Development without energy? On the challenge of sustainable development in the context of climate change mitigation

Jan Christoph Steckel*, Robert J. Brecha[+], Jessica Strefler, Michael Jakob, Gunnar Luderer

Potsdam Institute of Climate Impact Research PO Box 601203, 14412 Potsdam, Germany
[+] *Also with Dept. of Physics and Renewable and Clean Energy Program, University of Dayton, Dayton, OH 45469-2314, USA*

* Corresponding author, eMail jan.steckel@pik-potsdam.de, phone +49 331 288 2693

ABSTRACT

We analyze the relationship between economic development and energy consumption in the context of climate change mitigation. Bottom-up assessments of household and infrastructure energy needs are surveyed to derive estimates of minimal thresholds of energy consumption necessary to support economic development. Applying a simple econometric model on steel and cement production and economic development, it can be shown that energy required to build up infrastructure at low per-capita incomes is one explanation for the notion of an energy threshold in the development process. The main contribution of this work is to compare estimates of energy thresholds with output projections of per capita energy supply from a group of integrated assessment models. Scenarios project that reductions of carbon emissions in developing countries will be achieved not only by means of decreasing the carbon intensity, but also by making a significant break with the historically observed relationship between energy use and economic growth. We discuss the feasibility of achieving, on time scales acceptable for developing countries, both decarbonization and the needed structural changes, concluding that the decreases in energy consumption implied in numerous mitigation scenarios are unlikely to be achieved without endangering sustainable development objectives, such as universal energy access.

Keywords: Sustainable Development, Energy, Climate Change Mitigation, Integrated Assessment

JEL classification codes: Q01, Q43, Q54, O11

1 Introduction

With the publication of the United Nations Development Program report, "Our Common Future" in 1987 (WCED 1987), impetus was given to the world community to address in an integrated manner the interlinked challenges of environmental degradation and sustainable development. In many ways it is the current world energy system that is at the nexus of these two issues. As we will argue in this paper, access to the services provided by modern energy systems will very likely be a prerequisite for improving the standard of living of a large fraction of the world's population living in poverty. However, it is precisely the use of fossil-fuels that has been most useful in supplying needed energy services, while at the same time triggering one of the gravest threats to the ecosystem, global climate change (IPCC 2007).

In September 2000 leaders from 189 countries agreed to a set of goals for helping the world's poorest citizens. The eight Millennium Development Goals (MDGs) include 21 targets and a set of measurable indicators for assessing progress in relieving extreme poverty in the 21st century. In parallel, and as part of an ongoing set of meetings and documents sponsored by United Nations programs, the World Summit on Sustainable Development (WSSD) in Johannesburg emphasized the need to consider sustainability criteria while working toward improved human well-being (UN 2002). One outcome of the WSSD was the call for a mechanism to coordinate the work of UN and other agencies, which resulted in the formation of UN-Energy in 2004. In 2005, UN-Energy published their first report stressing the centrality of energy access to the achievement of the MDGs (UN 2005), followed by a report from the Global Network on Energy for Sustainable Development (GNESD 2007) and a special section in the International Energy Agency's World Energy Outlook 2010 (IEA 2010a). Thus, there is a clear linkage in international discourse between sustainable development and energy access; the publication in 2011 of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) made explicit the importance of careful consideration of the additional constraints due to the need for climate change mitigation in parallel with sustainable development (IPCC 2011).

Incorporating climate change mitigation into the discussion of sustainable development and requirements for energy system transformation implies a need for analyzing various scenarios for future greenhouse-gas emissions pathways. To this end, integrated assessment models (IAMs) project future emissions, given a set of assumptions about population, economic growth and technological progress, starting with data about the current state and past trends in the energy system, and allow comparisons between baseline scenarios designated as Business-As-Usual (BAU) and those in which climate mitigation policies are assumed (POL).

In the literature, "strong sustainability" is interpreted as the requirement to go beyond the mere substitution of natural capital with human capital. At some level, often difficult to define precisely, natural resources and ecosystem services must be preserved intact and are taken as irreplaceable. (Neumayer 2003). Most IAMs are primarily concerned with projecting the macroeconomic impacts of changes to the world energy system, given a constraint on GHG emissions (such as a maximum atmospheric concentration of GHGs). From a sustainability science point of view, this constraint may then be regarded as an indicator for strong sustainability, which must not to be violated on a sustainable development path[1].

A broad range of studies is available in which mitigation costs in terms of foregone GDP or consumption are evaluated under different circumstances (e.g. Edenhofer et al., 2006, Weyant et al., 2006, Clarke et al., 2009, Edenhofer et al., 2010, Luderer et al., 2011a). Generally, macro-economic costs are found to be moderate in a first-best world with full techno-economic flexibility. This finding crucially depends on the ambitiousness of the climate target, assumed technological change, availability of technologies and the starting point of global mitigation efforts. Sustainability literature, however, suggests that this macro-economic perspective should be complemented with a broader analysis of human development (Sathaye et al., 2007).

In this paper we aim to answer two research questions. First, to what extent is energy essential for economic development? Drawing on empirical observations and existing literature, we conjecture that economic development requires a minimum level of energy. This hypothesis is supported by an econometric analysis highlighting the role of energy in the development process over time notably with regard to the role of infrastructure.

Second, is energy consumption, as calculated in IAMs, consistent with how energy has been related to development in the past? We synthesize our insights from the analysis of historic patterns with the output projections of integrated assessment models (IAMs), particularly the ReMIND-R model, under both BAU and climate mitigation scenarios. We evaluate how the relationship between energy use and economic growth is represented in these models, particularly for developing regions. Our analysis raises doubts that this role is adequately considered in IAMs. Since IAMs have not been

[1] In this paper we focus on cost-effectiveness-mode models in which only this single indicator is explicitly taken into account . "Weak sustainability", in contrast, assumes substitutability between natural and physical capital, which is the underlying concept in models running in a cost-efficiency mode.

developed explicitly with the aim of taking into account issues that are of interest for a broader discussion of sustainability and sustainable development (SD), it will be necessary to proceed cautiously in drawing strong conclusions in this exercise. However, models are beginning to consider broader issues of SD (see e.g. Urban et al., 2007, van Vuuren et al., 2007, Bollen et al., 2009, van Ruijven et al., 2008), and some indicators useful for evaluating sustainability are commonly part of the IAM output.

We will show examples in which multiple technological pathways are able to achieve a given global mitigation target according to the output of an IAM, but where the application of additional sustainability criteria tends to call into question the feasibility of these mitigation pathways. These results may serve as a starting point for a discussion about the appeal of some of these pathways, in particular to developing countries. Therefore, we conclude with a discussion of our results with respect to their implications for future modeling exercises as well as climate policy, arguing that additional goals for sustainable development, such as access to energy, are closely related to economic development and hence must be included in the analysis of energy system transformation pathways.

2 Energy and Human Development

Is there a minimal amount of energy necessary to allow for economic development? We consider here some bottom-up investigations of energy consumption patterns. A first, qualitative consideration would be that households must have access to some forms of energy for cooking food, and depending on the climatic zone, to energy for heating their homes. Beyond this 'direct' energy use, there are also 'indirect' needs for energy, e.g. to produce consumer goods or build up infrastructure (such as buildings and roads).

2.1 Final energy consumption and economic development

One of the earlier works to look at this issue is that of Krugman and Goldemberg (1983) in which they determine a threshold of ~45 GJ/year for development to "acceptable" levels for Latin America, Africa and Asia. Their results come from bottom-up data, and include both commercial and non-commercial energy sources. A later paper by Goldemberg et al. (1985) attempts to determine energy needs for the future, given the ability to access an array of technologies to enhance energy efficiency. Under those conditions, the authors arrive at a figure of approximately 1 kW as the rate of minimum average energy consumption (equivalent to ~31 GJ/year), considering both direct and indirect energy consumption, using Western Europe and Japan in the early 1970s as the target level for acceptable development. Considering only rural households, Pereira et al.

(2011) set a level of ~10 GJ/year of direct energy consumption as a poverty threshold, using surveys of rural Brazilian households. This is not necessarily in conflict with the other references above, since indirect energy consumption can represent 50% or more of total energy, as shown by input-output analysis for Indian households, where similar primary energy consumption levels were found (Pachauri and Spreng 2002). In addition, our goal is not to set a threshold such that people are barely out of a state of absolute poverty, but rather to find a reasonable definition of how much energy is needed to achieve an "acceptable" development level.

With respect to sustained economic development, it is clear that monitoring GDP growth rates alone is an insufficient condition for ensuring development. Broader measures of social and economic development such as the Human Development Index (HDI) [2], although not without conceptual difficulties (see for example Fleurbaey, 2009), provide a first step toward a more comprehensive evaluation. In Fig. 1 we show the correlation between the Human Development Index (HDI) and energy use (here given in final energy consumption per capita in GJ/year). The United Nations Development Program (UNDP) defines four levels of development for the HDI: low (<0.475); medium (0.475 – 0.670); high (0.670 – 0.785); very high (0.785 – 1.0) (UNDP 2011). These levels are indicated by horizontal lines in Fig. 1.

[2] The HDI is defined as a geometric mean of three different components of human well-being: life expectancy, education, and income.The indices are relative and normalized, such that for each component the individual country component value is calculated with respect to the minimum value in the sample, then normalized to the maximum difference found in the sample. The education dimension is in turn made up of two parts, one being the mean years of schooling, the other being the expected years of schooling. A country potentially having the highest score across all three dimensions would have an HDI value of 1.0. The income dimension of HDI is included logarithmically in the index, acknowledging the decreasing return to well-being with increasing income.

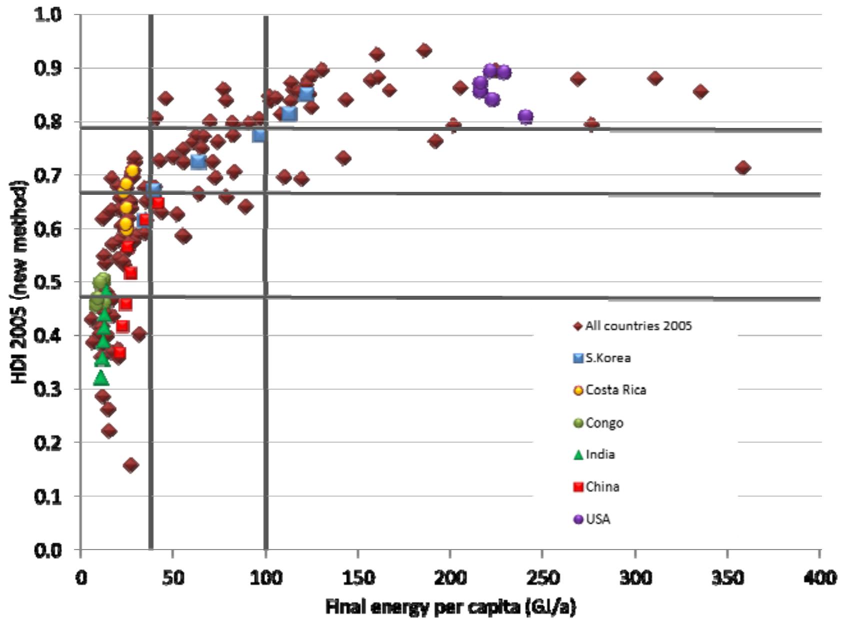


Figure 1: Correlation of (final) energy use (IEA 2010b) and HDI (UNDP 2010) in 2005 for 144 countries, together with development over the period 1980-2005 for selected countries in time steps of five years. Horizontal lines indicate the separation between "low", "medium", "high" and "very high" development categories. Vertical lines indicate per capita final energy levels of 42 GJ (1 toe) per year and 100 GJ per year.

For our purposes, the interesting feature is the correlation between HDI and per capita final energy consumption for countries in different stages of development, as shown in Figure 1. The trend of increasing HDI being correlated with increasing energy use saturates at a fairly low level. For those societies in which per capita energy use is less than about 42 GJ/year (one tonne of oil equivalent, or "toe"), HDI is very likely to be below the "high" level and certain to be below the "very high" level. On the other hand, countries with per capita final energy use of >100 GJ/year are likely to have a "very high" HDI (as denoted by the second vertical line in Fig. 1) and certain to be at least in the "high" HDI category. Only few exceptions exist (next to Costa Rica, shown here explicitly, also Hong Kong and Malta), but they all operate in very particular environments. A first conclusion is that we should be able to make judgements as to the aggregate energy access component of sustainable development for developing countries, all else being equal. Another interesting point that comes from Figure 1 is that countries having roughly the same level of economic development in the "high" and "very high" ranges as measured by HDI can have per capita energy consumption that varies by a factor of nearly ten.

Much of the literature relevant for our study is concerned primarily with energy use and income or GDP, rather than HDI; therefore the connection between HDI (or other measures of human well-being) and GDP must be established. This is especially true since the components of HDI beyond per capita GDP are not assessed by IAMs. An analysis of GDP and HDI data comes to the unsurprising conclusion that there is a high degree of correlation shown in a regression of ln(GDP/cap) and HDI. Therefore, in what follows we will use per capita GDP, as our proxy for development, remaining aware of the necessity to link this to other indicators.

2.2 Energy for infrastructure

Energy access is often understood as energy consumed at the level of households, which is also mirrored in how the topic is discussed in the literature. If we think of development beyond fulfilling basic needs, energy is also needed for the construction of infrastructure, including the use of cement and steel for buildings, railways and roads, electricity grids, etc., all of which come with a specific energy demand. We thus look at the energy used to build up infrastructure for which it would be difficult to find substitutes in near- to medium-term future development processes. In this sub-section we determine the role of infrastructure in development processes of the past, focusing on the production of cement and steel as major determinants of energy-use for infrastructure purposes. We then compare these historical observations with model scenarios in the following section. Our starting hypothesis is that infrastructure production increases with increasing levels of income, while it might eventually saturate once a certain capital stock has been built up. Thus, we presume that in developing countries inputs required for infrastructure increase with economic growth, while cement and steel production could be decoupled from economic growth in developed OECD countries. Empirical confirmation of this hypothesis would yield strong support for the existence of an energy threshold.

Data

We aggregate all data[3] into 11 regions as defined in the ReMIND-R model, in order to be able to use results from the historical analysis to estimate future energy demand resulting from infrastructure. Table 1 gives a more detailed description of aggregated regions. We further cluster these regions into developed (OECD) and developing countries. However, we exclude the regions ROW and RUS from these two clusters: For ROW the ReMIND region is composed of developed and developing countries, while for RUS historical data are not sufficiently available[4].

[3] Summary statistics for all data used can be found in the Appendix.

[4] Note that with respect to steel production not every country produces steel, thus an aggregation of countries is useful. A similar analysis with disaggregated regions holds qualitatively similar results for cement.

Model region	Countries[5]
AFR	Sub-Saharan Africa w/o South Africa
CHN	China
EUR	EU27 countries
IND	India
JPN	Japan
LAM	All American countries but Canada and the US
MEA	North Africa, Middle Eastern and Arab Gulf Countries, Resource exporting countries of FSU, Pakistan
OAS	South East Asia, both Koreas, Mongolia, Nepal, Afghanistan
ROW	Non-EU27 European states, Australia, Canada, New Zealand and South Africa
RUS	Russia
USA	USA

Table 1: Regions as defined in ReMIND-R and corresponding world regions

For macro-economic indicators we use data from Penn World tables 6.3 (Heston et al. 2009). Capital investments can be calculated from Heston et al. (2009) based on GDP (in MER). As the database on the amount of cement produced in each country is rather weak, we use production-based emissions data caused by cement (Boden et al. 2011) and use factors determined by the chemical processes involved to calculate cement production and consequently estimate the energy consumed in the process. This is possible because one step in the cement production process is the conversion of limestone to lime in the production of clinker, where CO_2 is emitted in a chemical reaction, i.e. $CaCO_3 \longrightarrow CaO + CO_2$. Thus, cement production can directly be calculated from emissions, using a constant of 0.5 t CO_2/t cement (IPCC 2000, USBM, 2009). For steel we use country disaggregated production data from IISI (2011) for the years 1980 – 2005 available for all steel producing countries.

Empirical method

A simple econometric model is used to estimate the role of infrastructure (*INF*), i.e. cement and steel in development processes. Demand for cement or steel are expected to depend on the population (*POP*) of a country or region, as well as on economic development (*ECON*). As a proxy for economic development both per-capita *GDP* and

[5] In the remainder of the paper we aggregate these regions into "OECD" countries and "developing countries" as follows: OECD countries are EUR, JPN and USA, while all other regions, but RUS and ROW are aggregated as "developing" countries. Note that singular countries in this group (i.e. South Korea and Mexico) are actually OECD countries.

per-capita capital investments (*INV*) are used, presuming that the latter are the decisive part of GDP driving the demand for infrastructure. A panel regression is performed between population, an economic development parameter (GDP or capital investments) and the infrastructure parameter (cement or steel production). A fixed-effects estimator is used to estimate the following equation:

$$\ln\left(INF_{jt}\right) = \alpha_j + \beta_j \ln\left(ECON_{jt}\right) + \gamma_j \ln\left(POP_{jt}\right) + \varepsilon_{jt} \quad , \tag{1}$$

where α_j are region-specific parameters constant in time and the error term ε_{jt} is assumed to be identically and independently distributed (iid). *j* specifies the respective region, for which country specific historic data series *INF*, *ECON* and *POP* are aggregated. Eqn. (1) is estimated separately for OECD countries and developing countries to allow for different functional relationships for these two country groups The logarithmic transformation of the variables are used, with the respective coefficients therefore denoting elasticities, (i.e. the percentage change of the dependent variable upon a one percent change of the explanatory variables, ceteris paribus). By means of a student t-test we assess whether the coefficients are individually significantly different from zero.

Results

Qualitatively the results for steel and cement production inputs are broadly similar, as summarized in Tables 2 and 3. However, we note important differences between developing and developed countries.

For developing countries the estimated coefficients are all statistically significant on the 1%-level. For steel, about 40% of the observed variation is explained by the independent variables, as indicated by the R^2-within (which excludes the explanatory power of the country-specific fixed effects), while for cement it exceeds 80%[6]. The estimated elasticity of steel production with respect to capital and investments and per-capita GDP are about 0.4 and 0.7, respectively, while the elasticity with respect to population ranges between 1.4 and 1.6, depending on model specification. For cement, the former elasticities are about 0.5 and 0.7, respectively, and the latter are 1.9 and 2.

For developed countries, the estimated elasticities for steel are considerably lower than for developing countries, on the order of 0.1 for both per-capita investments and per-capita GDP, respectively. Both are statistically significant at the 5% confidence level. For cement, however, the coefficients of *GDP* and *INV* are not statistically different from

[6] This observation could for instance be due to the fact that steel is more heavily traded than cement, such that the latter's production is more closely aligned to socio-economic development.

zero. Finally, we find insignificant coefficients on population size for steel production, but coefficients which are significant on the 1% level for cement, with values between 1.2 and 1.5. These observations suggest that for developed countries, steel production is more strongly affected by per-capita GDP and capital investments, while for cement the population size is of higher importance.

Steel	**Developing countries**		**OECD countries**	
β_{inv}		0.4435*** (4.7)		0.109** (2.54)
β_{GDP}	0.7051*** (5.77)		0.0969** (2.09)	
γ	1.4318*** (5.68)	1.6423*** (6.58)	0.3927 (1.41)	0.2926 (0.84)
α	-9.1858*** (-2.76)	-11.2636*** (-3.34)	6.6067* (1.95)	8.5324** (2.36)
R^2	0.4185	0.3852	0.2319	0.2523

t-values in parenthesis
*** p<0.01, ** p<0.05, *p<0.1

Table 2: Relationship between capital investment or GDP, respectively, population and steel production in OECD countries and developing countries in the years 1980 – 2005. Note that data are aggregated to match the regional fit of the ReMIND-R model. α denotes the average of country fixed effects for OECD and developing countries, respectively. The reported R^2 is the R^2-within.

Cement	**Developing Countries**		**OECD Countries**	
β_{inv}		0.5178*** (12.46)		0.0059 (0.14)
β_{GDP}	0.6809*** (12.16)		-0.0644 (-1.41)	
γ	1.8685*** (16.19)	1.9753*** (17.96)	1.5216*** (5.55)	1.2125*** (4.1)
α	-16.1634*** (-10.58)	-16.7480*** (-11.29)	-9.8383*** (-2.94)	-6.1233** (-1.68)
R^2	0.8163	0.8205	0.3803	0.3636

t-values in parenthesis
*** p<0.01, ** p<0.05, *p<0.1

Table 3: Relationship between capital investment or GDP, respectively, population and cement production in OECD countries and developing countries in the years 1980 – 2005 Note that data are aggregated to match the regional fit of the ReMIND-R model. α denotes the average of country fixed effects for OECD and developing countries, respectively. The reported R^2 is the R^2-within.

These results broadly support our hypothesis. In developing economies, higher per-capita GDP and capital investments are closely correlated with increased production of steel and cement. The low or statistically insignificant coefficients found for OECD countries suggest that once a certain level of development is reached, GDP or capital investments have a considerably less pronounced influence on these infrastructure-related variables. This finding supports the hypothesis of an energy threshold, as infrastructure inputs must first be provided in order to reach a decent level of development. This is also in line with previous literature suggesting that in developed countries the total stock of infrastructure inputs saturates (on a per capita level): for instance, Müller et al. (2006) point out that for the US per capita iron stock has stagnated since the early 1980s.

In this section we have presented evidence to support our hypothesis that developing countries require a minimum level of per capita energy for future gains in well-being. Keeping in mind that the goal of SD should go beyond simply enabling a subsistence level of development, energy consumption will occur not only at the level of individual households, but also in the form of infrastructure accumulation. The next step is to compare the indicated minimal levels of energy consumption with projections arising from IAMs.

3 Energy, development and scenarios of the future

In the following we assess a broader set of IAMs with respect to the question how growth and final energy supply are projected to develop in future scenarios with and without mitigation of climate change. As they are able to represent complex interrelations between the energy, socio-economic and climate systems, IAMs are a powerful tool for describing how growth and energy supply develop in the future. We will compare our hypothesis as formulated and backed by bottom-up analysis in Section 2 with top-down model results, before we discuss the implications of the results for (a) climate policy and (b) the consistency of IAM results in general.

3.1 Energy and development from a model perspective

Using the empirical correlations above as a basis, and recognizing that countries or regions in different stages of development will have differing goals for energy use, we compare final energy consumption under baseline and climate-policy scenarios for several different groups of countries, based on scenarios used by two recent model comparison exercises, ADAM (Edenhofer et al. 2010) and RECIPE (Luderer et al. 2011a). A variety of models has been used in these exercises, i.e. ReMIND-R (Leimbach et al., 2010; Bauer et al., 2011), MERGE-ETL (Kypreos and Bahn, 2003; Kypreos, 2005), IMAGE/TIMER (Bouwman et al., 2006; van Vuuren et al., 2006), POLES (European Commission, 1996), IMACLIM-R (Sassi et al., 2009; Waisman et al., 2011) and WITCH (Bosetti et al., 2006; DeCian et al., 2011). We organize available scenarios into clusters based on climate targets as defined by the IPCC (2007): baseline scenarios with atmospheric GHG concentrations higher than 710 ppm CO2-eq; so-called Category

3 & 4 scenarios with equilibrium atmospheric GHG concentrations between 535 and 710 ppm CO2-eq; and Category 1+2 scenarios, which result in concentrations lower than 535 ppm CO2-eq[7]. Edenhofer et al. (2010), Luderer et al. (2011a), Knopf et al. (2009), Tavoni et al. (2011) and Jakob et al. (2011a) give an overview and a more detailed description of the assessment framework.

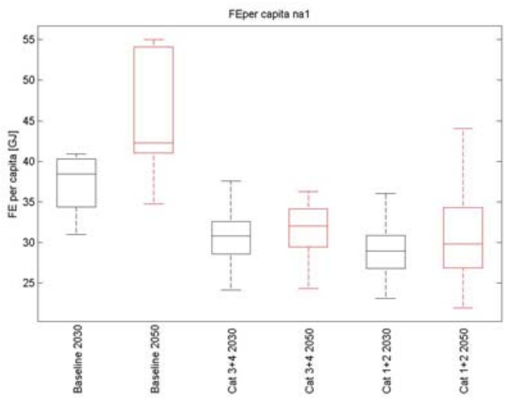
The results shown in Figure 2 represent the output of six IAMs for business-as-usual (BAU) and for two categories of climate policy scenarios. The boxes and bars represent the range of values from the different model runs, with the median of all model runs given by a horizontal bar, and the ends of the bars indicating the extreme values of model output. The boxes correspond to the interquartile range (25^{th} – 75^{th} percentile). We look at two points in time, 2030 (black boxes) and 2050 (red boxes) and different regions. The left-hand column shows the aggregate of all Non-Annex I[8] countries (a), China (b) and India (c), while the column on the right shows results for all Annex I countries (d), and for the US (e) and Europe (f). Note that across the different models the aggregation into regions is not necessarily harmonized and slight variations might occur.

---

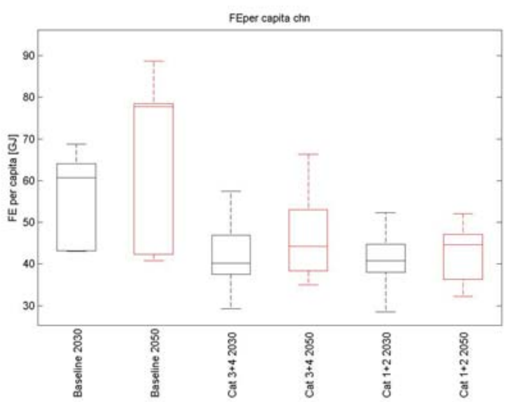
[7] In the IPCC AR4 stabilization categories are defined as follows: I: 445-490 ppm CO_2 eq; II: 450 – 535 ppm CO_2 eq.; III: 535 – 590 ppm CO_2 eq; IV: 590 – 710 ppm CO_2 eq; V: 710 – 855 ppm CO_2 eq; VI: 855 – 1130 ppm CO_2 eq.

[8] We refer to Annex I of the United Nation's Framework Convention on Climate Change (UNFCCC), which include the industrialized countries that were members of the OECD (Organization for Economic Co-operation and Development) in 1992, plus countries with economies in transition, including the Russian Federation, the Baltic States, and several Central and Eastern European States.

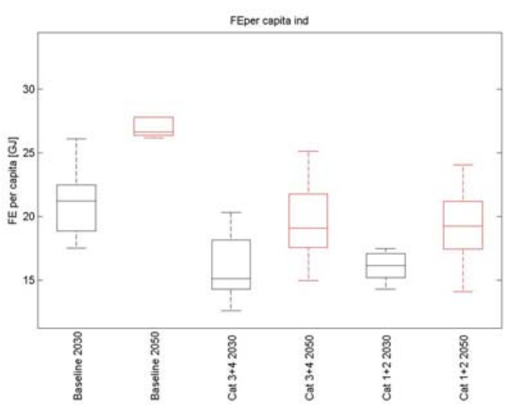
a) Non-Annex I countries



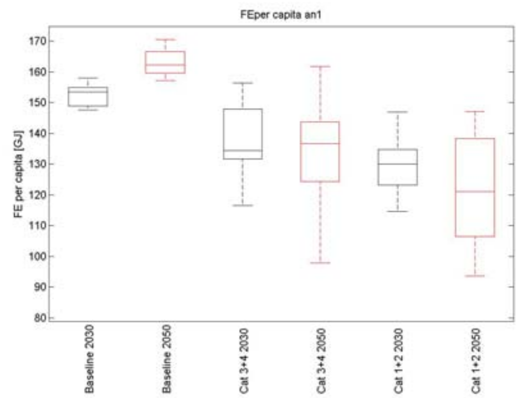
b) China



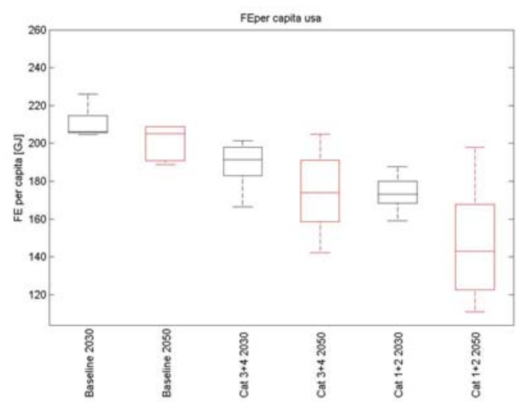
c) India



d) Annex I countries



e) USA



f) Europe

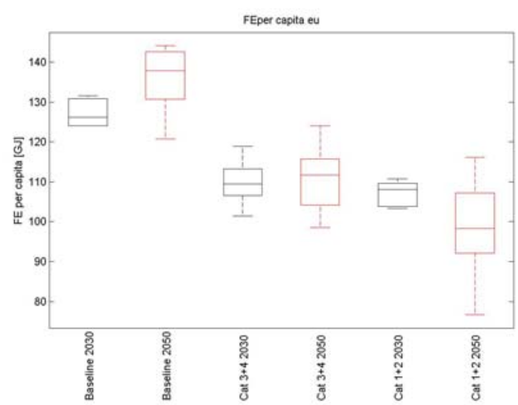


Figure 2: Final energy use per capita per year (in GJ) in all Non Annex I countries (a), all Annex I countries (b), China (c), the US (d), India (e) and Europe (f) for different scenario categories, i.e. baseline scenarios, category 3 and 4 scenarios and low stabilization (category 1+2) scenarios. The black boxes access data for 2030, the red boxes assess data for 2050. The thick black line corresponds to the median, the boxes correspond to the interquartile range (25th – 75th percentile) and the whiskers correspond to the total range across all reviewed scenarios.

From Figure 2 we can derive three major implications: First, we note a general trend that per capita final energy consumption decreases significantly in the policy cases with respect to the BAU case for all regions. Second, relative reductions between baseline and policy cases are slightly higher in Non-Annex I countries (20 – 30% lower FE per capita levels in policy cases) compared to Annex I countries (12 – 25% lower FE per capita levels in policy cases), i.e., despite much lower per capita FE consumption levels, models tend to project energy demand in developing countries to be more elastic than in developed countries. Third, while in the baseline scenarios, for Non-Annex I countries the 40 GJ/year threshold seems to be within reach and for China it is already crossed in 2030 for most models[9], the aggregate of Non-Annex I countries remains far below that threshold in mitigation scenarios. There is a slight trend toward increasing energy consumption between 2030 and 2050 in the policy scenarios in all regions; however, it does not catch up to levels that are reached without climate mitigation. While in Annex I countries including Europe and the USA, final energy consumption per capita is significantly lower in low stabilization scenarios, the differences between category 3+4 and category 1+2 scenarios can be neglected in Non-Annex I countries. Hence, the level of ambition in climate stabilization does not seem to make a major difference for developing countries in this respect.

The results from the model comparisons can be interpreted in different ways: On the one hand, decreasing FE levels could simply highlight the need for improved energy intensity across all countries and income groups. However, in the light of our results in Section 2 they also could hint at a possible overestimation of realistic energy intensity improvements in developing countries. To better understand these initial results, we further examine results of the ReMIND-R[10] model in higher temporal and regional detail[11].

Figure 3 shows per capita GDP in 2005 US$ as a function of final energy consumption per capita in GJ[12] for four different scenarios, which represent climate targets of varying ambitiousness. These targets are implemented by using carbon taxes, i.e. one scenario where no carbon tax is implied, defined as the business as usual scenario (BAU), and three scenarios with initial tax levels of $10, $30 and $50 per tonne of carbon, which all

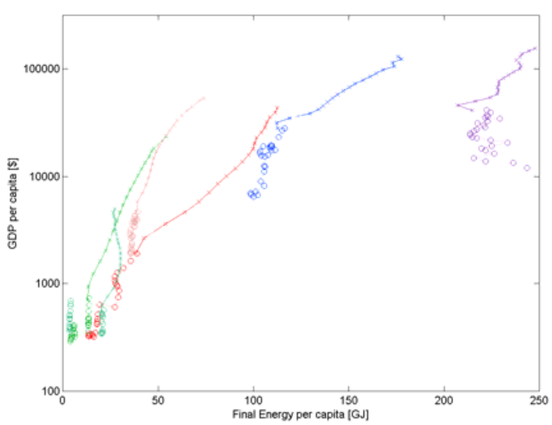
---

[9] Analysis of recent data suggests that China has crossed the threshold already.
[10] ReMIND-R couples a Ramsey-type economic growth model with a detailed bottom-up energy system model and a climate model. Please see http://www.pik-potsdam.de/research/sustainable-solutions/models/remind/REMIND_Description_June2010_final.pdf for a detailed model description.
[11] These data are part of the set of scenarios prepared for the Asia Modeling Exercise (Luderer et al. 2011b).
[12] GDP per capita is reported on a logarithmic scale in order to make results roughly comparable to Figure 1, where GDP per capita goes logarithmical into the calculation of the HDI.

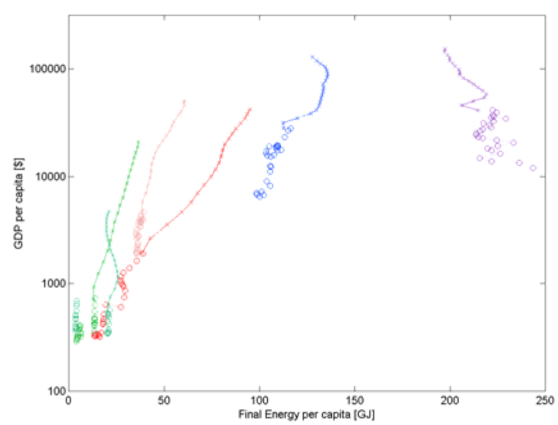
increase by 5% per annum from 2010 on in order to match the targeted levels of ambition. In our analysis we look at four developing regions, i.e. Latin America (LAM), Sub-Sahara Africa (without South-Africa), China (CHN) and India and two developed regions (Europe (EUR) and USA) with the aim of determining whether and how historic trends of energy use and welfare are reflected in our scenarios.

First, in the BAU scenario we find that historic trends are more or less reproduced for developed countries and China, which already crossed the threshold of 40 GJ per capita in 2005. For developing countries that have not crossed the threshold in 2005, historic trends are basically reproduced, i.e. increasing welfare is associated with increasing energy consumption if a certain threshold is crossed. Energy levels per capita are however lower for corresponding per capita GDP values, which could well be explained by technological improvements and leapfrogging very energy-intensive processes.

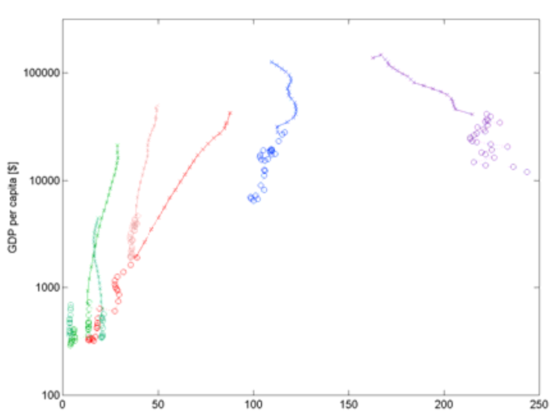
a) BAU (Category VI)



b) Medium stabilization (Category III*)



c) Low stabilization (Category II*)



d) Very low stabilization (Category I*)

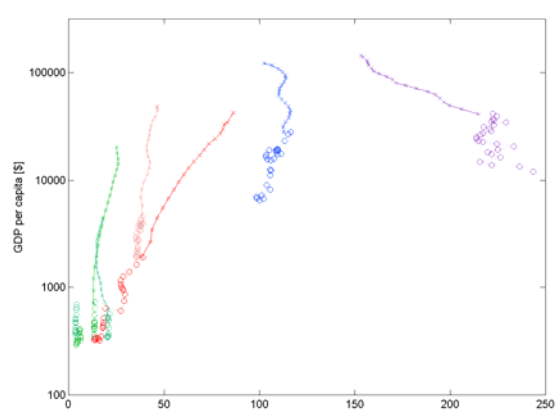


Figure 3: GDP per capita over final energy per capita for selected regions. Circles indicate historic data (based on Penn World Tables 2009), while crosses indicate ReMIND-R model results for different IPCC stabilization categories. *Stabilization scenarios shown here are calculated by using scenarios with progressive carbon taxes increasing by 5% per annum from 2010 with initial levels of US $10, US $30 and US $50, respectively.

Second, if the stabilization level remains relatively moderate, developing countries do not seem to show fundamentally different behavior than in the BAU case. On the other hand, in developed countries efficiency improvements are realized and energy consumption per GDP decreases significantly.

Third, for increasingly ambitious stabilization targets developing countries show significantly different behavior. For all developing regions but China, we can observe a decisive break with the historic trends. Final energy levels remain practically constant despite economic development. In some regions (Sub Saharan Africa (AFR), India) they even decrease initially. In India, which – in terms of GDP per capita - will reach development levels comparable to those of Europe today in the year 2100, FE per capita levels will be around 25 GJ per capita, which is only slightly above today's levels. Quite importantly, the per capita final energy consumption will never increase above this level during the entire century. Comparable patterns can be found in AFR and Latin America (LAM). At the same time, the EU27 and the US – despite reducing final energy per capita consumption significantly - are still seen to be at levels above 100 (EU27) and 150 (USA) GJ per capita in the year 2100[13].

To sum up, the above analysis of the IAM data indicates that climate policy is likely to reduce average per capita energy demand in developing countries to a level that lies below the critical threshold identified in Section 2.1. Particularly in ambitious mitigation scenarios, IAMs project energy consumption to decouple from economic growth in developing countries. This raises the question if climate change mitigation might be at odds with other sustainable development objectives, such as providing energy access for the entire population of these countries.

[13] It is important to understand that population is exogenous in ReMIND-R as in most other IAMs.

3.2 Infrastructure

As indicated in section 2.2 we use infrastructure inputs to bolster the threshold hypothesis. Based on our results from the historical analysis we estimate the future energy demand for steel and cement production using state-of the art technology estimates as well as projections for the future from the literature as well as scenario results from the ReMIND-R model (Leimbach et al., 2010; Bauer et al., 2011).

To estimate the combined energy demand for cement and steel we use model output for capital investment from the ReMIND-R model and use the estimates from 2.2. together with country-specific fixed effects (reported in the Appendix) to translate these results into steel and cement production. For developing countries we assume a switch to OECD values once a developing country reaches levels of affluence comparable to developed countries in 1980. We assume that best practice technologies today use on average 5 GJ/t (de Vries et al. 2006, Taylor et al. 2006, Worrell et al. 2000, Worrell and Galitsky 2008). Theoretically this can be lowered to the thermodynamic limit, which is estimated to be around 1.76 GJ/t (Taylor et al. 2006)[14]. We use an estimate of current best practice energy use for the production of steel of 18 GJ/t (IISI 2011), while we assume the minimum achievable energy intensity to be 2.5 GJ/t following long run estimations from de Beer et al. (1998).

Figure 4 shows results for the relation between cement and steel production and capital investments both historically (shown in black) and the projections derived using the coefficients of our econometric estimates (shown in blue) until the year 2050 for different regions. Historical correlations between investments and cement and steel, respectively, are continued in the future scenario with some minor differentiations between regions that can also be observed in historic data. As an interesting side result, we find an implicit level of per capita steel and cement production in developed societies that ranges between 0.4 and 2 t for cement[15] and 0.3 and 1 t for steel.

[14] The value for a tonne of cement is likely to be higher, as Taylor et al. 2006 give numbers for clinker production.

[15] Obviously there are large differences between country groups particular with respect to cement production. Asian countries have used significantly more cement per capita in their development process than European or North-American countries (see also Appendix for more detailed information on cement production in selected OECD countries). We presume that differences in urban development patterns and types of buildings can explain these differences; a detailed discussion of the phenomenon is however beyond the scope of this paper.

a) Cement **b) Steel**

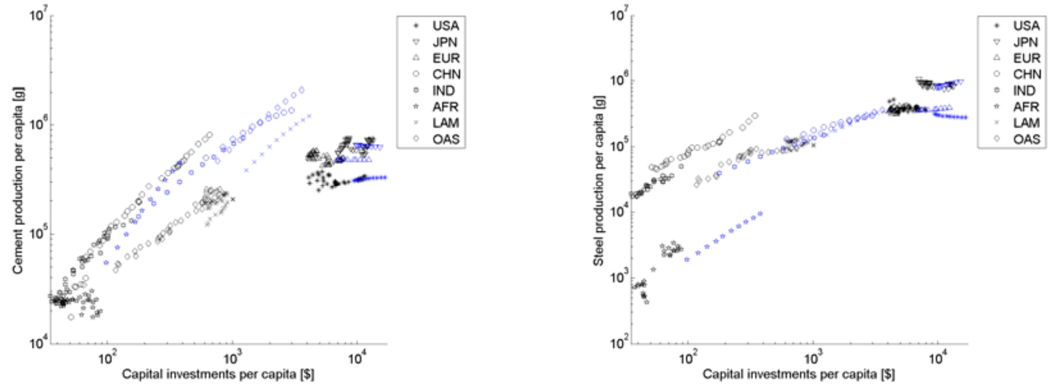


Figure 4: Correlation between capital investments for a) cement and b) steel production on a double log scale, separated by different regions for historic data from 1980-2005 (black), together with scenario results from 2005 to 2050 (blue). Note that the regional aggregation follows the regions that are represented in the ReMIND model.

We can use these results for the production of steel and cement to project the energy consumption required in the future. Implicitly we assume that cement and steel will not be substituted by other inputs of production in the future. The lower bounds of the ranges shown in Figure 5 are calculated using the minimum achievable energy input for steel and cement (i.e. the thermodynamic limits) while the upper bounds are calculated with today's state of the art technologies' energy need[16]. Realistic results in the near future will be close to the upper limit of the range, while due to technological progress future specific energy consumption from cement and steel can be expected to eventually decrease and thus results closer to the lower range become more likely.

[16] For cement we calculate with an energy input of 5 GJ/t for today (de Vries et al. 2006, Taylor et al. 2006, Worrell et al. 2000), which theoretically can be lowered 1.76 GJ/t in the future (Taylor et al. 2006). For steel production we estimate a current best practice energy use of 18 GJ/t (IISI 2011), which we assume to be lowered to 2.5 GJ/t in the future.

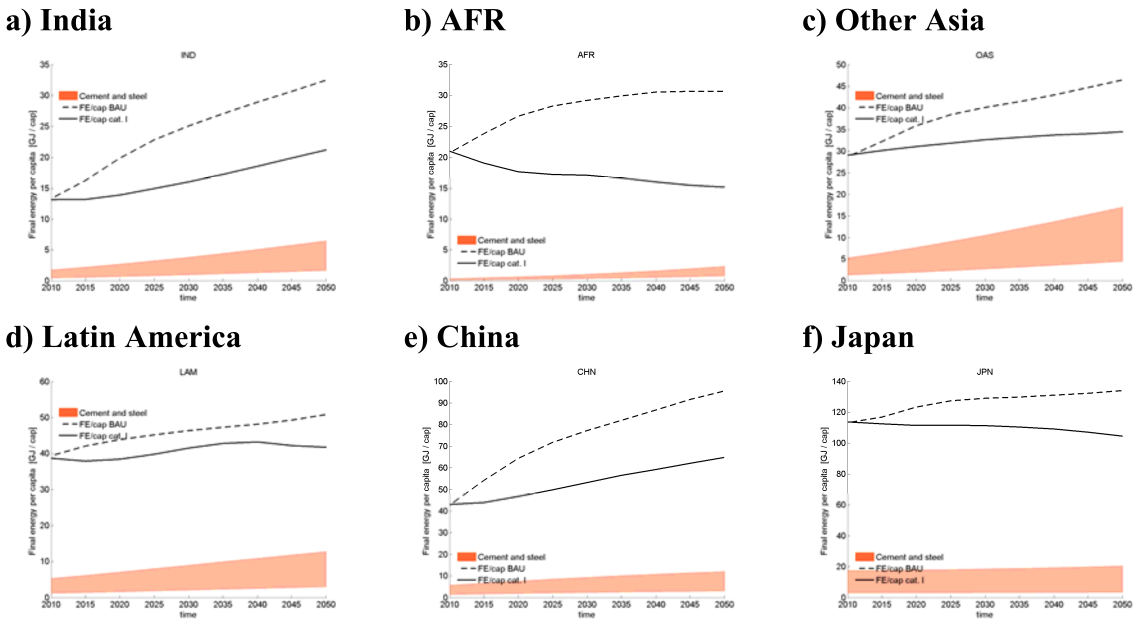


Figure 5: Ranges of energy demand for cement and steel production in comparison to FE demand in different mitigation scenarios as calculated by the ReMIND model. The upper bound assumes the current energy use and the lower bound the thermodynamic limit for future production of cement and steel. The projections are results from the econometric model based on capital investment and population. The black line indicates energy demand in a ReMIND policy scenario (cat I), while the dashed lined indicates energy demand in a ReMIND BAU scenario. Note that the regional aggregation follows the regions represented in the ReMIND model.

For countries that are currently developing, using historical fits leads to increasing energy demand for steel and cement until they reach comparable levels to developed countries towards 20 GJ per capita without improvements in the production techniques. While for developed countries and China, the energy needed for the supply of infrastructure accounts for only a small part of the overall energy supply, it makes up a significant share for India (a), OAS (c), and LAM (d). For Sub-Saharan Africa (b), we calculate lower levels of per capita energy for steel and cement in 2050, however increasing and converging towards developed country levels with increasing levels of development. In any case, economic development is expected to go hand in hand with additional energy use for infrastructure. For developed countries (here exemplarily shown for Japan, Figure 5f) we find that future energy demand for cement and steel ranges between 2 and 20 GJ per capita in the year 2050, depending on the energy intensity levels of the future and thus remaining roughly at today's levels.

In summary, we can conclude that additional energy will be needed for the construction of infrastructure in developing countries. Its magnitude will depend on the rate of technological progress, but – at least in the short to medium term – will likely exceed the level of final energy per capita that is thought to be needed for fulfilling basic needs, i.e. 10 GJ per capita. Taken literally, our results for developing countries, particularly India, Sub-Saharan Africa, Other Asia and Latin America imply that not much – if any – additional final energy would be left for these economies besides energy that is needed for steel, cement and fulfilling basic needs on the household level. It should be mentioned that for this calculation, we only considered energy needed for steel and cement production, which is not the only infrastructure that can theoretically be taken into account. Energy needed for transportation infrastructure (e.g. bitumen) as well as other metals like copper or aluminum would add to the numbers that are presented above. This puts into question the consistency of scenario results that foresee substantial economic growth in developing regions, while final energy per capita levels stagnate at today's levels or even decrease.

4 Implications for climate policy

Globally, human-kind is faced by the twin challenges of mitigating climate change and overcoming poverty. Despite the urgency of solving the climate problem, mitigation policy should not trap developing countries in a state of poverty. At the same time future development processes should avoid technological lock-ins, e.g. in a carbon-intensive infrastructure or energy systems.

When looking at low-stabilization scenarios produced by IAMs, here shown mainly using the ReMIND-R model but recognizing that other models give qualitatively similar results (see Annex B for a sensitivity analysis of ReMIND-R results compared to other IAMs), we find that historical correlations between economic growth and energy use are discontinued in mitigation scenarios, both with respect to a postulated (and observed) energy threshold as well as with respect to increasing energy use in the course of development. In model results for mitigation scenarios, final energy demand in developing regions (AFR, LAM) stays approximately at current (low) levels, whereas per capita GDP rises significantly. Importantly, BAU and less-ambitious climate mitigation scenarios do not project a decoupling between per capita final energy levels and economic development. At first sight, the model results seem to be either not realistic or driven by very strong implicit assumptions.

The most important question is whether developing countries will be able to decouple their growth from energy use and - looking at the differences between BAU and policy scenarios – how fast this can be achieved. We are rather pessimistic that it is possible for low income countries to develop without increasing their level of energy use, given the indicated need for energy to drive GDP growth. In addition to energy required to satisfy basic needs at the household level, energy is also embedded in the construction of infrastructure when development goes beyond the satisfaction of basic needs. All countries that have reached higher development levels in the past have increasingly used energy-intensive inputs like steel and cement and it is hardly plausible that this correlation will break, at least in the near future[17]. This impression is confirmed by an analysis of the current developing process in India or China (Steckel et al. 2011). Recent results from the literature (Jakob et al., 2011b) also imply that historical patterns of energy use are repeated for developing countries and leapfrogging in this respect will be hard to achieve if capital accumulation will remain an important driver of economic growth in the future. However, assuming that scenario results are robust, we can provide a twofold interpretation:

First, only with massive improvements of energy intensity will it be possible to dramatically reduce the energy used for capital accumulation as compared to patterns observed in the past. This result highlights the urgent need for drastic efficiency improvements and the simultaneous provision of latest technologies to developing countries. Our results imply that bringing production processes of infrastructure inputs to their thermodynamic limits might allow scenario results for developing countries to be achievable in reality. However, considering historic trends, no dramatic improvements in the efficiency of these processes can be expected in the near-term. Thus, the efficiency gains implicitly assumed by the model results seem to be out of reach. Alternatively a total or partial replacement of energy-intensive inputs by low energy alternatives is theoretically conceivable, e.g. by newly developed materials or methods; however, this option requires a significant leap of faith.

The second interpretation is that developing countries might reach high economic development without accumulating energy-intensive capital. Of course, for our analysis focusing on infrastructure it is also conceivable that necessary inputs are imported; however, as both steel and cement are not easy to transport, importing these inputs over large, trans-regional distances seems to be rather unlikely and would be unprecedented in the past. Also, it is not indicative from scenario results that energy for steel and cement is provided in other regions. In principle it is possible to imagine societies whose economic growth is not based on capital accumulation, thinking of a service-oriented society.

Both interpretations imply strong underlying assumptions. Some of the results are based on the ReMIND-R model, which does not explicitly include energy needs for development. However, we have shown that the general tendency of very low levels of final energy per capita consumption is robust over a whole set of different models. Our

[17] One could even argue that climate change impacts will increase the demand for cement, due to increased corrosive damages at existing infrastructure (Stewart et al. 2011).

results point to the need to spell out the details of energy demand structures more explicitly, in particular for the developing world. Analyzing energy needs at different stages of development is a promising future area of research. A possible outcome of calibrating IAMs to such bottom-up derivations of energy demand with could be that current mitigation scenarios are too optimistic with respect to energy consumption in developing countries. Such a finding could challenge one of the most important conclusions derived by IAMs, namely that mitigation costs can be expected to be comparatively modest. In general, this analysis raises the question whether a stronger differentiation between developed and developing countries is necessary in IAMs. For example, IA modelers could represent energy access policy targets in terms of a minimal energy input level that should be achieved to guarantee reasonable development levels. As of today, these questions – along with other important issues of sustainability - are not taken into account in most IAM analyses.

Our results further show that developing countries can hardly be expected to be the first to reduce their per capita final energy consumption (from already low levels), as implied in some IAM results under climate policy. Options for development should be left open to these countries, and this will likely include the use of energy for infrastructure, until a clear path for decoupling energy use from development can be shown. Global uniform carbon taxes as assumed in many models lead to results that could potentially harm their development, if highly efficient technologies are not available very soon. Therefore any international mitigation agreement should carefully take the needs of developing countries into account.

Acknowledgments

We thank Brigitte Knopf, Elmar Kriegler, Robert Marschinski, Robert Pietzcker, Eva Schmid and Christoph von Stechow for helpful comments and discussions. Parts of this work have been founded by the German Federal Ministry for Education and Research (BMBF) under the "EntDekEn" project. RJB acknowledges support from the German Fulbright Foundation for the 2010 - 2011 academic year, as well as periodic support from the Potsdam Institute for Climate Impact Research.

Appendix A: Summary statistics

DC	*Observations*	*Mean*	*Std. Dev.*	*Min*	*Max*
ln steel	156	9.592039	1.785397	5.370638	12.83397
ln cement	156	8.568707	1.09147	6.363028	11.21321
ln GDP	156	-.1455549	.6935545	-1.414846	1.046656
ln INV	156	-1.79617	1.002467	-3.773844	-.1269643
ln POP	156	13.36882	.392945	12.68064	14.10544

Table A1: Summary statistics for developing countries.

OECD	*Observations*	*Mean*	*Std. Dev.*	*Min*	*Max*
ln steel	78	11.66662	.2948216	11.12219	12.2184
ln cement	78	8.940087	.5110286	8.286269	9.778831
ln GDP	78	1.87636	.492687	.6317062	2.617282
ln INV	78	.6208335	.4117358	-.3879909	1.325895
ln POP	78	12.42075	.5565926	11.66828	13.10009

Table A2: Summary statistics for OECD countries.

Cement_GDP DC	*Coef.*	*Std. Err.*	*t*	*P>|t|*	*[95% Conf. Interval]*
β	.7431696	.0586947 |	12.66	0.000	.6271817 .8591575
γ	1.899377	.1173259	16.19	0.000	1.667527 2.131228
α_{MENA}	-16.19797	1.517162	-10.68	0.000	-19.19607 -13.19988
α_{CHN}	-16.67259	1.637676	-10.18	0.000	-19.90884 -13.43635
α_{IND}	-17.16932	1.626985	- 10.55	0.000	-20.38444 -13.9542
α_{AFR}	-17.36198	1.57274	-11.04	0.000	-20.46991 -14.25406
α_{LAM}	-16.42157	1.513404	-10.85	0.000	-19.41224 -13.43089
α_{OAS}	-16.4699	1.571013	-10.48	0.000	-19.57441 -13.36538
Cement_INV DC	*Coef.*	*Std. Err.*	*t*	*P>|t|*	*[95% Conf. Interval]*
β	.5523936	.0438784	12.59	0.000	.4656845 .6391026
γ	2.019974	.1137714	17.75	0.000	1.795147 2.2448
α_{MENA}	-16.8022	1.502156	-11.19	0.000	-19.77064 -13.83375
α_{CHN}	-17.61418	1.61167	-10.93	0.000	-20.79903 -14.42932
α_{IND}	-17.95363	1.604435	-11.19	0.000	-21.12419 -14.78307
α_{AFR}	-17.88295	1.558922	-11.47	0.000	-20.96358 -14.80233
α_{LAM}	-16.95098	1.501101	-11.29	0.000	-19.91734 -13.98462
α_{OAS}	-17.45866	1.542884	-11.32	0.000	-20.50759 -14.40973
Steel_GDP DC	*Coef.*	*Std. Err.*	*t*	*P>|t|*	*[95% Conf. Interval]*
β|	.7518711	.1359855	5.53	0.000	.483147 1.020595
γ	1.448846	.271824	5.33	0.000	.9116889 1.986004
α_{MENA}	-10.18157	3.515003	-2.90	0.004	-17.12765 -3.235493
α_{CHN}	-8.918611	3.794213	-2.35	0.020	-16.41644 -1.420782

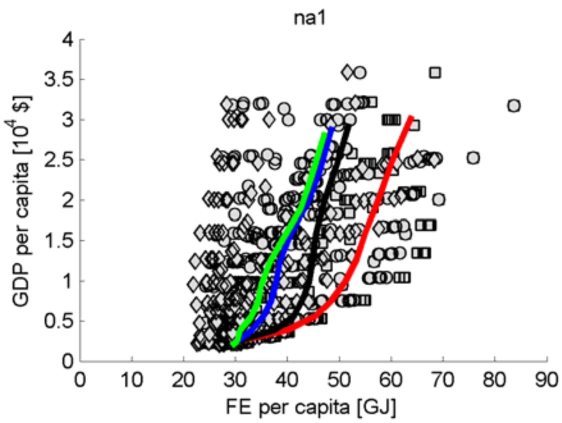
α_{IND}	-9.415145	3.769444	-2.50	0.014	-16.86403 -1.966262
α_{AFR}	-11.91986	3.643768	-3.27	0.001	-19.12039 -4.719323
α_{LAM}	-8.655937	3.506297	-2.47	0.015	-15.58481 -1.727064
α_{OAS}	-8.91623	3.639768	-2.45	0.015	-16.10886 -1.723602
Steel_INV DC	*Coef.*	*Std. Err.*	*t*	*P>|t|*	*[95% Conf. Interval]*
β|	.4643985	.1045849	4.44	0.000	.257726 .671071
γ	1.6638	.2711759	6.14	0.000	1.127923 2.199676
α_{MENA}	-12.11991	3.580412	-3.39	0.001	-19.19524 -5.044572
α_{CHN}	-11.27925	3.841441	-2.94	0.004	-18.87041 -3.688092
α_{IND}	-11.72973	3.824196	-3.07	0.003	-19.28681 -4.172646
α_{AFR}	-13.99472	3.715715	-3.77	0.000	-21.33743 -6.652015
α_{LAM}	-10.50539	3.577898	-2.94	0.004	-17.57576 -3.435026
α_{OAS}	-11.27217	3.677489	-3.07	0.003	-18.53934 -4.005
Cement_GDP OECD	*Coef.*	*Std. Err.*	*t*	*P>|t|*	*[95% Conf. Interval]*
β	-.0644126	.0456507	-1.41	0.162	-.1553943 .026569
γ	1.521589	.2739977	5.55	0.000	.9755122 2.067665
α_{EUR}	-10.10795	3.510918	-2.88	0.005	-17.10519 -3.110696
α_{USA}	-10.25885	3.34626	-3.07	0.003	-16.92794 -3.589763
α_{JPN}	-9.148183	3.169163	-2.89	0.005	-15.46432 -2.832051
Cement_INV OECD	*Coef.*	*Std. Err.*	*t*	*P>|t|*	*[95% Conf. Interval]*
β	.005888	.0433015	0.14	0.892	-.0804119 .0921878
γ	1.212466	.2957029	4.10	0.000	.6231307 1.801801
α_{EUR}	-6.212061	3.838023	-1.62	0.110	-13.86123 1.437109
α_{USA}	-6.546408	3.66286	-1.79	0.078	-13.84648 .7536607
α_{JPN}	-5.611443	3.456714	-1.62	0.109	-12.50066 1.277777
Steel_GDP OECD	*Coef.*	*Std. Err.*	*t*	*P>|t|*	*[95% Conf. Interval]*
β	.096907	.0463981	2.09	0.040	.0044358 .1893782
γ	.3927311	.2784835	1.41	0.163	-.1622857 .947748
α_{EUR}	6.704957	3.568399	1.88	0.064	-.4068511 13.81676
α_{USA}	6.303197	3.401045	1.85	0.068	-.475076 13.08147
α_{JPN}	6.812166	3.221048	2.11	0.038	.3926273 13.23171
Steel_INV OECD	*Coef.*	*Std. Err.*	*t*	*P>|t|*	*[95% Conf. Interval]*
β	.1090002	.0428477	2.54	0.013	.0236049 .1943955
γ	.2468864	.2926035	0.84	0.402	-.3362715 .8300444
α_{EUR}	8.730784	3.797795	2.30	0.024	1.16179 16.29978
α_{USA}	8.250037	3.624467	2.28	0.026	1.026485 15.47359
α_{JPN}	8.616486	3.420482	2.52	0.014	1.799476 15.4335

Table A3: Parameters from the econometric model including country-specific fixed effects.

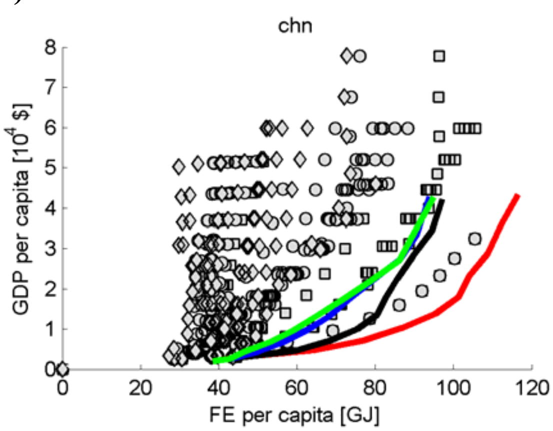
Appendix B: Sensitivity analysis of ReMIND-R results

To test whether ReMIND-R results are model-specific we also look at qualitative results from other integrated assessment models. In Figure scenarios from the analysis shown in Figure 3 (section 3.1) are compared to results from the model comparison projects ADAM (Edenhofer et al. 2010) and RECIPE (Luderer et al 2011a) (see also section 3.1). The BAU scenario is shown in red, the category III stabilization scenario is indicated in black, category II stabilization scenario is shown in blue and the category I stabilization scenario is shown in green. All other scenarios are shown by grey dots, of which squares indicate baseline scenarios, circles indicate category III and IV scenarios and diamonds indicate category I and II scenarios.

a) Non-Annex I countries

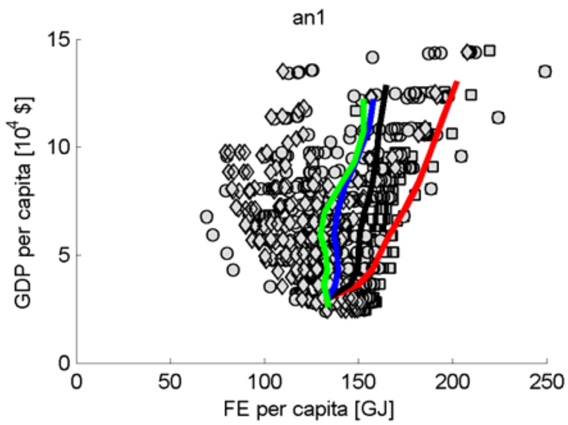


b) China

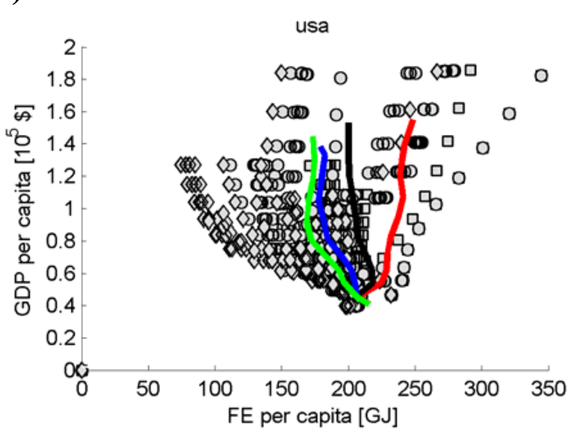


c) India

d) Annex I countries



e) USA



f) Europe

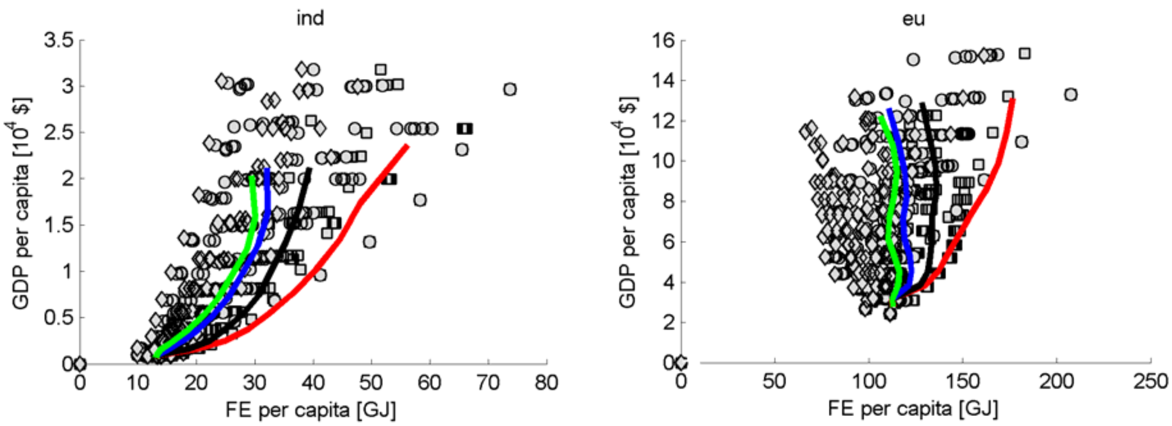


Figure B1: Comparison of ReMIND-R results with those of other models from the RECIPE and ADAM model comparison projects. Baseline scenarios are shown by squares, category 3+4 scenarios by circles and category 1+2 scenarios by diamonds. Different colors show differently ambitious ReMIND-R scenarios, i.e. baseline (red), category III (black), category II (blue) and category I (green) stabilization scenarios.

We find that ReMIND-R does not produce qualitatively different results than other models that participated in both model inter-comparison projects. Obviously other models also find that in stabilization scenarios the correlation between energy consumption and economic growth is broken to an extent that might have implications for future development.

Appendix C: Cement production in the past

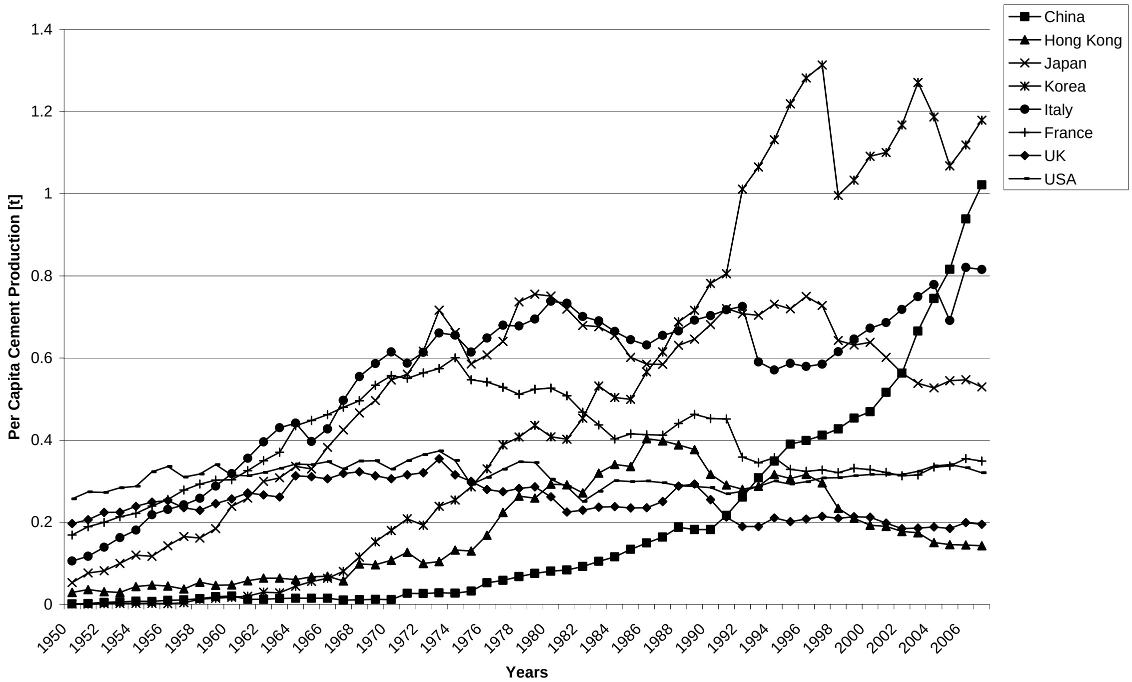


Figure C1: Cement production per capita in selected developed countries and China from 1950 to 2008. Data are based on Boden et al. (2011) for cement and Heston et al. (2009) for population.

References

Bauer N, Baumstark L, Leimbach M (*in press*) The REMIND-R model: The Role of Renewables in the low-carbon transformation. *Climatic Change,* DOI: 10.1007/s10584-011-0129-2

Boden, T., G. Marland, B. Andres (2011): National CO2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751 – 2008. Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory. Available online at: http://cdiac.ornl.gov/ftp/ndp030/nation.1751_2008.ems [Accessed November, 2011].

Bollen et al (2009) Local air pollution and global climate change: A combined cost-benefit analysis. *Resource and Energy Economics* 31: 161–181

Bosetti V, Carraro C, Galeotti M, Massetti E, Tavoni M (2006) WITCH: A World Induced Technical Change Hybrid Model. *The Energy Journal* 27(Special Issue 2): 13-38

Bouwman, A. F., Kram, T. and Klein Goldewijk, K. eds., (2006). Integrated modeling of global environmental change. An overview of IMAGE 2.4. Bilthoven, The Netherlands: Netherlands Environmental Assessment Agency (MNP).

Clarke L, Edmonds J, Krey V, Richels R, Rose S, Tavoni M (2009) International Climate Policy Architectures: Overview of the EMF22 International Scenarios. *Energy Economics* 31:S64-S81

De Beer, JG, E. Worrell, K. Blok (1998): Future technologies for energy efficient iron and steelmaking. *Annual Review of Energy and Environment*, 23: 123 – 205

De Cian, E., V. Bosetti, M. Tavoni (2011): Technology innovation and diffusion in “less than ideal” climate policies: An assessment with the WITCH model. *Climatic Change*, *in press,* DOI: 10.1007/s10584-011-0320-5

De Vries, HJM, K. Blok, M.K. Patel, M. Weriss, S. Joosen, E. De Visser, J. Sijm, H. de Wilde (2006): Assessment of the interaction between economic and physical growth. EPIST project. Utrecht: Utrecht Center for Energy Research (UCE). Available online at: http://ecn.nl/docs/libary/report/2006/b06004.pdf [June 2011]

Edenhofer O, Knopf B, Barker T, Baumstark L, Bellevrat E, Chateau B, Criqui P, Isaac M, Kitous A, Kypreos S, Leimbach M, Lessmann K, Magné B, Scrieciu S, Turton H, van Vuuren DP (2010) The economics of low stabili-zation: model comparison of mitigation strategies and costs. *Energy Journal* 31(Special Issue 1): 11-48

Edenhofer O, Lessmann K, Kemfert C, Grubb M, Köhler J (2006) Induced Technological Change: Exploring its Implications for the Economics of Athmospheric Stabilization. Synthesis Report from Innovation Modeling Comparison Project. *Energy Journal* 27(Special Issue 2): 57-107

European Commission (1996). POLES 2.2. European Commission DG XII. EUR 17358 EN.

Fleurbaey, Marc. (2009). Beyond GDP: The Quest for a Measure of Social Welfare. *Journal of Economic Literature* 47, no. 4 (12): 1029-1075. doi:10.1257/jel.47.4.1029.

GNESD, 2007: Reaching the Millennium Development Goals and beyond – access to modern forms of energy as a prerequisite. Global Network on Energy for Sustainable Development, Roskilde.

Goldemberg, J. TB Johansson, AKN Reddy, RH Williams (1985): Basic Needs and Much More with One Kilowatt per Capita. *Ambio*, Vol. 14, (4/5): 190-200

Goldemberg, J. (2001): Energy and Human Well Being. UNDP Human Development Occasional Papers (1992-2007) number HDOCPA-2001-02.

Heston, A., R. Summers and B. Aten (2009), Penn World Table Version 6.3, Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania

IEA (2010a): *Energy Poverty – How to make modern energy access universal*. Special excerpt from WEO 2010 with UNIDO and UNDP. International Energy Agency, Paris.

IEA (2010b). International Energy Agency – Statistics and Balances. http://www.iea.org/stats/index.asp [accessed 14 Feb. 2011].

IISI (International Iron and Steel Institute) (2011): World Steel Production 1980 – 2010. Data available online at: http://www.worldsteel.org [June 2011].

IPCC (2000): IPCC good practice guidance and uncertainty management in national greenhouse gas inventories. Chapter 3: Industrial Processes. Available online at: http://www.ipcc.nggip.iges.or.jp/public/gp/english/3_Industry.pdf [June 2011].

IPCC (2007): B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds): *Contribution of Working Group III to the Intergovernmental Panel on Climate Change, 2007*. Cambridge; New York: Cambridge University Press.

IPCC (2011): Sathaye, J., O. Lucon, A. Rahman, J. Christensen, F. Denton, J. Fujino, G. Heath, S. Kadner, M. Mirza, H. Rudnick, A. Schlaepfer, A. Shmakin, 2011: *Renewable Energy in the Context of Sustainable Energy. In IPCC Special Report on Renewable Energy Sources and Climate C hange Mitigation* [O. Edenhofer, R. Pichs□Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadne r, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jakob M, Luderer G, Steckel JC, Bosetti V, Tavoni M, Waisman H (2011a) Time to act now? Assessing the costs of delaying climate measures and benefits of early action, *Climatic Change, in press,* DOI: 10.1007/s10584-011-0128-3.

Jakob, M., Haller, M., Marschinski, R. (2011b): Will history repeat itself? Economic convergence and convergence in energy use patterns. *Energy Economics, in press*, DOI:10.1016/j.eneco.2011.07.008

Knopf B et al. (2009): The Economics of low stabilization: implications for technological change and policy. In: M. Hulme, H. Neufeldt (Eds.). *Making climate change work for us – ADAM synthesis book.* Cambridge University Press, Cambridge

Krausmann, F., H. Schandl, and R.P. Sieferle, 2008: Socio-ecological regime transitions in Austria and the United Kingdom. *Ecological Economics*, 65(1): 187-201.

Krugman, H. and Goldemberg, J., (1983) The energy cost of satisfying basic human needs, *Technological Forecasting and Social Change*, 24: 45-60.

Kypreos, S., and Bahn, O. (2003). "A MERGE model with endogenous technological progress." *Environmental Modeling and Assessment*, 8: 249-259.

Kypreos, S. (2005). "Modeling experience curves in MERGE (model for evaluating regional and global effects)." *Energy*, 30(14): 2721-2737.

Leimbach M, Bauer N, Baumstark L, Edenhofer O (2010) Mitigation costs in a globalized world: climate policy analysis with ReMIND-R. *Environmental Modeling and Assessment*, 15(3): 155-173. doi: 10.1007/s10666-009-9204-8

Lenton, T., H. Held, E. Kriegler, JW Hall, W. Lucht, S. Rahmstorf, HJ Schellnhuber (2008): Tipping elements in the Earth's climate system. *PNAS*, 105 (6): 1786 – 1793

Luderer, G., V. Bosetti, M. Jakob, M. Leimbach, J. Steckel, H. Waisman, O. Edenhofer (2011a): On the Economics of Decarbonization – Results and Insights from the RECIPE Model Intercomparison. *Climatic Change, in press*

Luderer, G., R. Pietzcker, E. Kriegler, M. Haller, N. Bauer (2011b): Asia's Role in Mitigating Climate Change: A Technology and Sector Specific Analysis with ReMIND-R. Submitted to *Energy Economics*.

Müller, D.B., T. Wang, B. Duval and T.E. Graedel (2006): Exploring the engine of anthropogenic iron cycles. *PNAS*, 103 (44), pp: 16111-16116

Neumayer, Eric. 2003. *Weak versus strong sustainability : exploring the limits of two opposing paradigms.* 2nd ed. Northampton MA: Edward Elgar

Pachauri, S. and D. Spreng, 2002: Direct and indirect energy requirements of households in India. *Energy Policy* 20: 511-523.

Pereira, M. G., Sena, J. A., Freitas, M. A. V., & da Silva, N. F. (2011). Evaluation of the impact of access to electricity: A comparative analysis of South Africa, China, India and Brazil. *Renewable and Sustainable Energy Reviews, 15*(3): 1427–1441.

Sassi, O, Crassous R, Hourcade JC, Gitz V, Waisman H, Guivarch C (2010) IMACLIM-R: a modelling framework to simulate sustainable development pathways. *Int. J. Global Environmental Issues* 10: 5-24.

Sathaye, J., A. Najam, C. Cocklin, T. Heller, F. Lecocq, J. Llanes-Regueiro, J. Pan, G. Petschel-Held , S. Rayner, J. Robinson, R. Schaeffer, Y. Sokona, R. Swart, H. Winkler (2007): Sustainable Development and Mitigation. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Steckel, JC. M. Jakob, R, Marschinski, G. Luderer (2011): From carbonization to decarbonization? Past trends and future scenarios for China's CO_2 emissions. *Energy Policy*, 39 (6): 3443 – 3455

Stewart, M.G., Wang, X., Nguyen, M.N. (2011) Climate change impact and risks of concrete infrastructure deterioration. *Engineering Structures*, 33: 326–1337

Tavoni, M., E. De Cian, G. Luderer, JC. Steckel, H. Waisman (2011): Technology Option Values and Technological Change towards a Low Carbon Economy. *Climatic Change, in press*, DOI: 10.1007/s10584-011-0294-3

Taylor, M., C. Tam and D. Gielen (2006): *Energy Efficiency and CO2 emissions from the global cement industry*. Paper prepared for the IEA-WBCDS workshop, Paris 4-5 September 2006. Paris: IEA. Available online at: http://195.200.115.136/work/2006/cement/taylor_background.pfg [accessed 2011-06-01]

UN, 2002: *Report of the World Summit on Sustainable Developmen*t (Plan of Implementation). United Nations, Johannesburg, New York.

UN 2005: *The Energy Challenge for Meeting the Millennium Development Goals*. Available at http://esa.un.org/un-energy

UNDP (2010). United Nations Development Program - Worldwide Trends in Human Development. http://hdr.undp.org/en/data/trends/ (accessed 14 Feb. 2011).

UNDP (2011) United Nations Development Program – Human Development Index. http://hdr.undp.org/en/statistics/hdi/ (accessed June 2011).

Urban, F., R. M. J. Benders, et al. (2007). "Modeling energy systems for developing countries." *Energy Policy* 35 (6): 3473-3482.

van Ruijven, B., F. Urban, et al. (2008). Modeling Energy and Development: An Evaluation of Models and Concepts. *World Development* 36 (12): 2801-2821

van Vuuren, D. P., Van Ruijven, B., Hoogwijk, M.M., Isaac, M., De Vries, H.J.M., (2006). "TIMER 2: Model description and application. Integrated modeling of global environmental change. An overview of IMAGE 2.4". In Bouwman, A. F., T. Kram, and K. Klein Goldewijk. Bilthoven, The Netherlands: Netherlands Environmental Assessment Agency (MNP), 39-59.

Van Vuuren, D., MGJ den Elzen, PL Lucas, B Eickhout, BJ Strengers, B van Ruijven, S Wonink, R van Hoult (2007). Stabilizing greenhouse gas emissions at low levels: an assessment of reduction strategies and costs. *Climatic Change* 81: 119-159

Waisman H, Hourcade JC, Guivarch C, Grazi F (2011): The IMACLIM-R model: the role of infrastructures, technical inertia and imperfect foresight in the costs of low carbon futures. *Climatic Change, forthcoming*

Weyant JP, de la Chesnaye FC, Blanford GJ, (2006) Overview of EMF21: Multigas mitigation and climate policy. *Energy Journal* 27(Special Issue3):1–32

WCED (World Commission on Environment and Development) (1987): *Our common future*. Oxford; New York: Oxford University Press.

Worrell, E. and C. Galitsky (2008): *Energy efficiency improvement and cost saving opportunities for cement making. An Energy Star Guide for Energy and Plant Managers*. Berkeley: University of California

Worrell, E., N. Martin and L.K. Price 2000: Potentials for energy efficiency improvement in the US cement industry. *Energy*, 25: 1189 - 1214