FROM CARBONIZATION TO DECARBONIZATION? – PAST TRENDS AND FUTURE SCENARIOS FOR CHINA'S CO$_2$ EMISSIONS

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Abstract

Along the lines of the Kaya identity, we perform a decomposition analysis of historical and projected emissions data for China. We compare the results with reduction requirements implied by globally cost-effective mitigation scenarios, and official Chinese policy targets. For the years 1971-2000 we find that the impact of high economic growth on emissions was partially compensated by a steady fall in energy intensity. However, the end–and even reversal–of this downward trend, along with a rising carbon intensity of energy, resulted in rapid emission growth during 2000-2007. By applying an innovative enhanced Kaya decomposition method, we also show how the persistent increase in the use of coal has caused carbon intensity to rise throughout the entire time-horizon of the analysis. These insights are then compared to model scenarios for future energy system developments generated by the ReMIND-R model. The analysis reaffirms China's indispensable role in global efforts to implement any of three exemplary stabilization targets (400, 450, or 500 ppm CO$_2$-only), and underscore the increasing importance of carbon intensity for the more ambitious targets. Finally, we compare China's official targets for energy intensity and carbon intensity of GDP to projections for global cost-effective stabilization scenarios, finding them to be roughly compatible in the short- to mid-term.

Keywords: *China, Carbon Intensity, Kaya-Decomposition, Climate Policy*

1 Introduction

China's breath-taking economic growth during the last decades has helped to lift hundreds of millions of people out of poverty. But, this success has also turned China into the world's largest emitter of carbon dioxide.[1] Figure 1 depicts the influence of different countries on global emissions growth for the period of 1971-2007. It highlights the rapid increase of China's 'weight' in recent years. In fact, the data indicate that around 50% of the total global increase in CO_2 emissions since 2002 can be attributed to China alone.[2]
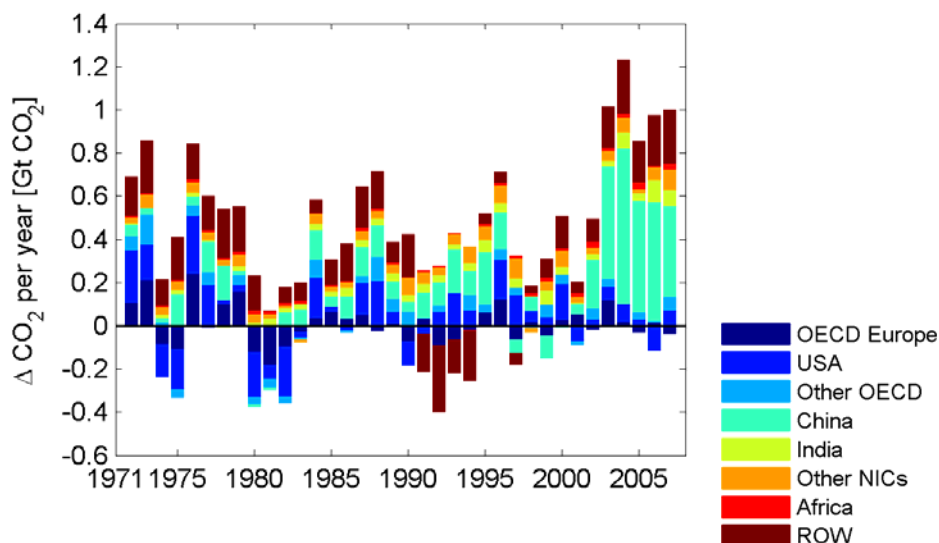

Figure 1: Influence of selected countries and country groups on global CO_2 emissions growth.

In the face of anthropogenic climate change, China's emission intensive growth poses a serious challenge for the success of global mitigation efforts. However, from an equity point of view, China and other developing countries cannot be denied the right of economic catch-up with industrialized countries, which have supported their economic development with cheaply available fossil fuels for centuries. Solving this dilemma will be crucial for successfully averting dangerous climate change.

Given its dramatic emission increase, its persistent economic growth on a high level, and its high reliance on carbon-intensive coal, China is often considered to be a case of its own. This is also reflected by the high attention given to China in the academic literature, which we will review in the first part of this paper. However, what are specific characteristics to turn China into a special case? And what are feasible strategies for putting the Chinese economy on a path towards low-carbon growth, without

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[1] Unless otherwise specified, all historical data used in this paper are taken from IEA (2009a) and refer to CO_2 emissions from fossil-fuel combustion (IEA sectoral approach). GDP data are expressed in purchasing power parity (PPP).
[2] Interestingly, it also shows that hardly any country ever managed to reverse the trend of positive emissions growth, except in times of economic crisis (former Soviet-Union countries in early 1990s), and as a reaction to the 1973 and 1979 oil crises.

compromising the need for development? More precisely, are the country's own targets sufficient?

To answer these questions we first systematically investigate historical emissions and their driving forces along the lines of the Kaya decomposition (Kaya 1990), considering in particular energy intensity, i.e. energy used per unit GDP, and carbon intensity, i.e. carbon emissions per unit energy. We find that decreasing energy intensity has primarily contributed to decelerating emission growth in the last decades of the 20th century, while a reversed trend of energy intensity and a continuously carbonizing and fast growing economy were responsible for China's accelerated emissions growth in the first decade of the 21st century. We then introduce an enhanced decomposition technique for analyzing the carbon intensity time-series to determine how the influence of coal has evolved over the last three decades. It turns out that exploiting coal indeed had a significant impact on China's emission growth as compared to other transitional countries, industrialized countries, and the global average; however, the scale of China's economic growth very clearly constitutes the main driver behind its increasing emissions.

The article then confronts the characteristics of China's energy system with a set of globally cost-effective mitigation scenarios obtained from the integrated assessment model ReMIND-R (Leimbach et al. 2010a; Leimbach et al. 2010b; Bauer et al. 2011). Our results suggest that under business-as-usual assumptions, China's emissions could increase about threefold by 2050, underlining its status as a crucial actor in global mitigation efforts. In fact, in a globally cost-optimal scenario aiming at stabilization of atmospheric CO_2-concentrations at 450 ppm CO_2-only, China's emissions would be 43% lower than in the baseline. Applying the decomposition methodology previously used with historical data on model results further indicates that in addition to energy efficiency improvements, reversing the trend in carbon intensity is essential for transforming the Chinese energy system. Renewable energies are identified as the most important option for decreasing carbon intensity, with significant but smaller roles for the expansion of biomass, nuclear energy, and CCS.

Finally, we present an evaluation of China's current energy and mitigation policies and international pledges. In fact, even though China as a developing country has so far refused to accept binding emission targets, it has put a number of policies into place which directly or indirectly aim to reduce energy- as well as carbon intensity. We find China's short- to mid-term targets for energy- and carbon-intensity of GDP to be in line with the values suggested by our cost-optimal 450 ppm stabilization scenario, while the target for renewable energy falls short. The Chinese government's objective formulated for nuclear energy in 2020 lies significantly above our benchmark values.

2   Literature Review

Numerous previous studies have applied decomposition methods to analyze the driving forces behind past changes in China's energy use and carbon emissions: Raupach et al. (2007) point out the importance of China's high rates of economic growth that – together with other developing countries – account for the lion's share of global emission

increases. This conclusion is confirmed by Zhang et al. (2009), who show that for China economic activity had the largest effect on CO_2 emission changes during 1991–2006, while energy intensity declined. CO_2 intensity of energy and structural changes are found to have relatively small overall impacts. In the same vein, Liao et al. (2007) decompose industrial energy intensity in China into sectoral composition of energy use and efficiency improvements and find that the decline in energy intensity between 1997 and 2002 can mainly be attributed to efficiency improvements. Zhao et al. (2010) show that energy savings from efficiency improvements have occurred in China's industrial sector, but that the expansion of production scale and a heavier industrial structure contribute to increases in total energy use. Finally, Guan et al.'s (2009) decomposition of carbon emissions by economic sectors emphasizes the role of global trade for China's development model, as it indicates that Chinese export production is responsible for half of the emission increase in the period 2002 - 2005.

The bottom-up model presented by Cai et al. (2008) suggests that China's emissions will continue to grow quickly until at least 2020 in any case, but that a sustainable development strategy and additional future unilateral policies might help to slow down the increase. All bottom-up studies reviewed (Dai and Zhu, 2005; IEA, 2007; Cai et al., 2008; Ma et al., 2009) agree in their evaluation of energy efficiency and renewable energies as the dominant mitigation options. Dai and Zhu (2005) as well as the IEA World Energy Outlook (IEA, 2007) further emphasize the potential role of structural change and restructuring of energy-intensive sectors. Ma et al. (2009) stress the pivotal role of decarbonizing the power sector (while they identify a significantly lower mitigation potential in transportation) and mandate R&D in solar and CCS for future deployment.

The importance of energy efficiency improvements and renewable energies as the most prominent mitigation options is confirmed by several top-down studies that construct long-term scenarios for the Chinese energy system (Larson et al. 2003; van Vuuren et al. 2003; Wang and Watson 2008). Larson et al. (2003), also suggest that coal gasification technologies (that co-produce electricity and liquid and gaseous energy carriers) combined with some CCS might be a viable low-cost mitigation option, while Wang and Watson (2008) underline the importance of economic and industrial structural change in order to achieve the reductions required in their climate policy scenarios.

The decomposition studies cited above heavily focus on changes in industrial structure and efficiency improvements to explain changes in energy intensity, but devote little attention to the factors affecting the carbon intensity of energy production, i.e. the energy mix. Modeling results, on the other hand, often feature a technology-rich description of the energy system, but suffer from a lack of empirical backing and do not discuss the implications of their findings with regard to energy and climate policies that are either already implemented or currently under discussion. To fill these gaps and contribute to the existing literature, this paper (1) introduces an enhanced decomposition methodology for emissions time series that encompasses changes in the energy mix, (2) applies this decomposition to plausible future scenarios that are consistent with historical

developments, and (3) uses the insights gained to evaluate China's current energy and mitigation policies and international climate policy pledges.

3 China's Carbon Emissions in Retrospective

This section investigates the evolution of China's energy-related emissions between 1971 and 2007 and identifies major emission drivers at the macro level. To this end, we consider the time-series of the standard Kaya factors (Kaya 1990), which are commonly used to study emission dynamics (see e.g. Rogner et al. 2007), and include: population, GDP per capita, energy intensity of GDP, and carbon intensity of energy. In order to determine the characteristics of historical emission dynamics, data for China are confronted with world averages, and an aggregate of six newly industrialized countries composed of Brazil, India, Indonesia, Mexico, South Africa and South Korea. At the starting point of our analysis in 1971, the NIC aggregate had a total population nearly on par with China's (884 million versus 845 million) and GDP and emissions per capita were of similar magnitude, too.

Analysis along Kaya Factors

Analyzing historical emissions data in terms of the underlying Kaya components and carrying out a comparison between world average, OECD,[3] China, and NIC provides a number of insights. First, we observe that China and NIC have followed a similar general trend of per-capita CO_2 emissions until the early 2000s, when emission growth in China accelerated substantially (Figure 2b). Initially, NIC had a higher GDP per capita but were surpassed in the year 2000 by the faster growing China (Figure 2a).

Second, for both China and NIC the evolution of carbon intensity of energy has been characterized by an upward trend, albeit with a much faster overall rise and higher base level in China. Although China's and NIC's carbon intensity were initially below the world average, a persistent rise in China and the negative trend in the world average has driven Chinese carbon intensity above the global and OECD average by the early 1980s, while NIC's carbon intensity converged towards global and OECD levels (Figure 2d). Today, China's carbon intensity is about 30%-35% higher than global and OECD averages, since - after half-a-decade of stabilization and short decline after 1995 - it has again strongly risen after 2001.[4]

Third, the starkest difference with respect to all other regions is seen in China's extremely high energy intensity in the 1970s, and its subsequent sharp drop (Figure 2c). It fell below world averages in the late 1990s, and touched the even lower OECD level shortly thereafter.[5] Although it eventually returned to world average levels, it has recently started to fall again, which could be explained by the latest 2006-2010 five-year-plan to reduce

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[3] For the analyses presented here, OECD covers all OECD countries but Korea and Mexico.

[4] However, it has been suggested that manipulations in the official statistics of energy supply from coal–rather than real changes in the energy system–were responsible for this drop-and-rebound effect in carbon intensity (Streets et al. 2001, Peters et al. 2007).

[5] This observation holds when GDP is considered in PPP. See below for a detailed discussion on the sensibility of this assumption.

energy intensity by 20 percent and related measures (see also Section 5 in this paper). For NIC, energy intensity was initially below world and even OECD levels, but gradually converged to the (steadily declining) OECD level.

a) GDP per capita

b) Per capita emissions

c) Energy Intensity
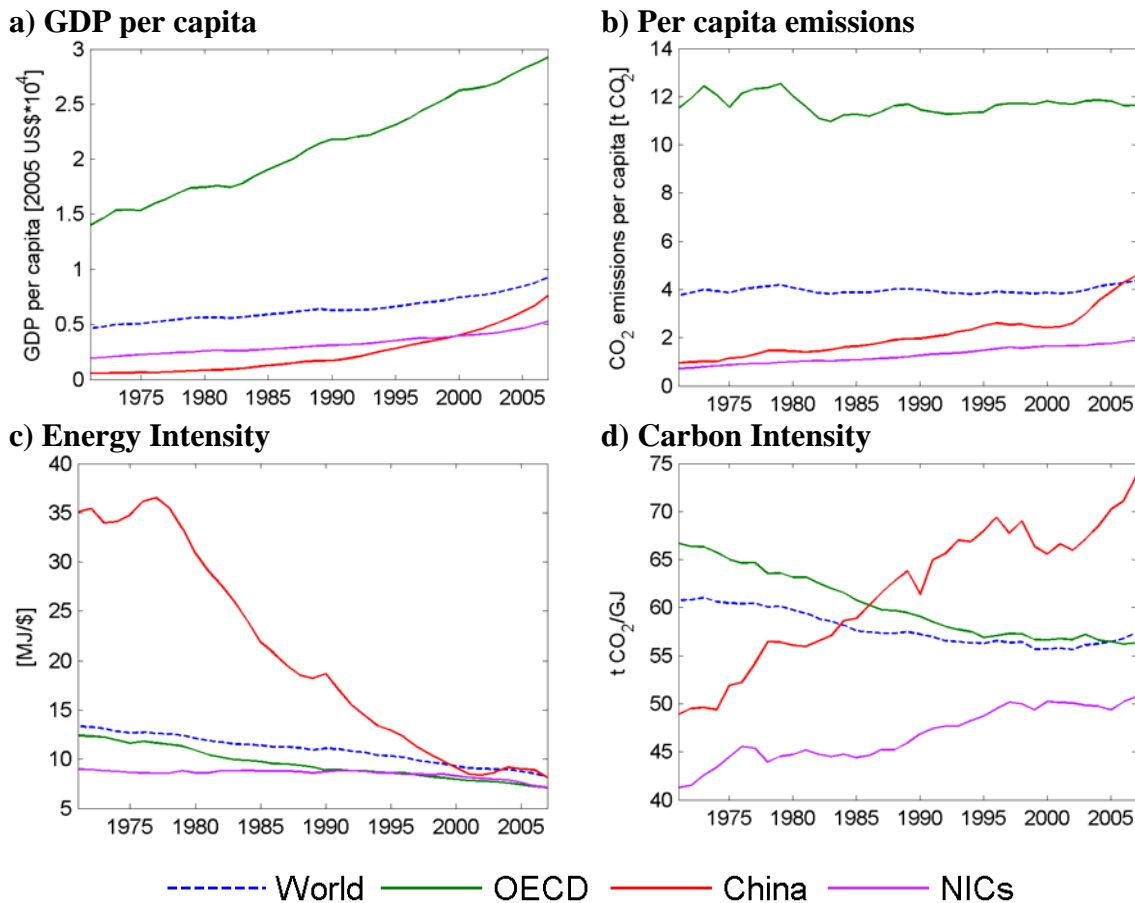
d) Carbon Intensity

Figure 2: Key indicators of the Chinese economy compared to values for OECD, NIC and world average. NIC represents an aggregate of six newly industrializing countries (Brazil, India, Indonesia, Mexico, South Africa and South Korea).

Fourth, by today China's per capita emissions and energy intensity are very close to world averages, while GDP per capita is still below the world average and carbon intensity is considerably higher. Overall, we can conclude that China–as compared to NIC–was actually quite an average country also in the past, except for two aspects: its persistently high growth of GDP until today and its dramatically high initial energy intensity that fell just as dramatically until the year 2000. With regard to CO_2 emissions, the two 'particularities' worked in opposite directions, at least until the year 2000. Thereafter, energy intensity reached 'normal' levels, which in combination with rising carbon intensity resulted in the well-known boost in Chinese per-capita and absolute emissions.

Influence of the GDP accounting method

The findings presented above are sensitive on whether we choose GDP considered in market exchange rates (MER) or in purchase power parities (PPP) as presented in Figure 3.
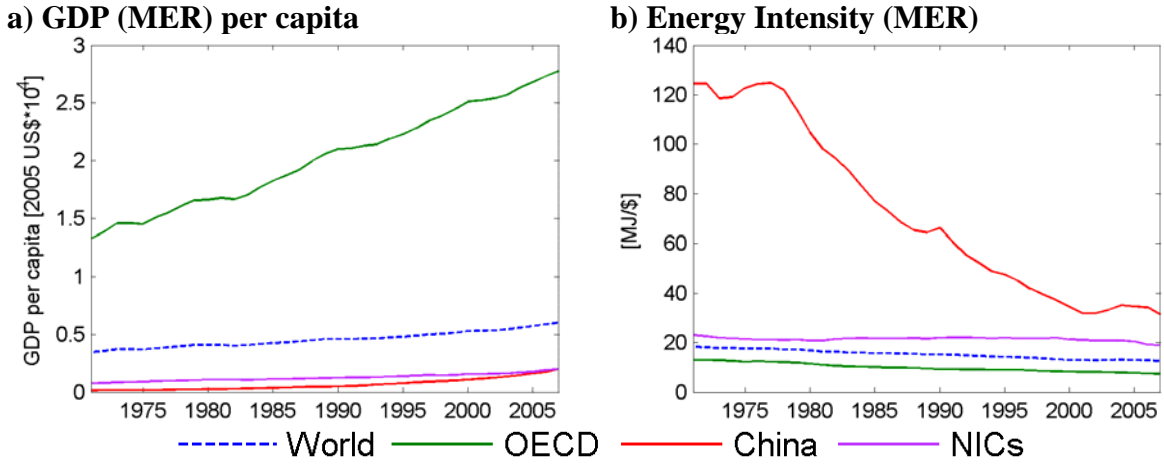
a) GDP (MER) per capita

b) Energy Intensity (MER)

Figure 3: GDP and energy intensity for the World, OECD countries, China and newly industrializing countries (NIC) in MER

Using MER the pattern of energy intensity development does not change considerably compared to using PPP as shown in Figure 2. However, we find that China's energy intensity in 2007 was about twice the world average and three times the OECD average. This implies that there is some room for improvement with respect to energy intensity improvements in the future. With respect to the question, which approach should be preferred, some difficulties have been identified using either approach and there has been a lively debate for years. Briol and Okugu (1997) argue that PPP systematically leads to higher energy efficiency levels in developing countries. Nordhaus (2007) underlines the shortcomings of both approaches and proposes an alternative approach, which shall not be considered here. For the Kaya analysis that is presented in the following, the differentiation does not cause major deviations, as we concentrate on relative changes, which are majorly independent from the choice of the GDP reporting. In the IPCC AR4 (Rogner et al. 2007) PPP is used for a comparable analysis. Therefore, in the remainder of the paper, we will refer to PPP if not otherwise stated.

Kaya analysis

To corroborate the qualitative findings presented above, we draw on the Kaya decomposition, as shown in Figure 4. We break up emissions-growth along the factors of the Kaya identity (Kaya 1990), which expresses carbon emissions F as a product of the underlying factors GDP G, primary energy E, and population P:

$$F = P\left(\frac{G}{P}\right)\left(\frac{E}{G}\right)\left(\frac{F}{E}\right) =: P\,a\,e\,k\,, \tag{1}$$

The right-hand-side refers to the relative variables per-capita GDP (affluence) $a = G/P$, energy intensity $e = E/G$, and carbon intensity of energy $k = F/E$. Using the Laspeyres

index method[6] (Sun and Ang 2000), a change over time in emissions ΔF can be expressed as the joint contribution of the four underlying effects (indicated by subscript f),

$$F(t + \Delta t) - F(t) = \Delta F = P_f + a_f + e_f + k_f,$$ (2)

where each effect can be derived from multiplication, as done here exemplarily for population,

$$
\begin{aligned}
P_f = &\ \Delta P \cdot a_t \cdot e_t \cdot c_t \\
&+ \frac{1}{2} \cdot (\Delta P) \cdot \left[(\Delta a) \cdot e_t \cdot c_t + a_t \cdot (\Delta e) \cdot c_t + a_t \cdot e_t \cdot (\Delta c)\right] \\
&+ \frac{1}{3} \cdot (\Delta P) \cdot \left[(\Delta a) \cdot (\Delta e) \cdot c_t + (\Delta a) \cdot e_t \cdot (\Delta c) + a_t \cdot (\Delta e) \cdot (\Delta c)\right] \\
&+ \frac{1}{4} \cdot (\Delta P) \cdot (\Delta a) \cdot (\Delta e) \cdot (\Delta c)
\end{aligned}
$$ (3)

The first part of Eq (3) ($\Delta P \cdot a_t \cdot e_t \cdot c_t$) can be interpreted as the partial effect of the population component on the change of CO_2 emissions between time step t' and the preceding step t. The following parts capture interactions between the remaining variables and form the so called residual term. Results are shown in Figure 4 for China and NIC, where the color-coded stacked bars indicate the contributions from the different effects. For example, in 2007 we find that for China population growth (red) barely contributed to overall emissions growth (0.5%), whereas the increase in per capita GDP (orange) and carbon intensity (green) would jointly induce a 16% increase, were it not for the countervailing effect of decreased energy-intensity (-9%). The convenient property of the Kaya decomposition consists in its completeness: adding the values of the four components gives again the total change of emissions, namely +7.5% in 2007, as indicated by the small black triangle.[7]

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[6] Different methods can be used to decompose the Kaya identity into additive effects, see, e.g. Ang (2004) for a review of different approaches.
[7] Likewise, the first year in the graph for China, where all Kaya factors contributed positively to emission growth, has the triangle simply located on top of the bar.
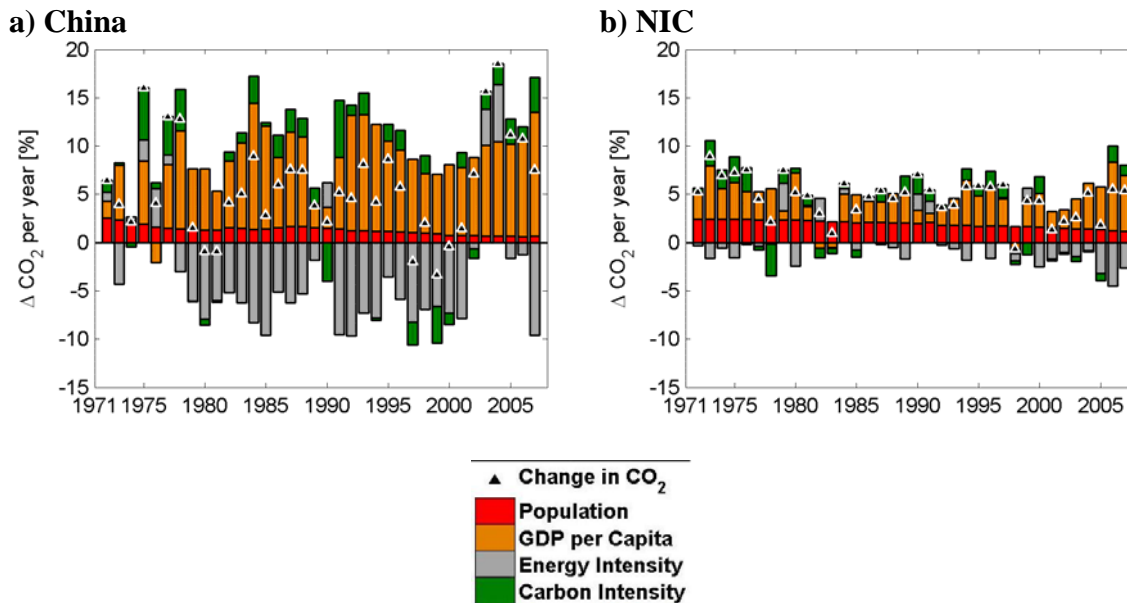
a) China

b) NIC

Figure 4: Kaya decomposition of (a) China's and (b) NIC energy related CO_2 emissions as a sum of contributions from population (red), GDP per capita[8] (orange), energy intensity (grey) and carbon intensity (green). Black triangles indicated the resulting net change of CO_2 emissions in the time period.

The main difference between China and NIC is the significantly stronger emission impact of GDP-growth in the former, which was–at least until the year 2001–partly offset by strong negative impacts from improved energy intensity. In both regions population has had a similar steadily positive but declining effect on emissions, whereas the effect of carbon intensity was more erratic, but with an overall tendency to raise emissions.

Extended Kaya-Decomposition for Carbon-Intensity: Method

In view of the Kaya decomposition of emission drivers it is evident that policy measures to reduce emissions must address energy intensity and–in the long run–especially carbon intensity, while the effects due to growth of GDP and population are either hard to control, judged to be unavailable for political reasons, or face moral controversies. Hence, in order to get a better understanding of the specific dynamics of China's carbon intensity, we subject its time-series to an extended decomposition that allows expressing the change in carbon-intensity as a sum of changes in the supply from specific energy carriers. Namely, carbon intensity $k_{t'}$ at time t' can be expressed relative to a preceding time step t as

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[8] Results are shown in PPP. Decomposition results that use GDP in MER (not shown) show very similar results with only very minor deviations compared to PPP.

$$k_{t'} = k_t \frac{E_t}{E_{t'}} + \sum_j \left(\frac{k_{jt'} E_{jt'} - k_{jt} E_{jt}}{E_{t'}} \right), \tag{4}$$

where j indexes the different energy carriers, e.g. natural gas, coal etc., and k_{jt} represents the specific carbon intensity of energy carrier j at time t,[9] which supplies carrier-specific energy E_{jt}. Given that by definition we have

$$E_t = E_{t'} - \sum_j \left(\Delta E_j \right), \tag{5}$$

where ΔE_j denotes the change between t and t' in energy supply E_j, one can write

$$k_{t'} = k_t \frac{E_{t'} - \sum_j \left(\Delta E_j \right)}{E_{t'}} + \sum_j \left(\frac{k_{jt'} E_{jt'} - k_{jt} E_{jt}}{E_{t'}} \right). \tag{6}$$

The first part of the expression can be interpreted as the energy carrier's changing contribution to the overall energy mix, while the second term of the expression indicates the change of the energy carriers' specific carbon intensity. This can be reformulated to express the change Δk in carbon intensity between t and t' as a sum over contributions from all energy carriers:

$$\Delta k = \frac{1}{E_{t'}} \sum_j \left(k_{jt'} \cdot E_{jt'} - k_{jt} \cdot E_{jt} - \Delta E_j k_t \right) \tag{7}$$

Δk so far only captures the partial effect. In a complete Laspeyres decomposition, all residuals are taken into account, implying that the effect of carbon intensity k_f can be written as $k_f = \Delta k \cdot R$, where R represents the residual (compare also Eq (3)). R can then be written as:

$$R = (P_t \cdot a_t \cdot e_t) + \frac{1}{2} \cdot (\Delta P \cdot a_t \cdot e_t + \Delta a \cdot P_t \cdot e_t + \Delta e \cdot P_t \cdot a_t)$$
$$+ \frac{1}{3} (\Delta P \cdot \Delta a \cdot e_t + \Delta P \cdot \Delta e \cdot a_t + \Delta e \cdot \Delta a \cdot P_t) + \frac{1}{4} \cdot \Delta P \cdot \Delta a \cdot \Delta e) \tag{8}$$

In order to adapt the decomposition of carbon intensity, i.e. the effect k_f of carbon intensity on the change of emissions, we need to multiply Δk (Eq.7) by R on both sides. This leads to the graphs shown in Figure 5, which allow to directly observe the influence of specific changes in the energy mix on emissions.

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[9] Changing specific carbon intensity over time might be confusing at first sight. However, the composition of energy carriers, e.g. coal, changes over time, as for example lignite is replaced by hard coal or vice-versa.

Applying the Extended-Decomposition: The Role of Coal

The expansion of coal-based power generation in China has recently received a lot of attention (e.g. Rosen and Houser 2007; Ma and He 2008). In fact, Figure 5 confirms that the factor coal explains almost all of the historical changes in China's carbon intensity. However, the general trend of steadily increasing carbon intensity due to an expanding coal sector has been present throughout the last 35 years. Thus, one cannot actually single out the last years for being exceptional in terms of the role of coal. What can be affirmed is that due to the greater absolute economic size of China, the same percentage increase in carbon intensity now leads to much higher absolute emission increases than 30 years ago. This 'scaling effect' is also manifest in the graph for global carbon intensity, where the influence of Chinese coal becomes visibly more pronounced at the end of the time-horizon.

At the global level, the results indicate that in the past a major driver of decarbonization has been the massive expansion of nuclear power in the 1970s and 1980s. As seen in the graph, this specific option has had a particularly strong role for the group of OECD countries. A priori, such a development could also constitute a plausible scenario for China, at least under business-as-usual assumptions. With respect to natural gas and oil, a persistent effect towards either rising or declining emissions cannot be affirmed, as strong fluctuations prevail throughout the observation period. Qualitatively, oil tends to have a decreasing effect, implying that its share in the overall energy mix has fallen, while natural gas shows a slightly positive effect. In fact, global shares of primary oil in the total primary energy supply decreased from roughly 45% to 35%. At the same time, the share of natural gas has increased from 16% to 20%.[10]

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[10] Biomass and waste also contributed to decarbonization, but as traditional biomass is included in the data, the effect of a rising population in least developing countries using more traditional biomass cannot be separated from other effects, as for example the wider use of biofuels in the transportation sector, or co-fired waste in power generation.

a) World

b) China

c) OECD

d) NIC

Coal
Natural Gas
Crude Oil
Nuclear
Biomass and Waste
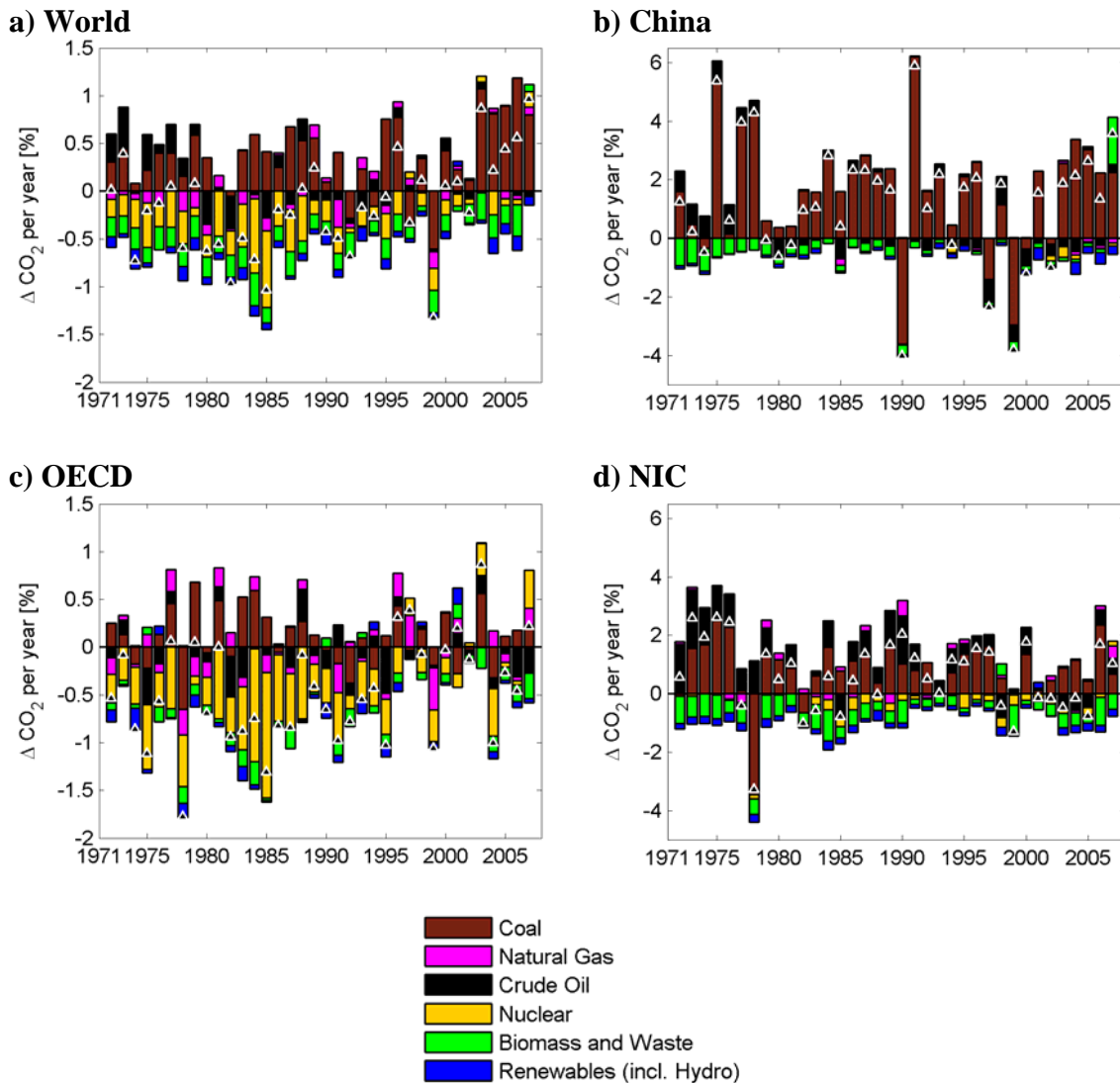Renewables (incl. Hydro)

Figure 5: Extended decomposition for the Kaya contribution from carbon intensity on overall emissions, in terms of energy carriers coal (brown), natural gas (pink), crude oil (black), nuclear (yellow), biomass and waste (green) and renewables (blue). Black triangles indicate the net effect of carbon intensity on CO_2 emission change. Note the different scales on the Y-axis.

Table 1 summarizes the findings from the extended decomposition of carbon-intensity and puts them into perspective with regard to the 'size' of the other Kaya factors, indicating each factor's net contribution to emissions-growth, averaged over the entire time horizon. It confirms that coal dominated the trend towards carbonization of energy in China, which could not be reversed by renewables or nuclear power at any time. Compared to the world average, the effect caused by the increased usage of coal is much larger in China (1.6% vs. 0.4%), with a less pronounced difference to NIC (0.9%).

Overall, the table suggests four main conclusions regarding the *evolution* of emissions over the last 35 years: first, the overall very high annual percentage growth in emissions is a special characteristic of both China and NIC. Second, among the Kaya factors,

growth of GDP per capita has for both regions been the largest single driver of emissions growth. Third, the main difference between China and NIC consists in the former's relatively stronger economic growth and its resulting larger contribution to emission growth (7.5% vs. 2.8%), and not primarily in different dynamics of carbon intensity or coal. Fourth, the most characteristic feature of China is the exceptionally high contribution of energy intensity, which partially counterbalanced the high growth in per-capita GDP.

		World	OECD	NIC	China	China 2000-2007
Population		1.59	0.71	1.93	1.29	0.67
GDP per Capita		1.96	2.07	2.84	7.51	9.27
Energy Intensity		-1.36	-1.55	-0.66	-4.13	-2.34
Carbon Intensity		-0.16	-0.47	0.59	1.2	1.37
CI attributed to	*Coal*	0.36	0.1	0.86	1.61	1.9
	Gas	-0.04	-0.06	0.04	-0.02	-0.07
	Oil	0.02	-0.01	0.52	0.004	-0.19
	Nuclear	-0.24	-0.37	-0.15	-0.04	-0.11
	Biomass and Waste	-0.18	-0.09	-0.49	-0.24	0.08
	Renewables (incl. Hydro)	-0.08	-0.05	-0.18	-0.11	-0.24
Net Annual CO$_2$ Growth		2.02	0.76	4.71	5.88	8.97

Table 1: Average annual change (1971-2007) of regional CO$_2$ emissions in percent that can be attributed to specific energy carriers, here compared to the regions' average annual CO$_2$ growth. Note: Any differences between sums and stated values for 'Carbon Intensity' and 'Net Annual CO$_2$ Growth' are due to rounding.

One could use the findings above for a naive exploration of future Chinese emissions under business-as-usual assumptions, assuming that carbon intensity eventually falls and reaches the world-average level, which would imply a drop in emissions by around 20%. However, due to the required changes in energy infrastructure, it seems unlikely that this could be achieved in the near-term. Low-hanging fruits in form of further drastic improvements of energy intensity as in the past also do not seem plausible, since China has practically reached the world-average level on this measure. This is not to say that energy intensity could not be reduced much further, as, e.g., a comparison with the current level of Japan (in 2005 6.4 MJ/$ vs. 9 MJ/$ in China) might suggest. However, further improvement will likely need significant (and costly) efforts.

If continued high economic growth prevails, the trend in per-capita emissions in China can be expected to continue on the path taken since 2002/03, implying an emissions growth-rate exceeding 5% per year. Such a value would, however, be well above official reference estimates of 2.6% average annual growth from 2010-2015 (EIA 2009), or 3.6% from 2008 to 2020 (IEA 2010). Most probably, this reflects the extrapolation of global long term trends and the incorporation of the various domestic measures the Chinese government has announced recently, e.g. on energy efficiency, renewables, and carbon intensity of GDP, which will be discussed in detail in Section 5.

4   Future Options for Decarbonization

Wheras the previous section has been concerned with the historical development of energy use and carbon emissions in China, this section analyses plausible future scenarios using the integrated assessment model ReMIND-R[11] (Leimbach et al. 2010a, Leimbach et al. 2010b, Bauer et al. 2011). A more detailed model description of ReMIND-R is provided in the Appendix. Two of the scenarios outlined here (baseline and 450 ppm stabilization) are identical to those described in detail in the RECIPE project (see Luderer et al. 2011, Bauer et al., 2011). After outlining the baseline scenario, this section assesses China's role in cost-efficient global mitigation efforts. We then contrast the energy system developments required to achieve emission reductions with historical trends by subjecting our numerical model results to the decomposition introduced in the previous section. Finally, this section concludes by comparing China's energy mix in the baseline and one selected stabilization scenario (450 ppm CO_2) and presents estimates of energy system investments for both scenarios.

Baseline Assumptions in ReMIND-R

To assess the role of China in globally efficient mitigation efforts, we use a set of plausible, self-consistent scenarios as generated by the multi-region integrated assessment model ReMIND-R (Leimbach et al. 2010a, b; Bauer et al. 2011). ReMIND-R is a hybrid model that combines a Ramsey-type optimal growth model of the macro-economy with a technology-rich energy system model. It is characterized by joint inter-temporal optimization of both model components, thus assuming perfect foresight by all economic agents. It incorporates a detailed description of energy carriers and conversion technologies (including a wide range of carbon free energy sources) and allows for unrestricted inter-temporal trade relations and capital movements between the eleven macro-regions that are represented. Due to the model's optimizing behavior and the assumption of perfect foresight the resulting stabilization scenarios should not be interpreted as forecasts but rather as first-best scenarios regarding a cost-optimal transition towards a low-carbon energy system. Therefore they could be seen as a benchmark outcome, against which real world developments can be compared.

The baseline scenario describes plausible future developments in a world without climate mitigation policy (Jakob et al. 2009).[12] China's population is assumed to keep growing at a relatively low rate until 2030 and to stabilize at about 1.4 billion people afterwards (UN 2004). Its GDP per capita is projected to grow at an average of slightly above 4%,[13] corresponding to increases in average income per capita from currently roughly US$

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[11] In its structure the ReMIND-R model is comparable to other integrated assessment models, e.g. RICE (Nordhaus and Yang 1996) or MERGE (Manne et al. 1995), but features a detailed resolution of the energy sector. The model as well as its baseline assumptions are discussed in more detail in the Appendix..

[12] Economic damages caused by climate change are not taken into account by this version of REMIND-R.

[13] Economic growth is assumed to slow down from currently about 8% per year to 4.5% in 2030 and 3% in 2050

1,800 in 2005 to US$ 14,000 in 2050. As improvements in energy efficiency are outpaced by growing economic activity, total primary energy consumption grows steadily at around 2% per year, increasing almost threefold throughout the first half of the century. Without additional measures to limit carbon emissions, China's energy system will likely remain dominated by fossil fuels (especially coal) and continue the past trend of carbon intensive growth and rising carbon emission. According to our scenarios, CO_2 emissions would increase more than threefold between 2005 and 2050[14].

In the short- to mid-term - i.e. until 2030 - our assumptions on population growth and GDP are practically identical to the ones used by the IEA in its World Energy Outlook 2010 (IEA 2010), resulting in very similar projections for energy demand[15]. One considerable difference, however, concerns carbon emissions: while WEO2010 expects carbon emissions to rise by 2.4% per year in the period 2008-2035, our baseline assumes coal to account for a larger share of total energy consumption, which leads to an increase of CO_2 emissions of 3.9% per year in the period 2005-2030.

The Role of China in Global Mitigation

Table 2 lists global as well as Chinese carbon emissions for several scenarios: the baseline (BAU) scenario as well as several climate policy scenarios aiming at stabilization of atmospheric concentrations at 400, 450, and 500 ppm CO_2-only with minimized global costs. Note that in the baseline scenario the model maximizes welfare without taking into account any additional constraints, i.e. already existing energy or climate policies are not included in the baseline.

The results illustrate the efforts that need to be undertaken to stabilize emissions at various climate policy targets. It gets obvious that China needs to take more responsibility in global mitigation the more ambitious climate policy targets are set, both in absolute numbers as well as relatively to other world regions. The share of global emission reductions that is undertaken in China increases with more ambitious climate targets, ranging from 11% in the 500 ppm to 14% in the 400 ppm scenario. This corresponds to cumulative emission reductions ranging from 27% (in the 500 ppm scenario) and 43% (in the 450 ppm scenario) to 71% (in the 400 ppm scenario) below business-as-usual. The fact that such sizable reductions in China are needed is intuitively clear: stabilizing atmospheric CO_2 concentrations requires limiting cumulative carbon

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[14] Trade is frequently mentioned as a driving factor for China's emission growth (Guan et al. 2009). First, trade is likely to have an impact on China's emissions by driving economic growth. Our scenario takes into account that China cannot indefinitely increase current account surpluses, projecting average per-capita GDP growth of roughly 4% per year in the period 2005-2050, substantially below the growth rates that China displayed in the last decades. Secondly, trade plays a role for China's emissions if the carbon per value embedded in exported goods is significantly different compared to production for domestic consumption. Several studies point out that the amount of carbon embedded in Chinese exports is very similar to the emissions avoided by imports (i.e .the emissions that would have been generated if imported goods had been produced in China instead) such that the composition of China's exports does not significantly influence the country's emissions (Peters and Hertwich 2008).

[15] WEO2010 projects energy demand to increase by 2.6% per year in the period 2008-2035, while for ReMIND the respective figure is 3% in 2005-2030

emission in the period 2005-50 to 1350 GtCO$_2$ globally (in the 450 ppm scenario). This corresponds to about 4.5 t CO$_2$ per person per year, i.e. very close to China's current level and well below the baseline, which projects an almost threefold increase of Chinese annual per-capita emissions by 2050.

	BAU	500ppm	450ppm	400ppm
Global cumulative emissions 2005-50 [Gt CO$_2$]	2604	1655	1350	642
Global reduction below BAU [%]	-	36%	48%	75%
China's cumulative emissions 2005-50 [Gt CO$_2$]	381	278	218	110
China's share in global emissions [%]	15%	17%	16%	17%
China reduction below BAU [%]	-	27%	43%	71%
Share of global reduction [%]	-	11%	13%	14%

Table 2: Role of China in global reduction efforts.

Table 3 shows results of the enhanced Kaya decomposition for absolute emission changes between 2005 and 2050 for different scenarios. For population and GDP per capita we find a decreasing contribution to emission changes with more ambitious climate policy targets, which can be explained by the lower total emission levels in the policy scenarios. For example, in a relatively carbon-neutral economy, a unit of GDP per capita or population growth will contribute less to emissions growth than in a carbon-intense economy. Most importantly, Table 3 illustrates the interplay between energy- and carbon intensity for different stabilization targets. With increasingly ambitious climate policy targets the importance of energy intensity decreases, while carbon intensity reductions get more and more important. In the BAU scenario energy intensity contributes most, which can – as explained above for population and GDP per capita – be explained with higher absolute emission levels. Thus, significant emission reductions that can be derived from energy intensity improvements are already undertaken in the BAU scenario[16], but only limited additional reduction potential from decreasing energy intensity can be realized when climate targets become more ambitious. Therefore a focus on carbon intensity becomes increasingly important. Determining the drivers of carbon intensity in more detail, we find that its reduction is mainly triggered by renewable energy in the 450 ppm scenario, while CCS and a decrease in the use of coal are majorly important for the 400 ppm low stabilization scenario. [17]

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[16] This could be interpreted to be in line with static marginal abatement cost analyses, which see negative abatement costs for a significant share of energy efficiency improvements, i.e. measures to decreases energy intensity. As REMIND-R is an intertemporal optimization model these options will naturally be realized in the BAU case. For a more detailed discussion see Van Vuuren et al. (2009)

[17] REMIND-R allows for negative emissions that are generated by biomass in combination with CCS. This mitigation option gets particularly important for very low stabilization scenarios, such as the 400ppm scenario considered here. For a more detailed discussion see Edenhofer et al. (2010).

		BAU	500ppm	450ppm	400ppm
Population		20.0	14.3	12.2	10.1
GDP per Capita		481.5	373.2	331.2	291.3
Energy Intensity		-333.0	-288.0	-252.9	-182.1
Carbon Intensity		39.8	-55.0	-95.5	-167.6
CI attributed to	*Coal w/o CCS*	58.7	13.4	-3.3	-20.7
	Gas	-0.3	0.2	0.1	0.6
	Oil	-1.3	-1.0	-0.7	-0.9
	Nuclear	0.3	-6.9	-6.9	-2.9
	Biomass w/o CCS	-13.6	-21.9	-23.9	-13.7
	Renewables (incl. Hydro)	-4.0	-31.8	-50.1	-52.1
	CCS	0.0	-7.0	-10.8	-78.1
Absolute emission change in 2050 compared to 2005 [%]		208.4	44.5	-5.0	-48.3

Table 3: Decomposition of China's absolute emissions change from 2005 to 2050 in different scenarios in per-cent.

Crucial assumptions for the policy scenarios in this analysis are (a) immediate action on climate change mitigation, and (b) the presence of an international carbon market. Therefore, mitigation of carbon emissions features full 'where-flexibility', i.e. it can be undertaken at the location where it generates the lowest costs. In the intertemporal optimization framework applied here, this implies that the allocation of emission rights among nations only affects the incidence of mitigation costs, while, for a given mitigation target, the distribution of physical emission reductions remains independent of allocation (Manne and Stephans 2005). The sizable physical emission reductions in China projected here thus point to the presence of ample low-cost mitigation options, but not as an indicator of the reduction target in terms of emission rights. It does not imply that China will necessarily bear a large share of the costs of climate stabilization.

*Macroeconomic Effects of Climate Policy*

To keep the analysis tractable, we discuss macroeconomic effects of climate policy, mitigation options, and investment needs taking the 450 ppm target as an example. Depending on assumptions about emissions of other greenhouse gases, this target corresponds to overall GHG concentrations of 500–550 ppm CO_2-eq. (Fisher et al. 2007). In terms of temperature changes, the cumulative emission budget until mid-century corresponds to a probability of slightly less than 50 % of keeping global warming below 2°C compared to preindustrial levels (Meinshausen et al. 2009).

Figure 6 illustrates the driving forces of carbon emissions as observed in the past and projected for the future under business-as-usual as well as for the 450 ppm stabilization scenario. As can be seen from the Kaya decomposition in panel (a), robust economic growth in China has put - and is supposed to continue to do so in the future –

considerable upward pressure on emissions, while population growth (which is expected to turn negative from 2030 on) has only minor impacts. Even in the baseline scenario declining energy intensity acts as a counterweight to economic expansion, limiting the increase of energy consumption to rates well below the rate of economic growth. Without policy intervention, the move towards higher shares of (abundantly available) coal in the energy mix increases the carbon intensity of energy production, especially in the near term (panel b). However, this effect is by an order of magnitude smaller than the effects of changes in GDP and energy intensity.

In the 450 ppm CO_2 climate policy scenario Chinese emissions peak in 2020 and decline constantly after that date. Climate measures can be targeted at decreasing the energy intensity of GDP (e.g. through energy efficiency improvements or industrial policies to shift the production structure towards less energy intensive sectors) or lowering the carbon intensity of energy production (e.g. by encouraging the use of low-carbon energy technologies). The most remarkable feature of the stabilization scenario, depicted in panel (c), is the continued decrease in carbon intensity from 2020 onwards, triggered by structural changes in China's energy system. With improvements in energy efficiency that only partially compensate economic growth, lowering carbon intensity is essential to reduce carbon emissions without compromising development. The differences in per-capita CO_2 emissions between the baseline (where they grow by about 2.2% per year on average) and the policy scenario (where they slightly decline) can to a large part be explained by the different trends in carbon intensities: While in the baseline carbon intensity grows by a little less than 1% per year on average, this trend is reversed in the policy scenario, in which it declines by roughly 2% per year. The decomposition of carbon intensity shown in panel (d) reveals that decreasing the consumption of coal and increasing use of renewables and biomass can make the largest contribution to reverse the current trend and achieve lower carbon intensity, with additional but smaller roles for nuclear power and CCS.
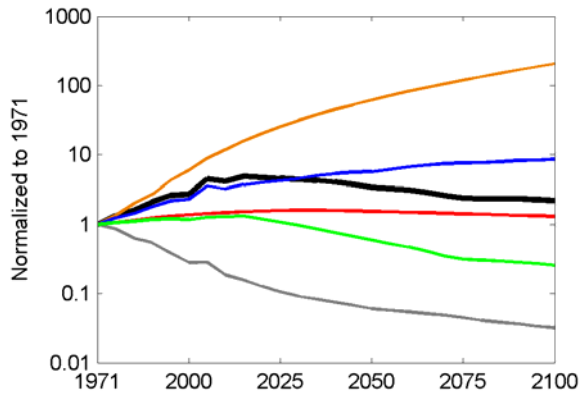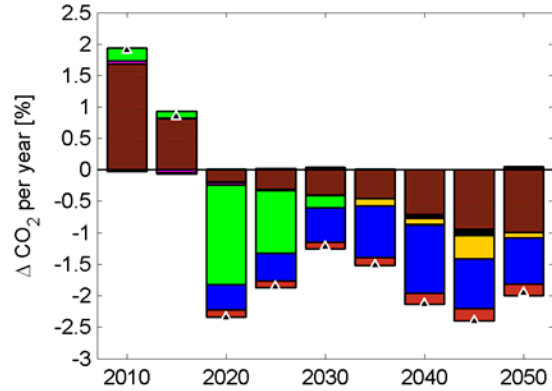
a) Kaya factors for China: baseline
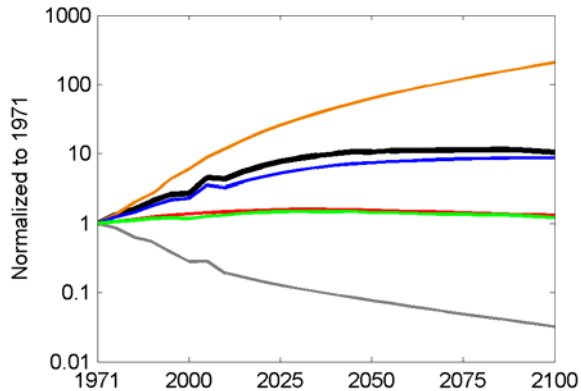
b) Decomposition of CI: baseline
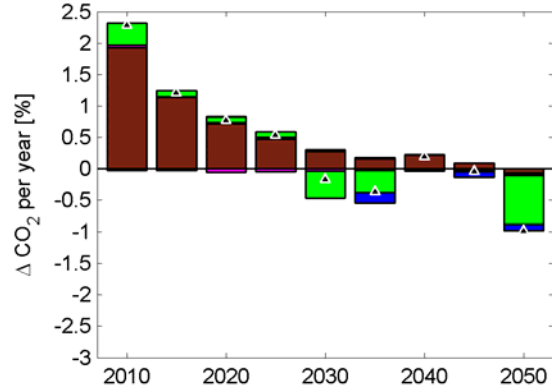
c) Kaya factors for China: 450ppm

d)Decomposition of CI: 450ppm

Figure 6: Kaya decomposition factors for historic data[18] and model results for the baseline and the 450 ppm scenario (a, c), results are shown normalized to 1971 and decomposition of carbon intensity for model results (b, d).

Assessment of Mitigation Options

According to the baseline scenario (i.e. in the absence of climate policies) China's energy system will remain carbon-intensive, with the largest share of primary energy demand met by fossil fuels (Figure 7a). Even in the absence of climate policy it can be expected that oil and gas become scarce. As they are replaced by coal, this results in increasing

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[18] Out of consistency reasons with model results, historic GDP data are shown in MER for this analysis.

shares of coal (but also of biomass and renewable energies) in China's energy mix, while nuclear energy is projected to remain at a negligible level.[19]

As we have argued above, stabilizing atmospheric CO_2 concentration at 450 ppm CO_2-only is only feasible with significant reductions of carbon emissions below business-as-usual and contingent on a timely transformation of the Chinese energy system. As in the short- and mid-term the capital stock in the energy system is relatively inflexible, energy efficiency improvements can make a significant contribution to abate carbon emissions, such that energy consumption in the policy scenario grows at lower rates and is about one third below business-as-usual in 2050.

Initiating a transition towards a low-carbon energy system implies quickly phasing out conventional fossil fuel based capacities, which are projected to peak around 2015 and become continuously replaced by renewables, biomass, and CCS. However, the model results suggest that in the year 2050 almost half of total primary energy will still be supplied by conventional fossil fuels. Renewables, which grow from 2015 on and account for about 25% of primary energy by 2050 (not including biomass) in the policy scenario, can arguably make the largest contribution to limiting the increase of carbon emissions in China. Increasing use of biomass (which is an important energy carrier in the baseline, too), CCS, and nuclear energy are expected to constitute less important mitigation options. The model results further suggest that decarbonization of electricity generation is key to mitigating carbon emissions in China. In the stabilization scenario, by 2050 roughly 40% of electricity is generated from renewables and 20% from biomass, while transportation and the stationary sector display relatively low mitigation potentials.
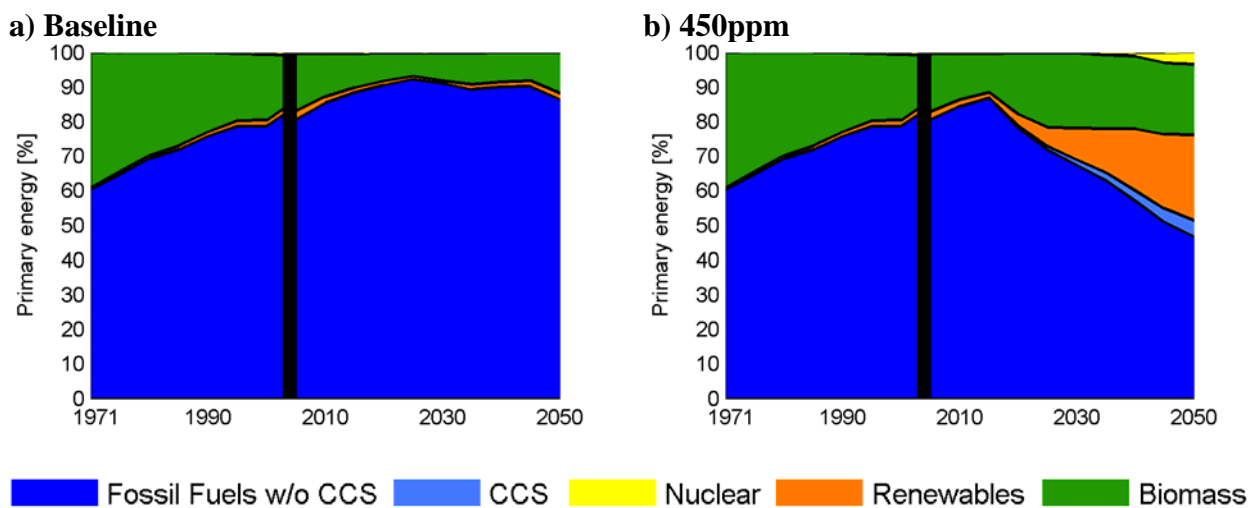

a) Baseline **b) 450ppm**

Legend: Fossil Fuels w/o CCS | CCS | Nuclear | Renewables | Biomass

Figure 7: Composition of energy supply in the Chinese energy system from 1971 to 2050 for (a) the baseline and (b) the 450 ppm CO_2 only policy scenario. The vertical black line indicates the change from historic data (IEA) to model results (ReMIND-R).

Investment Needs

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[19] Without climate policy, no incentives to apply CCS exist. Hence, this option is not employed in the baseline scenario.

In order to satisfy China's growing energy demand (directly linked to its rapid economic growth) sizable energy system investments will be needed in the next couple of decades – even in the case that climate change is not addressed in the country's energy strategy. The bulk of these investments occur in the power sector (see Figure 8). In the baseline case (depicted in panel a), our scenarios suggest that investments in the power sector will predominantly be focused on conventional fossil-fuel based generation capacities with some investments in renewables and biomass, triggered by scarcity induced price increases of fossil resources. Over the period 2005-2050, the scenario projects a relatively flat trend with annual energy system investments between US$ 50 bln and US$ 100 bln.

The effect of climate policy on the investments is twofold: A rapid switch toward low-carbon technologies occurs, and the overall investment volume increases markedly (panel b). Since the low-carbon energy carriers are highly capital-intensive, on the long run the annually required energy system investments are projected to exceed baseline investment by a factor of two and reach about US$ 200 bln in 2035. ReMIND-R projects a complete phase-out of investment in conventional fossil fuel based forms of energy by 2015, suggesting that from this point on, renewable energy generation is likely to attract the largest part of investments, while considerably smaller shares will be targeted at biomass, nuclear and CCS.
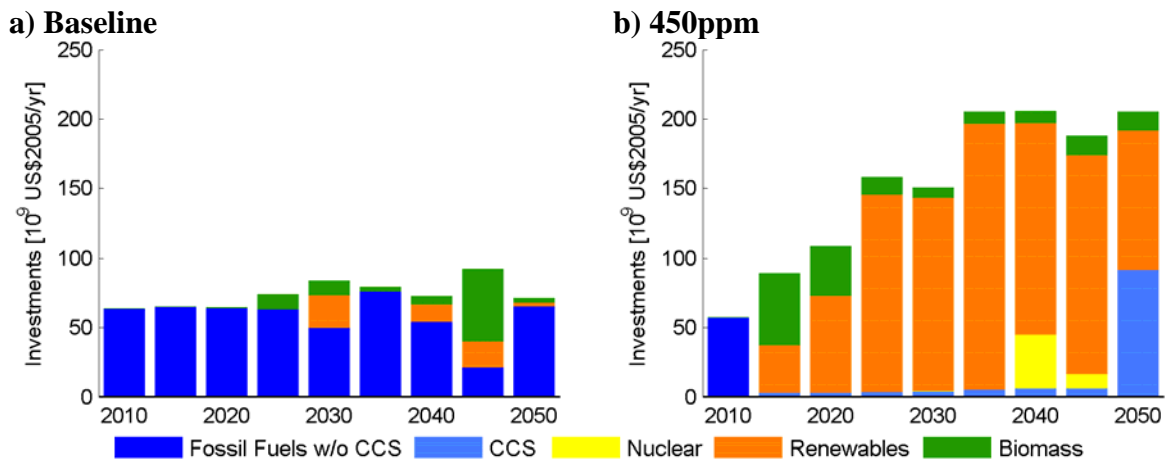
a) Baseline   **b) 450ppm**

Figure 8: Investments in the Chinese power sector from 2010 to 2050 according to the ReMIND model in billion year 2005 US$ per year for (a) the baseline and (b) the 450 ppm policy scenario.

5   Assessing China's Energy and Climate Policies

In the first sections of this paper we have analyzed historic drivers of China's energy-related emissions and measures needed to restructure the energy system in the future. In this section we discuss the contribution of current domestic policies to a decarbonisation of the energy system.

Climate Change and Sustainable Development in China

China has repeatedly expressed its intention to address climate change in the context of implementing a sustainable development strategy. A recent White Paper (State Council 2008) emphasizes that economic development is regarded as the core objective of policy making. Hence, policies related to climate and energy issues are evaluated according to their potential to further this objective along multiple dimensions, which include safeguarding environmental integrity, but also economically efficient resource use, limiting dependency from energy imports, etc.

In international negotiations, China has declared its will to limit global warming to 2°C but refused to take binding reduction commitments (at least until 2020), and emphasized that according to the principle of 'common but differentiated responsibility', industrialized countries should take the lead in reducing emissions. Within the current UNFCCC process, the country is the most important host for CDM projects and is continuously lobbying for an enlarged technology transfer scheme as a foundation for strengthening international cooperation.

Domestic Measures

After energy intensity had fallen significantly for decades,[20] this trend reversed in the early 2000s. As a reaction, the 11th five-year-plan includes a target to reduce energy intensity by 20% below 2005 levels by 2010. Even though not an official target, energy intensity is envisaged to be further reduced to 40% below 2005 levels by 2020, which can be derived from the Chinese government's national development goal to quadruple GDP while only doubling energy demand in the period 2000 to 2020[21]. This target is backed by a number of different measures, including specific energy conservation targets for China's 1000 most energy-consuming enterprises, forced phase-outs of inefficient power plants, a requirement to use commercially viable state-of-the art technology for all new coal-fired power plants, and vehicle fuel efficiency standards. In addition, targeted industrial policies, such as export taxes on energy-intensive exports, aim at limiting the expansion of energy-intensive industries and promote structural change towards service-based and high-tech industries (Price et al. 2008).

In the run-up to COP15 held in Copenhagen, the Chinese government announced to reduce carbon intensity of GDP by 40 – 45% below its year 2005 level until the year 2020. Proposals to implement a carbon tax in China are currently discussed (Reuters 2009), and it does not seem to be completely unlikely that a uniform carbon tax will be implemented in the next five-year-plan.

Several laws and regulations promote the uptake of low-carbon technologies: the renewable energy law, enacted in 2005, provides specific targets for different energy

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[20] As shown in Section 3, China's energy intensity was nearly three times higher than the OECD average in 1971, but only 14% higher (and slightly below the global average) in 2007 using GDP in PPP.
[21] The goal was set by the 16th National Congress of the Chinese Communist Party in 2004 as reported by Wang and Tao (2009)

carriers,[22] feed-in tariffs and privileged grid access for wind energy, solar energy and energy from biomass. It aims at raising the share of renewables in the national energy mix to 15% by 2020 (NDRC 2007). Nuclear energy, which currently plays only a minor role in China's current energy portfolio, is planned to be expanded to 86 GW until 2020,[23] and several pilot projects for CCS have been recently built or are currently under construction (Fenn 2009), showing a principle interest of Chinese energy planners to develop this technology.

Evaluation of Chinese Climate Change Policy

Table 4 compares China's announced policies with the simulation results for our baseline as well as 450 ppm stabilization scenario. The energy intensity target is only slightly more ambitious than the improvements projected under business-as-usual (-40% versus -37.6% by 2020, respectively), strengthening the presumption that economic efficiency rather than environmental concerns might be the primary motivation behind its adoption. However, it is basically still sufficiently close to the energy intensity reduction suggested by the 450 ppm stabilization scenario (45% reduction), which highlights the fact that energy efficiency improvements have a limited scope if they are to be cost-efficient.[24]

Policy	China – targets	Baseline scenario	450ppm stabilization scenario
Energy Intensity	40% reduction in 2020 compared to 2005[25]	- 37.6% in 2020	- 45 % in 2020
Carbon Intensity of GDP	40 – 45% reduction until 2020 compared to 2005	- 24.8% in 2020	- 44.8% in 2020
Renewable energy (all)	15% of total energy by 2020	9.2% in 2020	21% in 2020
Nuclear	86 GW until 2020	5 GW in 2020	5 GW in 2020 (111 GW in 2050)
CCS	no official target	N/A	0.6% in 2020

Table 4: China's technology targets for carbon-free technologies compared to actual values in ReMIND projections.

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[22] Wind capacity for example shall be expanded to 100 GW

[23] The initial goal of 40 GW was revised in 2009, see http://www.chinadaily.com.cn/china/2009-07/02/content_8346480.htm [February 2010]

[24] However, small differences in energy efficiency improvements can have significant effects if they are maintained over long intervals. This explains the importance of energy efficiency as a mitigation option in our stabilization scenario.

Our business-as-usual scenario foresees significantly lower carbon intensities of GDP than other projections (e.g. IEA 2009b; IEA 2010; EIA 2009)[26]. This is due to the fact that the latter are mainly based on the extrapolation of long-run trends and also incorporate recent policy developments, while our baseline assumes a continuation of the more recent shift towards coal, at least in the short- and mid-term.[27] Unlike the energy intensity target, the target set for the carbon intensity in 2020 of GDP (-40% to -45%) is considerably below the baseline (about -25%), and well in line with the development path suggested by our 450 ppm stabilization scenario (about -45%). However, it should be noted that transforming China's energy system requires sustained effort over several decades, and that no long-term targets extending beyond 2020 have been formulated.

With regard to renewable energies, our cost-effective policy scenario calls for a larger share than what the current renewable energy target envisages for 2020 (21% versus 15%), while the proposed 86 GW of nuclear capacity in 2020 are multiple times above what our simulations suggest. However, in the longer term up to 2050, nuclear energy plays a role that is more congruent with ReMIND scenarios. As ReMIND-R projects only a limited amount of abatement via CCS in the short- and mid-term, China's engagement in pilot projects can be seen as appropriate to explore the potential of this technology within the overall portfolio of mitigation options.

6   Conclusions

In the analysis of historical emission patterns, we show that China can in two respects be seen as a special case, indeed: first of all, China has grown at an exceptional rate over the last decades, which can be identified as the main driver for the growth of emissions. At the same time, emission increase has been decelerated by improving energy intensity levels. However, this effect of partial off-set only lasted until the early 2000s, when energy intensity levels started to increase again. As a consequence emissions growth accelerated significantly. Second, over the entire time horizon of 1971-2007 coal has contributed more significantly and more consistently to emissions growth in China than in other regions considered in this paper. However, the effect is small compared to the effect of economic growth.

For the future, a strong contribution to international mitigation efforts *taking place* in China (independent of who bears the costs) is seen as necessary to achieve stabilization of the atmospheric CO_2 concentration. Model results underline the importance of physical reductions in China if global costs are to be kept at acceptable levels. It is important to point out that these reduction needs are independent from equity considerations, which should be addressed independently, e.g. by initial allocations in emission trading schemes (Schmidt and Marschinski 2010).

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[25] Note that this is not an official target, see also footnote 22

[26] For instance, IEA (2010) projects energy intensity in China to decrease by 3.3% per year over the period 2008-2035. Applying this rate for the period 2010-2020 yields a decrease of 38.4%, very similar to our figure of 37.6%. For carbon intensity of GDP, however, the IEA projects an annual decrease of 3.1%, which corresponds to 36% over the period 2010-2020. This decrease is hence much more pronounced than the 24.8% found with our model.

[27] See Bosetti et al. (2009) for a discussion

The trend reversal of decreasing energy intensity in the mid 2000s suggests that future options to reduce CO_2 emissions will be much more limited than in the past, as the general level of energy efficiency has nearly reached OECD levels. This is backed by model results showing that China's energy intensity target is only slightly more ambitious than our business-as-usual projection. Even though energy efficiency improvements are surely one important aspect, the decarbonization of the energy system requires the promotion of carbon-neutral energy carriers to reach the announced goal of bringing down the carbon intensity of GDP by 40-45% below 2005 levels by 2020. China has implemented a number of policies to increase energy efficiency and make energy supply cleaner and more secure,[28] which are an important first step. However, as long as coal retains its position as dominant energy carrier, the effects of promoting renewables, CCS and nuclear power will only have a minor impact.

Acknowledgements

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[28] Whether the motivation is always triggered by climate change or whether climate friendly policies are rather a co-benefit of other policy priorities is not always easy to say.

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7 Appendix

Model description

ReMIND-R is a multi-regional hybrid model which couples an economic growth model with a detailed energy system model and a simple climate model. Macro-economic output, i.e. gross domestic product (GDP), is determined by a constant elasticity of substitution (CES) production function with labor, capital and final energy as input factors. GDP can be used for consumption, investments into the macroeconomic capital stock (for which a depreciation rate of 5% is assumed), all expenditures in the energy system (fuel costs, investment costs and operation and maintenance costs) and for the export of a final good. Final energy is modeled as a CES production function comprising transport energy and stationary energy. REMIND-R takes into account exogenous technical change in the macroeconomic system (expressed as changes in factor productivities) as well as endogenous technological evolution in the energy system (i.e. learning curves for energy technologies).

The energy system module (ESM) comprises a detailed description of energy carriers and conversion technologies. It is embedded into the macroeconomic growth model through the techno-economic characteristics and the system of balance equations that set up the energy system. Multiple primary energy sources are available in the ESM. These include renewable primary energy sources defined by region-specific and energy source-specific potentials, which are classified into different grades. In addition, there are exhaustible primary energy sources (coal, oil, gas, and uranium). These are tradable and characterized by region-specific and energy source-specific extraction cost functions, which increase with cumulative extraction.

Each region is modeled as a representative household maximizing an inter-temporal utility function that depends on instantaneous utility in each time-step (discounted at a pure rate of time preference of 3%), which is derived from per capita consumption. The individual regions are linked by trade relations. The present version of ReMIND distinguishes 11 world regions, linked through trade in coal, gas, oil, uranium, goods, and emission permits. Trade and capital mobility (implied by trade in the composite final good) are driven by differences in factor endowments and technologies and modeled as exports into in and imports from a common pool. The balance between exports and imports for each kind of good in each period is guaranteed by adequate trade balances. For individual regions, current account deficits and surpluses in any period are permitted as long as inter-temporal trade is balanced.

Baseline description

The baseline scenario depicts future developments in a world without climate mitigation measures. Based on UN projections, global population is expected to keep growing and reach roughly 9 billion in 2050. GDP is assumed to grow at rates close to historical values in industrial regions but more rapidly in newly industrializing and most (but not

all) developing and least developed countries. The underlying storyline is that the US, Europe, and Japan are expected to remain the regions with the highest incomes in 2050, with other countries, especially China and India, closing the gap. Thus, global GDP is projected to grow at an average of 3.1% per year, resulting in income levels in 2050 which are almost 4 times their 2005 value. This corresponds to a rise in GDP per capita from roughly US$ 6,800 in 2005 to US$ 18,400 in 2050.

ReMIND-R projects a strong initial growth of energy use, which slows down considerably after 2040. Total energy use increases from 400 EJ in 2005 to 830 EJ in 2050, an annual increase of 1.6%. 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. Fossil fuels are expected to account for almost 90% of total primary consumption in 2050. However, due to scarcity of fossil fuels and technological progress in the renewable energy sector, fossil fuels become more expensive compared to renewables and from 2030 on, and non-fossil sources of energy (i.e. renewables and nuclear) are projected to gain in importance, even in the absence of climate policy.

The model assumes continuous improvements in energy efficiency due to technological progress, resulting in an average annual decline in energy intensity of about 1.5%. 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, ReMIND-R projects a more than doubling of global annual CO_2-emissions, from 32 Gt CO2 in 2005 to almost 65 Gt CO_2 in 2050 (i.e. an annual growth rate of about 1.6%).