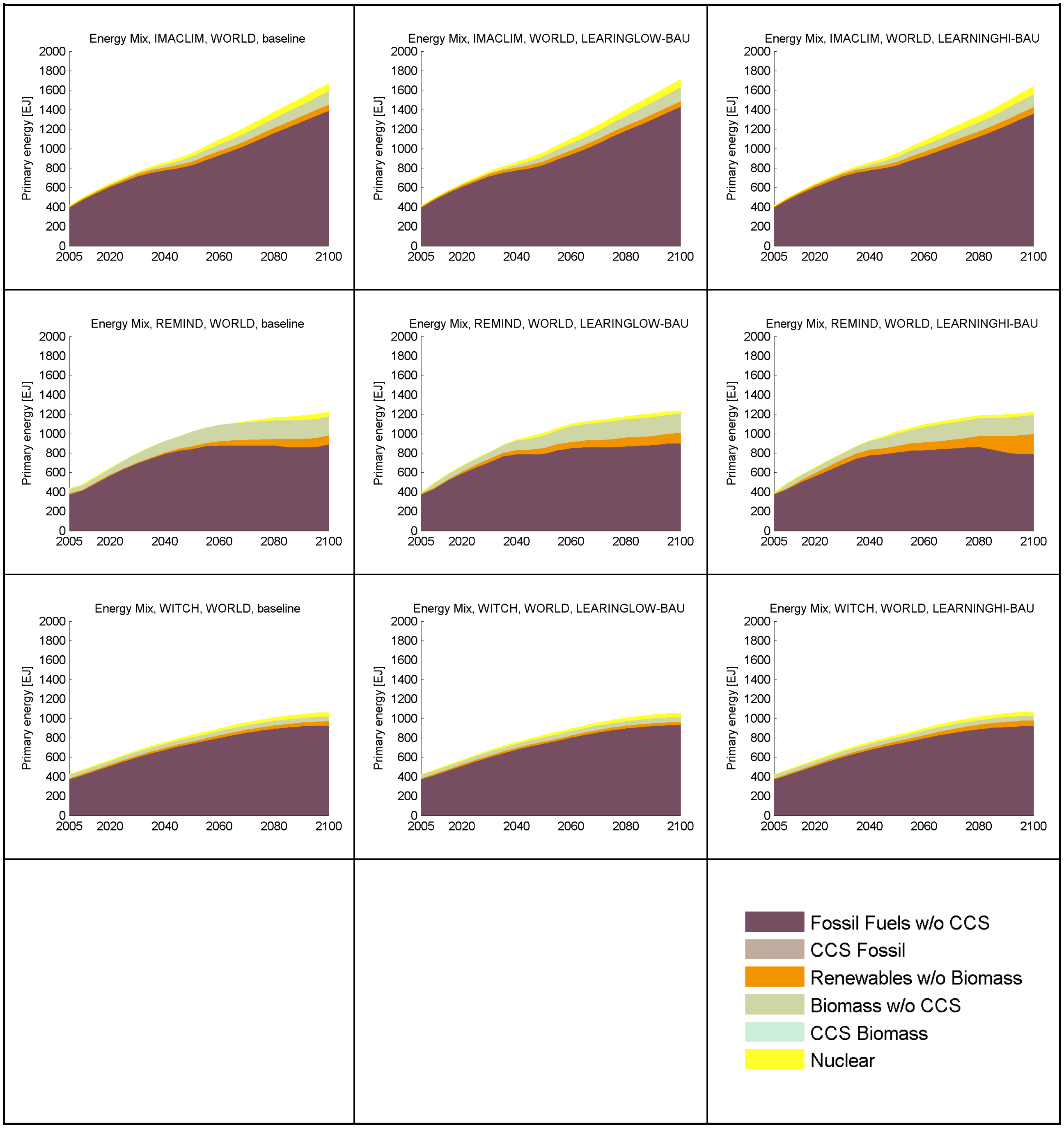

Figure 14: Sensitivity of the energy mix with respect to changes in learning rates

6 Comparison to Other Studies

Recently a number of prominent assessments of future energy use and carbon emissions have been carried out. Two of the most cited ones include the IEA's World Energy Outlook 2008 (WEO) and the Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations by the U.S. Climate Change Science Program (CCSP, 2007). In the following, we briefly compare our model results to the business-as-usual scenarios depicted in the aforementioned studies.

Comparison to WEO

The WEO projections, derived from the IEA's World Energy Model (WEM), apply in the short and medium term. They assume moderate population growth averaging 1% per year, and rapid growth of world GDP of 3.3% over the period 2006-2030. This is in line with the assumptions in RECIPE, where the average annual growth rate over the same period lies between 3.1% and 3.4%, depending on the model. Despite optimistic assumptions concerning energy intensity, high GDP growth rates are responsible for a rise of primary energy demand of 45% in the period 2006-2030, corresponding to an annual increase of 1.5%. The largest part of this increase is met by fossil fuels and mostly takes place in developing countries (with China and India alone accounting for more than half of the total increase). These developments cause global energy-related carbon emissions to be 45% higher in 2030 compared to 2006. The WEO numbers are lower than those projected by any of the models in the RECIPE model comparison. They are closest to WITCH results, where increases in energy use and carbon emissions to the tune of 60% are projected, but significantly lower than those for IMACLIM and REMIND, where energy use increases by more than 80%, and carbon emissions approximately double until 2030. These different results are mainly due to different assumptions concerning energy intensity between WEM and WITCH on the one hand, where energy intensity improves by 1.8% and 1.4% respectively, and IMACLIM and REMIND on the other, where the improvements are only 0.6% and 0.7% respectively.

Comparison to CCSP

The CCSP study compares the Integrated Assessment Models IGSM, MERGE, and MiniCAM. This study assumes a demographic transition by the middle of the century and a stabilising or slightly declining population thereafter, resulting in a global population between 8.6 and 9.9 million in 2100, depending on the respective model. Global GDP growth is projected to lie between 2.2% to 2.5% over the course of 100 years. Hence, the assumptions on long-term population and GDP growth are very similar to those in RECIPE. In the CCSP reference scenario, the models employed predict a strong increase in primary energy consumption to levels in 2100 three to four times as high as the year 2000 value of 400 EJ. This is not too far away from RECIPE, where increases to levels between two-and-a-half fold (WITCH) and five-fold (IMACLIM) were found. The three CCSP reference scenarios show considerable differences in term of the respective energy mix. However, all of them predict substantial increases in fossil as well as non-fossil fuel use and a continued dominance of fossils throughout the century. As a result, carbon emission from combustion of fossil fuels and industrial sources are expected to rise almost linearly to between 82 GtCO2 and 88 GtCO2 per year in 2100. Compared to emissions in the RECIPE reference scenario, the latter values come pretty close to those predicted by WITCH (86 GtCO2), but are slightly above those in REMIND (72 GtCO2), and well below those in IMACLIM (124 GtCO2).

7 Discussion of Model Results and Conclusions

As the preceding sections clearly illustrate, the three models employed in the RECIPE project represent very similar assumptions regarding the future development of socio-economic drivers of global change (i.e. global population and world GDP), but very different visions when it comes to the development of new technologies, and hence the associated levels of energy use and carbon emissions.

In terms of energy use and carbon emissions, the IMACLIM reference scenario can best be described as a ‘black baseline’: Energy consumption rises nearly fourfold over the century. At the same time the energy mix remains dominated by the use of fossil energy carriers. Coal, of which large amounts are cheaply available, plays a more and more important role. This results in a dramatic, almost five-fold, increase in annual carbon emissions to levels which are much higher than predicted by the other models.

The REMIND reference scenario is what can best be characterised as a ‘green baseline’: While energy consumption is expected to rise rapidly until 2040 and increase more than three-fold until 2100, a considerable part of this increase can be met by the provision of carbon-free sources of energy, above all biomass and renewables. Therefore, carbon emissions increase rapidly until 2040, but stabilize at a comparably low level and even decline after 2050 to a final level that is the lowest of the three models compared in this study.

The WITCH reference scenario lies somewhere in between REMIND and IMACLIM and should be considered a ‘moderate baseline’. While the energy mix hardly changes and most of the world’s energy needs are met with fossil fuels, the total amount of energy consumed increases at ever lower rates and reaches an almost constant level roughly two-and-a-half times its current value in the final years of the century. Therefore, annual carbon emissions increase steadily, albeit at lower rates than for the other models, and start to level off around 2080.

Sensitivity checks suggest that the results appear to be quite robust to variations in exogenous assumptions regarding two important model parameters: coal reserves and learning rates for renewable energies. Neither lowering assumptions on economically exploitable coal reserves by 33%, nor up- or downward adjustments of 50% in rates of technological learning (in combination with floor-costs that are raised/lowerd by 30%, respectively) for renewable energies result in drastic changes in the total amount of energy consumed or the primary energy mix.

A comparison to two other studies reveals some striking similarities as well as differences: The WEO foresees increases in energy use and carbon emissions close to 45% in the period 2006-2030, significantly less than what the models employed in this study project. This is especially true for IMACLIM and REMIND, which expect a significantly higher increase in energy use (>80%), and more than a doubling of annual carbon emissions until 2030. To a large part these differences arise from different assumptions on future improvements in energy intensity, for which the IEA's WEM and WITCH are more optimistic than IMACLIM and REMIND. For the long-run both REMIND and WITCH arrive at results comparable to those of the CCSP study, namely a roughly three- to four-fold increase of energy use and a threefold increase in carbon emissions. IMACLIM, in turn, is more pessimistic, predicting a four-fold increase in energy use and a five-fold increase of annual carbon emissions by the year 2100.

References

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