Development without energy?

Assessing future scenarios of energy consumption in developing countries

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ABSTRACT

We analyze the relationship between economic development and energy consumption in the context of greenhouse gas mitigation. The main contribution of this work is to compare estimates of energy thresholds in the form of minimum energy requirements to reach high levels of development with output projections of per capita final energy supply from a group of integrated assessment models (IAMs). 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 or efficiency improvements, concluding that the decreases in energy consumption implied in numerous mitigation scenarios are unlikely to be achieved without endangering sustainable development objectives. To underscore the importance of basic energy needs also in the future, the role of infrastructure is highlighted, using steel and cement as examples.

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. On the one hand – even though not incorporated directly in the Millennium Development Goals (MDG) – energy is undoubtedly essential for human development (GNESD, 2007). On the other hand, supply of energy in the past has been strongly connected to the combustion of fossil fuels and emission of GHG. From a developing country perspective, it is essential to understand how poverty alleviation and acceptable development levels that go beyond pure subsistence can be reached; at the same time the necessity of leap-frogging unsustainable development pathways that have been witnessed by developed countries in the past is highly obvious (World Bank, 2010).

Incorporating GHG 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, and starting with data about the current state and past trends in the energy system. IAMs allow comparisons between baseline scenarios designated as Business-As-Usual (BAU) and those in which GHG mitigation policies are assumed (POL).

A broad range of studies is available in which mitigation costs in terms of foregone GDP or consumption[1] 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., 2012a). 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.

Analyses by IAMs have been at the heart of recent IPCC reports as for example the Fourth Assessment Report (AR4) (Fisher et al., 2007) or the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (Fischedick et al., 2011) and will continue to play an important role in the Fifth Assessment Report (e.g. Kriegler et al., 2012). Given the central role of IPCC assessments of published literature for international climate policy negotiations, it is important that IAMs provide robust estimates of future mitigation costs and transition pathways.

When evaluating possibilities to avoid carbon emissions in the future, two options are at the heart of the current debate; cutting carbon-intensity by promoting carbon-free

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[1] IAMs start only slowly to take broader aspects of development and sustainability into account, see e.g. Urban et al., 2007, van Vuuren et al., 2007, Bollen et al., 2009, van Ruijven et al., 2008.

technologies like renewable energy technologies, nuclear energy or CCS, and improving energy intensity, either by higher levels of efficiency or through structural change.

Past studies have critically assessed the robustness of scenario analyses with respect to assumed energy- and carbon-intensity improvements. Pielke et al. (2008) argue that scenarios assessed for AR4 systematically overestimate the role of energy intensity improvements in the future and at the same time underestimate the carbonization dynamics of newly industrializing countries, like China or India.

In this paper we assess the role of energy consumption in scenarios of the future, particularly highlighting the essential role of energy in development processes. We start by evaluating the role of energy for human development by drawing on existing literature. We conjecture that economic development very likely requires a minimum level of energy.

We continue by asking whether energy consumption, as calculated in IAMs, is consistent with how energy has been related to development in the past[2]. 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 GHG mitigation scenarios. We evaluate how the relationship between energy use and economic growth is represented in these models, particularly for developing regions.

To better understand the nature of energy requirements in growth processes, we look at the role of infrastructure and related energy requirements. By means of extrapolation of historical patterns regarding the relationship between economic variables and infrastructure, we aim to provide a rough estimate of a lower bound of minimum requirements for energy use in the future.

Our analysis raises doubts that the role of energy in development processes is adequately considered in IAMs. We 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, i.e. energy access tends to call into question the internal consistency 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 for 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

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[2] Please note that IAMs usually report consumption or GDP as development indicators and do not take broader concepts of development into account. We view GDP as at best a rough proxy since alternatives are not available in the IAM literature.

A substantial literature shows a robust positive correlation between per-capita income and energy consumption, at least at relatively early stages of development (e.g. Schäfer 2005, Grübler 2008). It has repeatedly been argued that due to increased demand for a clean environment and structural economic change, environmental pressures might decrease

5   with rising incomes. However, this so-called 'Environmental Kuznets Curve' relationship that has been derived for certain local pollutants, such as SO_2 and PM (e.g. Grossman and Krueger 1995; Selden and Song 1994), does not seem to apply for energy use or CO_2 emissions (Luzzati and Orsini 2009, Stern 2004).

10   Consequently, the question of whether there is a minimal amount of energy necessary to allow for economic development arises. 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,

15   there are also 'indirect' needs for energy, e.g. to produce consumer goods or build up infrastructure (such as buildings and roads), which we will discuss in more detail in section 4 of this paper.

     One of the earlier works to look at this issue is that of Krugman and Goldemberg (1983)

20   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 significantly enhance energy efficiency.

25   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

30   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), and because of a difference in defining the threshold (poverty vs. acceptable living standard).

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     IAMs also have begun to include consideration of energy access and minimal thresholds Using a bottom-up model specifically developed to address the question of household energy needs, Daioglu et al. (2012) and van Ruijven et al. (2011) investigate regional variations in final household energy needs and find, although with large variations, a

40   rough average in line with 10 GJ/capita. Energy access is the focus of the MESSAGE-Access model (Ekholm et al. 2010 and Narula et al. 2012); current levels of household energy use in India, for example, are found to be less than 10 GJ per capita. Analyses of IAM output for different regions (China and India) and societal groups (urban vs. rural), show the same broad picture for household energy consumption (Krey et al. 2012).

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A key point we wish to make with this paper is to make a distinction between minimal energy threshold for emerging from a state of absolute poverty, and the amount energy needed to achieve high or very high development levels, e.g. in terms of the Human Development Index (HDI). A consistent feature of the literature is that energy needs for households continue to increase during the development process. If climate policies starkly reduce the amount of per capita final energy available for a developing country, there must be a clear description of how this is to be achieved, given large amounts of historical experience that indicates otherwise. Furthermore, the emphasis in the literature cited thus far has not been on a direct comparison between energy needs under Business-as-usual vs. climate policy scenarios.

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 HDI[3], although not without conceptual difficulties (see for example Neumayer, 2001; Böhringer and Jochem, 2007; 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 five levels of development for the HDI: very low (<0.456); low (0.456 − 629); medium (0.630 − 0.741); high (0.742 − 0.888); very high (>0.889 − 1.0) (UNDP 2011). These levels are indicated by horizontal lines in Fig. 1.

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[3] 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.
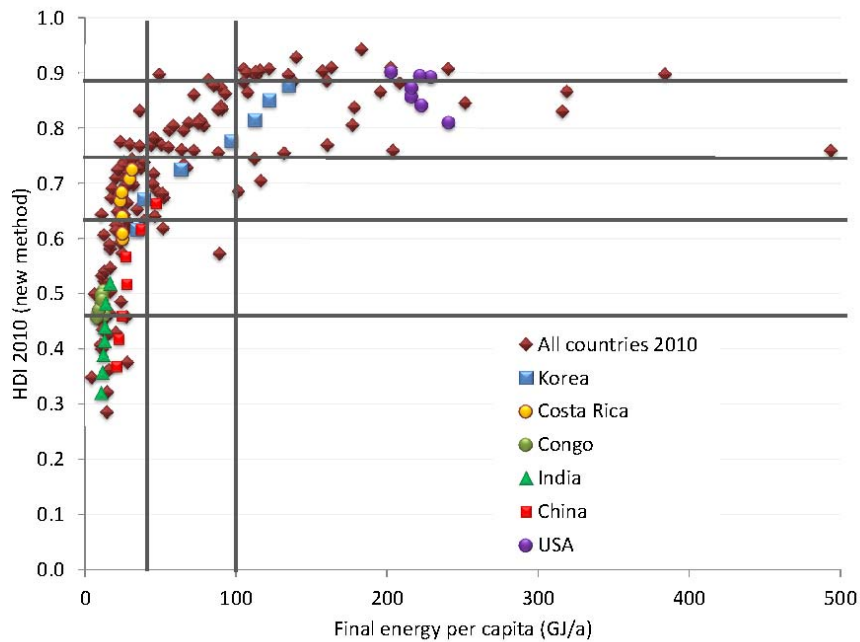
Figure 1: Correlation of (final) energy use (IEA 2012) and HDI (UNDP 2012) in 2010 for 144 countries, together with development over the period 1980-2005 for selected countries in time steps of five years. Horizontal lines indicate the separation between "very low", "low", "medium", "high" and "very 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, 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 almost certain to be at least in the "high" HDI category. Only few exceptions exist (Hong Kong and Malta being prominent examples), but they all operate in very particular environments. 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 (Martinez and Ebenhack, 2010).

In this respect we can show that results from Steinberger and Roberts (2010) evaluating the relationship between primary energy and HDI can also be replicated when looking at the actual energy consumption, i.e. final energy supply. It is obvious that a given level of minimum energy requirements for a sufficiently high development level today is not necessarily stable, i.e. it could be decreased in the future. Extrapolating threshold

functions for primary energy observations of the past, Steinberger and Roberts (2010) find minimum future primary energy levels for high development levels to decrease – a result that can also be expected when looking at final energy levels. It is however questionable whether and to what extent historical trends can be expected to continue in the future. In order to shed light in this question, it must be better understood how thresholds – here understood as minimum energy requirements for high or very high development levels - can be explained. Infrastructure, which we discuss in section 4 might provide one potential explanation for the existence of thresholds.

3 Energy, development and scenarios of the future

In the following we assess a broader set of IAMs with respect to the question of how growth and final energy supply are projected to develop in future scenarios with and without mitigation of GHG emissions. 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. As IAMs usually do not take broader concepts of development into account (although are starting to do so, as discussed above), we will refer to GDP or consumption per capita in the following, acknowledging the difficulties that are connected to this indicator. However, particular for low income levels, GDP per capita is strongly correlated with the HDI (Islam, 1995).

## 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. 2012a). We thus can capture a broad range of different model philosophies and assumptions regarding model inputs, e.g. with respect to the role of technological change. Edenhofer et al. (2010), Luderer et al. (2012a), Knopf et al. (2009), Tavoni et al. (2012) and Jakob et al. (2012) give a more detailed description of the assessment framework. A variety of models has been used in these exercises, i.e. ReMIND-R (Leimbach et al., 2010; Bauer et al., 2012), 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., 2012) and WITCH (Bosetti et al., 2006; DeCian et al., 2012). 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 CO_2-eq; so-called Category 3 & 4 scenarios with equilibrium atmospheric GHG concentrations between 535 and 710 ppm CO_2-eq; and Category 1&2 scenarios, which result in concentrations lower than 535 ppm CO_2-eq[4].

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[4] 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.

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 (25th – 75th 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[5] 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.

a) Non-Annex I countries
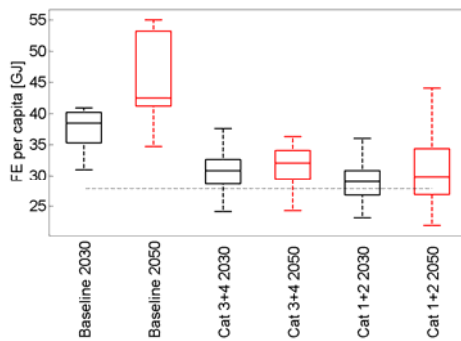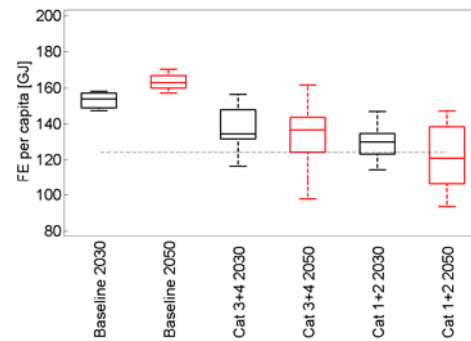
d) Annex I countries

b) China
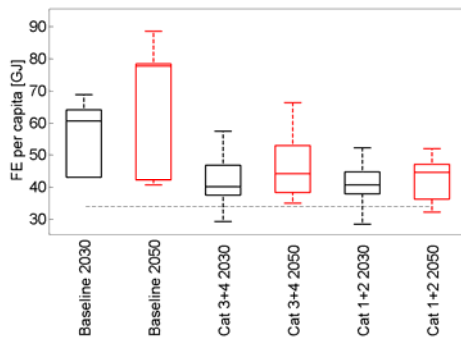
e) USA
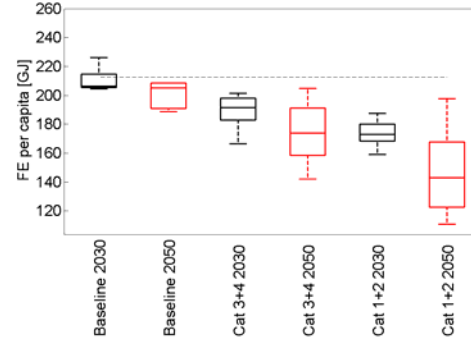
c) India

f) Europe

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[5] 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.

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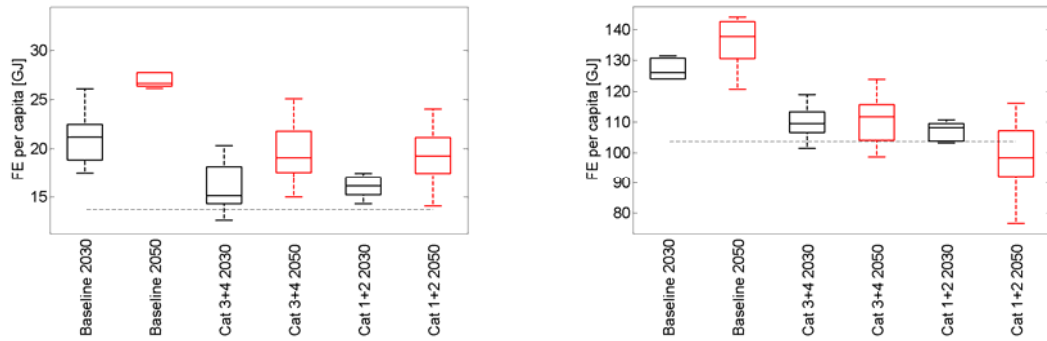
Figure 2: Final energy use per capita per year (in GJ) in all Non Annex I countries (a), all Annex I countries (b), China (c), the US (d), India (e) and Europe (f) for different scenario categories, i.e. baseline scenarios, category 3 and 4 scenarios and low stabilization (category 1&2) scenarios. The black boxes access data for 2030, the red boxes assess data for 2050. The thick 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. The dotted horizontal line indicates the per capita FE level in 2005. Please note different scales.

From Figure 2 we can derive three major insights: First, we note that per capita final energy consumption decreases significantly in the policy cases with respect to the BAU case for all regions, falling back to approximately today's levels by 2030. Second, 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[6], 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 remains far below levels that are reached without GHG mitigation. In Annex I countries including Europe and the USA as well as in Non-Annex I countries, final energy consumption per capita is lower in low stabilization (categories 1 and 2) scenarios compared to medium ones (categories 3 and 4). Third, relative reductions between baseline and policy cases are higher in Non-Annex I countries compared to Annex I countries in all cases (see also Table 1); hence, 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.

|	2030				2050			
	Category 3&4		**Category 1&2**		**Category 3&4**		**Category 1&2**	
	Annex I	**Non-Annex I**	**Annex I**	**Non-Annex I**	**Annex I**	**Non-Annex I**	**Annex I**	**Non-Annex I**
Median	11%	14%	14%	20%	18%	21%	24%	27%
Mean	12%	15%	15%	20%	21%	24%	25%	28%
Min	1%	1%	7%	9%	4%	4%	10%	11%
Max	26%	38%	24%	30%	50%	52%	39%	46%

Table 1: Reduction of FE per capita between mitigation and baseline scenarios in 2030 and 2050 in Annex I and non-Annex I countries

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[6] Analysis of recent data suggests that China has crossed the threshold already.

Exploring a bit further, Figure 3 shows annual changes in energy- and carbon intensity levels in mitigation scenarios of different ambitions in the period form 2010 – 2030. When looking at final energy- and carbon intensity reductions in mitigation scenarios compared to BAU scenarios (Figure 3a and b), non-Annex I countries show reductions in energy intensity at least as high as Annex I countries in both low (category 1 & 2) and medium (category 3&4) stabilization targets.
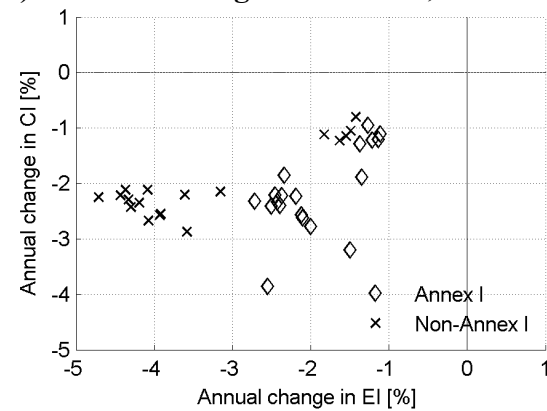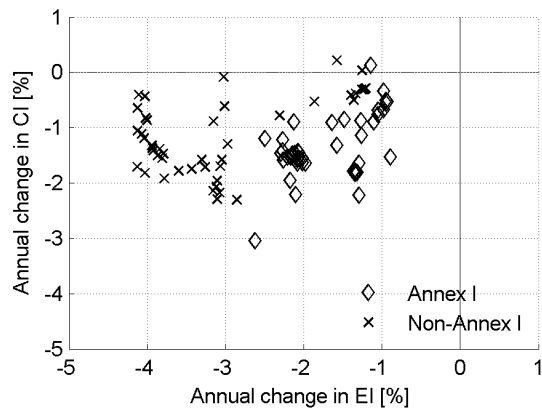
a) Change relative to BAU, 2010 – 2030, Cat 1&2
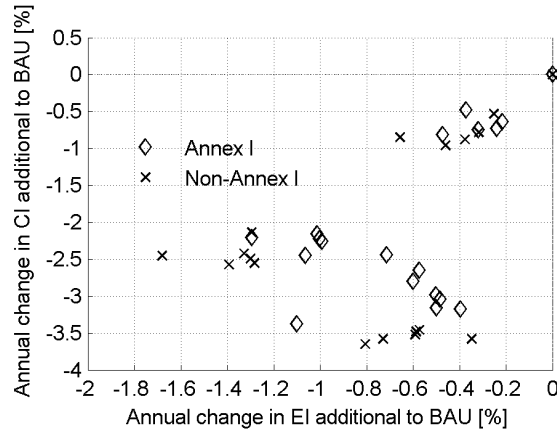
b) Change relative to BAU, 2010 – 2030, Cat 3&4
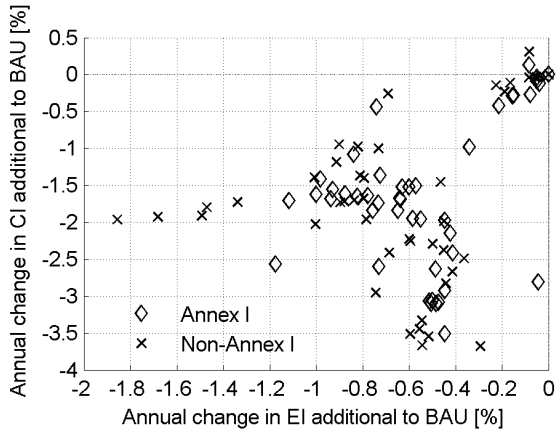
c) Absolute change 2010 - 2030, Cat 1&2

d) Absolute change 2010 – 2030, Cat 3&4

Figure 3: Annual change in carbon intensity of energy and energy intensity of GDP for the period 2010 to 2030 in scenarios of the future for Annex I and non-Annex I countries for category 1&2 (a) and category 3&4 (b) scenarios as well as changes compared to the respective BAU scenarios for category 1&2 (c) and category 3&4 (d) scenarios in percentage points.

When turning to absolute reduction rates (see Figure 3c and d) annual reduction rates of final energy intensity of GDP are systematically higher in developing countries than in Annex I countries. With respect to carbon intensity, no major differences can be found, i.e. annual changes are of a comparable order of magnitude in both income groups. Even though non-Annex I countries start from higher initial values of energy intensity the result is remarkable, as those countries can be expected to undergo structural changes that have been energy intensive in the past. For instance, for low-income countries economic

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growth goes hand in hand with an increasing share of industry in total production, which in general displays higher energy intensity than e.g. agriculture or the service sector (Schäfer, 2005). Hence, structural economic change towards more energy-intensive activities could – at least to some extent – counterbalance decreases in economy-wide energy intensity triggered by efficiency improvements (see e.g. Zhao et al., 2010 for the case of China).

The results from the model comparisons can be interpreted in different ways: On the one hand, decreasing absolute FE levels as well as high energy intensity reductions 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. Even though IAMs are generally designed to study longer-term changes, it is important to evaluate shorter-term trends and potential for major breaks with the past that are important for questions related to development. It is important to note that models make different assumptions on the drivers of energy demand, and the mechanisms leading to energy intensity improvements under climate policy. For instance, in models with explicit vintage structure, emerging economies with high growth rates and young capital stocks could be faster in adopting, energy efficient technologies than established industrialized countries with old vintage structures. A dedicated model comparison would be required to dismantle these underlying dynamics, which is beyond the scope of this study. Instead, we further examine results of the ReMIND-R[7] model in higher temporal and regional detail[8].

Figure 4 shows per capita GDP in 2005 US$ as a function of final energy consumption per capita in GJ[9] for four different scenarios, which represent climate targets of varying ambition. 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 ton of carbon, which all 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

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[7] 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.
[8] These data are part of the set of scenarios prepared for the Asia Modeling Exercise (Luderer et al. 2012b).
[9] 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.

however lower for corresponding per capita GDP values, which could well be explained by technological improvements and leapfrogging very energy-intensive processes.
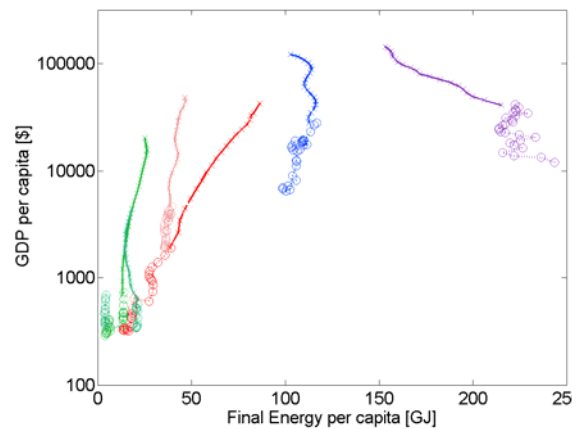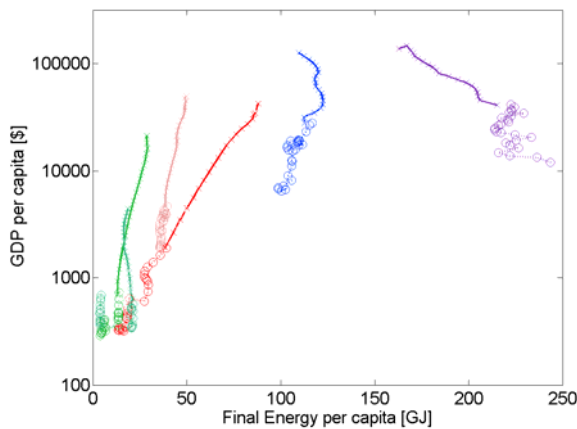
a) BAU (Category VI)   **b) Medium stabilization (Category III[*])**
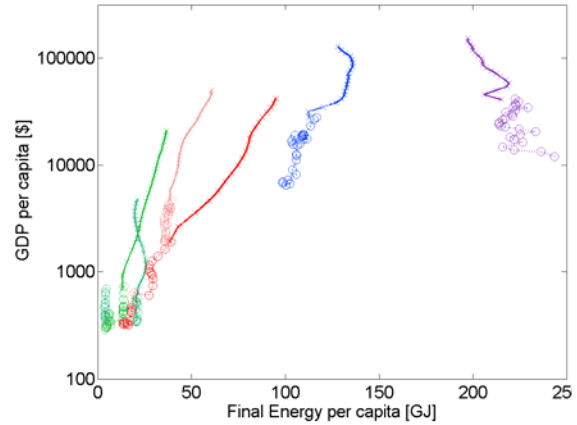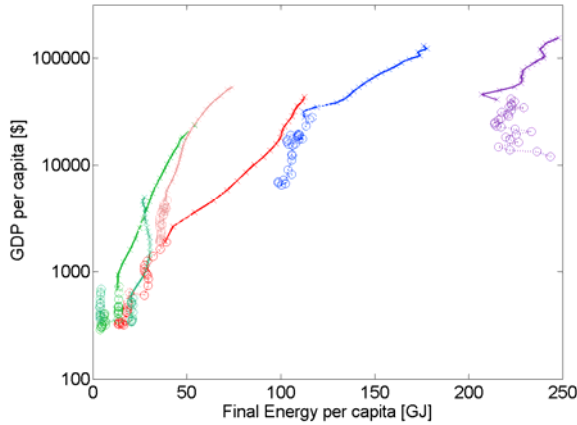
c) Low stabilization (Category II[*])   **d) Very low stabilization (Category I[*])**

Figure 4: 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 a 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 a significantly different behavior. For all developing regions but China, we can observe a

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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 - reaches development levels comparable to those of Europe today in the year 2100, FE per capita levels is projected to be around 25 GJ per capita, which is only slightly above today's levels and about one quarter of today's energy consumption in the EU27. 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). AFR, approximately reaching today's GDP levels in LAM by the end of the century shows slightly lower FE per capita levels than LAM (in 2005) in the baseline scenario (30 GJ compared to 39 GJ per capita), but significantly lower (18 GJ per capita) levels in a low stabilization scenario. 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[10].

To sum up, the above analysis of the IAM data indicates that climate policy is likely to reduce average per capita energy consumption in developing countries to a level that seems to be difficult to reconcile critical thresholds for development identified in Section 2. Particularly in ambitious mitigation scenarios, IAMs project energy consumption to decouple from economic growth in developing countries, suggesting that potentials for energy intensity improvements in developing countries are (at least implicitly) assumed to be higher than in developed countries. Taking into account that in recent decades developing countries that have experienced economic catch-up have by and large reproduced the energy-intensive development patterns of industrialized countries (Jakob et al. 2012) it is important to understand that the IAM results indicate a radical break of historic observations. In the light of the need for aggressive GHG mitigation, radical breaks with historic development patterns are surely needed. With respect to carbon intensity and the decarbonization of the energy system, IAMs generally put much emphasis on possible future transformations, e.g. by a detailed techno-economic description of energy systems. However, considerably less attention is given to the demand side in general, and the role of energy access for development processes in particular. Our results indicate that it deserves more attention for future modeling efforts.

4. Energy thresholds and the role of infrastructure

In sections 2 and 3 of this paper, we argue that there is a minimum level of energy needed for reaching high or very high development levels. We find that IAMs do not take these considerations into account. However, one could argue that future efficiency improvements will lower the amount necessary in the future (see for example Steinberger and Roberts, 2010). Therefore it is important to understand why we observe minimum levels of energy consumption in the past.

If we think of development beyond fulfilling basic needs, energy is *inter alia* also needed for the construction of infrastructure, including the use of cement and steel for buildings,

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[10] As in most IAMs, population is exogenously given in ReMIND-R.

railways and roads, electricity grids, etc., all of which come with a specific energy demand. The important role of infrastructure in development processes in general is well known in the literature, with the assumption generally being that there is a positive impact of infrastructure investment on economic development and growth (Gramlich,
5   1994). Different channels are identified as to how investments in public capital, i.e. infrastructure could impact growth (for a detailed review see Agénor and Moreno-Dodson, 2006). Most importantly, Aschauer (1989) - followed by many others - was the first to hint at the positive effects of infrastructure investments on other production inputs, as for example labor or the private capital stock. Infrastructure investments can
10   thus increase the marginal productivity of private investments. Additionally, Calderón and Servén (2004) also highlight the positive effects of infrastructure investments on the reduction of income inequalities, particularly in developing countries.

In this sub-section we determine the role of infrastructure in development processes of
15   the past, particularly focusing on the energy demand that comes with investments in infrastructure. We focus on the production[11] of cement and steel as major determinants of energy-use for infrastructure purposes[12]. 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, our hypothesis is that in developing
20   countries inputs required for infrastructure increase with economic growth. A stylized econometric model lends support to our conjecture that infrastructure uptake is an important component of an energy threshold. In order to be able to link historical econometric patterns of the past to the output of the integrated assessment model ReMIND-R in a second step, we keep the econometric part relatively simple. Hence, we
25   can compare potential energy demand for infrastructure of the future with energy consumption patterns calculated by the model.

4.1 Energy for infrastructure in the past

30   *Data*
   To use results from the historical analysis to provide rough estimates of future energy demand resulting from infrastructure, we aggregate all data[13] into 11 regions as defined in the ReMIND-R model. Table 1 gives a more detailed description of aggregated regions. We further cluster these regions into developed (OECD) and developing countries.
35   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[14].

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[11] Using production instead of consumption data might be a weakness of the analysis; it is however necessary in order to link econometric results to model output in the next step.

[12] Note that other inputs might become more important for higher incomes, which is however not regarded here.

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

[14] 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[15]
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 w/o Russia, Pakistan
OAS	South East Asia, both Koreas, Mongolia, Nepal, Afghanistan
ROW	Non-EU27 European states w/o Russia, Australia, Canada, New Zealand and South Africa
RUS	Russia
USA	USA

Table 2: Regions as defined in ReMIND-R and corresponding world regions

As 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 is 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 per-capita capital investments (*INV*) are used (in two separate regressions), 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 respectively) and the infrastructure parameter (cement or steel production). A fixed-effects estimator is used to estimate the following equation:

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[15] 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) now are actually OECD countries, but were not at the starting year of our sample.

$$\ln(INF_{jt}) = \alpha_j + \beta \ln(ECON_{jt}) + \gamma \ln(POP_{jt}) + \varepsilon_{jt} \ , \tag{1}$$

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[16]. 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 is 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%[17]. 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, in 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 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)

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[16] Using panel data with a fixed-effect estimator is a common practice in the literature. See e.g. Markandya et al. (2006) or Burke (2010) for examples that employ this estimation technique to analyze the relationship between economic growth and energy use.

[17] 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.

	Developing Countries		OECD Countries	
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 3: 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 4: 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 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. Thus, a decreasing threshold would imply improvements in the supply of infrastructure inputs.

In this section we have presented evidence to support our hypothesis that infrastructure uptake is one explanatory element of an energy threshold. Keeping in mind that the goal of sustainable development 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.

4.2 Infrastructure in scenarios of the future

As indicated in Section 4.1 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 Section 4.1. together with country-specific fixed effects (reported in the Appendix) to translate these results into steel and cement production. When looking at historical data for per capita cement and steel production, we find that it is rising in non-Annex I countries, whereas it remains relatively stable in Annex I countries (cp. Fig. 5). We therefore conjecture that two different regimes exist. As long as infrastructure is being built up, the demand for cement and steel increases. When a certain level of per-capita GDP or capital investment is reached the demand stabilizes. Annex I countries have already been in the stable regime in 1980, the earliest date of available data. Therefore, for developing countries we assume a switch to OECD values once a developing country reaches levels of affluence comparable to developed countries in 1980. However, as non-Annex I countries do not reach the per-capita investment levels expected for a regime change until 2050 accounting for a regime shift in this respect is not necessary.
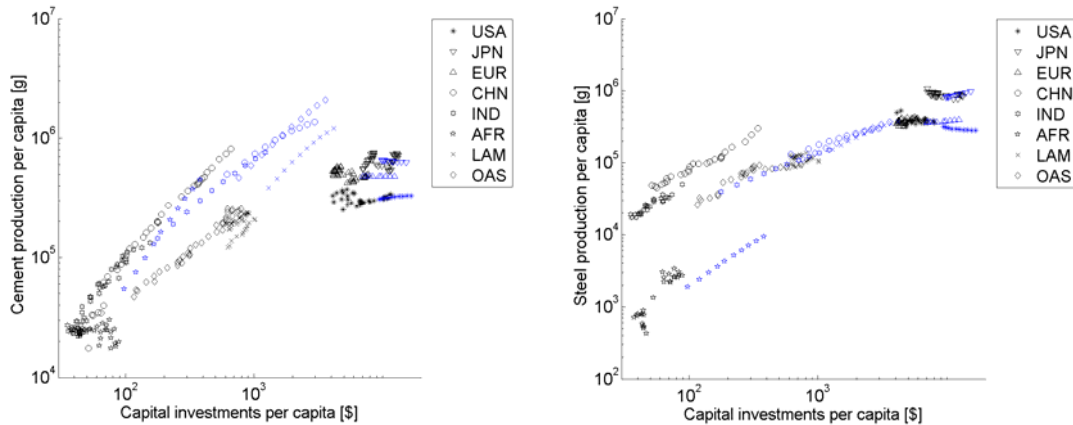
Figure 5 shows results for the relation between cement and steel production and capital investments both historically (shown in black) and the projections derived using the coefficients of our econometric estimates (shown in blue) to the year 2050 for different regions. Historical correlations between 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[18] and 0.3 and 1 t for steel.

a) Cement   **b) Steel**

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[18] 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. Interestingly, newly developing countries in particular China stabilize at higher levels than previously observed. A detailed discussion of the phenomenon is however beyond the scope of this paper.

Figure 5: 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.

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We can use these results for the production of steel and cement to project the energy consumption required in the future. 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)[19]. 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). Implicitly we assume that cement and steel will not be substituted by other inputs of production in the future, or that future substitutes would have comparable energy intensities. The lower bounds of the ranges shown in Figure 6 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[20]. 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.

a) India   b) AFR   c) Other Asia

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[19] The value for a ton of cement is likely to be higher, as Taylor et al. (2006) give numbers for clinker production. It is important to understand that thermodynamic limits are unlikely to be reached in reality, as other constraints (e.g. time) need to be regarded (Spreng, 1993).

[20] 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.

d) Latin America   e) China   f) Japan
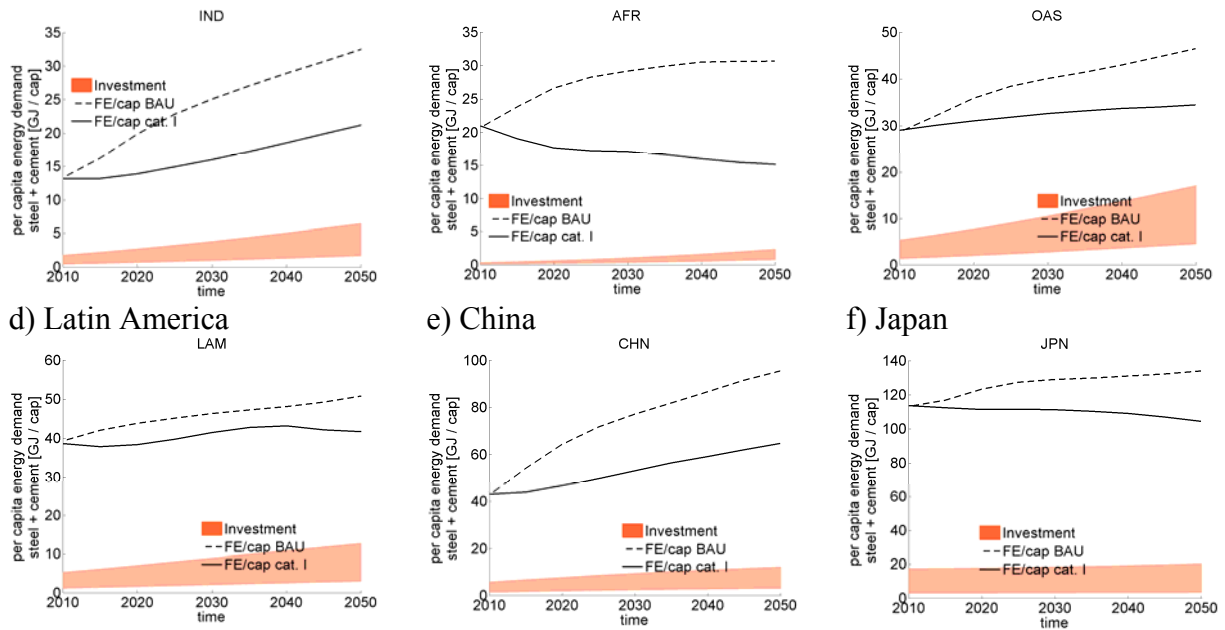
Figure 6: Ranges of energy demand for cement and steel production in comparison to FE demand in different mitigation scenarios as calculated by the ReMIND model. The upper bound assumes the current energy use and the lower bound the thermodynamic limit for future production of cement and steel. The projections 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. Regional aggregation follows the regions represented in the ReMIND model. Please note different scales.

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 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 GDP. 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 in the future for the construction of infrastructure in developing countries. The magnitude of infrastructure energy needs will depend on the rate of technological progress, but – at least in the short to medium term – will likely be of a similar magnitude as, and in addition to, the level of final energy   that appears   necessary for fulfilling basic household needs, i.e. approximately 10 GJ per capita. As discussed in our analysis of IAM outputs, and particularly for developing countries and regions such as India, Sub-Saharan Africa, Other Asia and Latin America total available final energy of 20 GJ per capita is projected. This quantity of energy would hence roughly be in line with what will be

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needed to fulfill basic needs on the household level and for steel and cement production, but would not leave energy available neither for consumption beyond the subsistence level nor other infrastructure needs. Energy for transportation infrastructure (e.g. bitumen) as well as other metals like copper or aluminum would add to the numbers 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.

5 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 carbon-intensive infrastructures 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 comparison of ReMIND-R results with 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. At the same time, developing countries are projected to face higher energy intensity improvements than developed countries. At first sight, the model results seem to be either not realistic or driven by very strong implicit assumptions.

To understand the plausibility of model results, 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 affluence levels go 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[21]. 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., 2012) 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 remains an important driver of economic growth in the future. However, assuming that scenario results are robust, we can provide a twofold interpretation:

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[21] 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).

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 towards 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 models 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 levels of 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 represent the energy needs for the infrastructure build-up during the development process, nor includes any explicit energy access targets for development. 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 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 that is in its infancy in the IAM community (Krey et al. 2012, Daioglu et al. 2012). A possible outcome of calibrating IAMs to such bottom-up derivations of energy demand 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.

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.

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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

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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 4 (section 3.1) are compared to results from the model comparison projects ADAM (Edenhofer et al. 2010) and RECIPE (Luderer et al 2012a) (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.
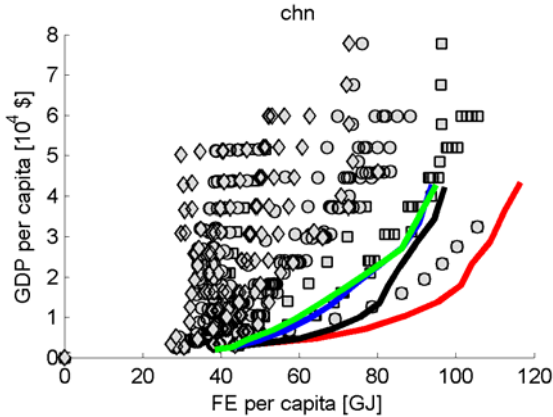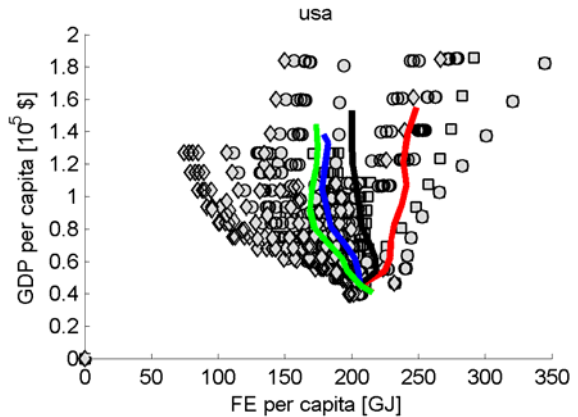
a) Non-Annex I countries
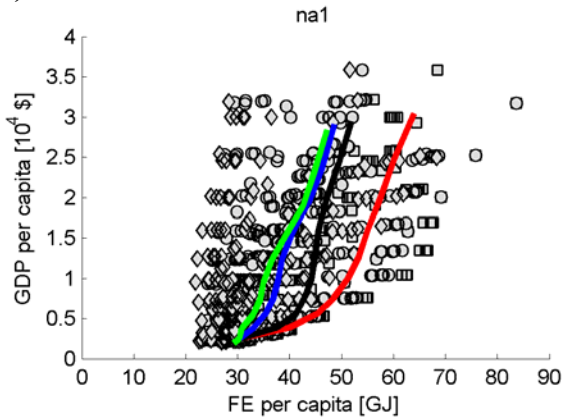
d) Annex I countries
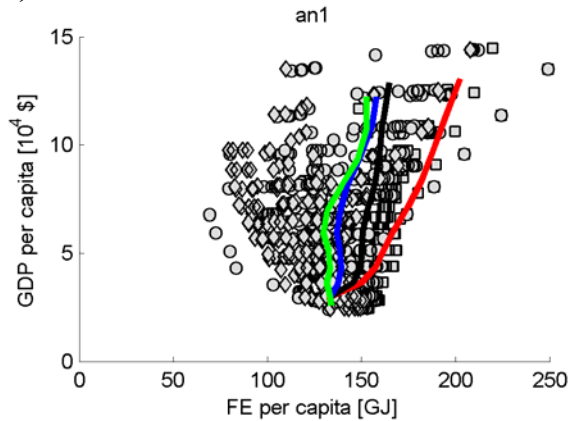
b) China

e) USA

c) India

f) Europe
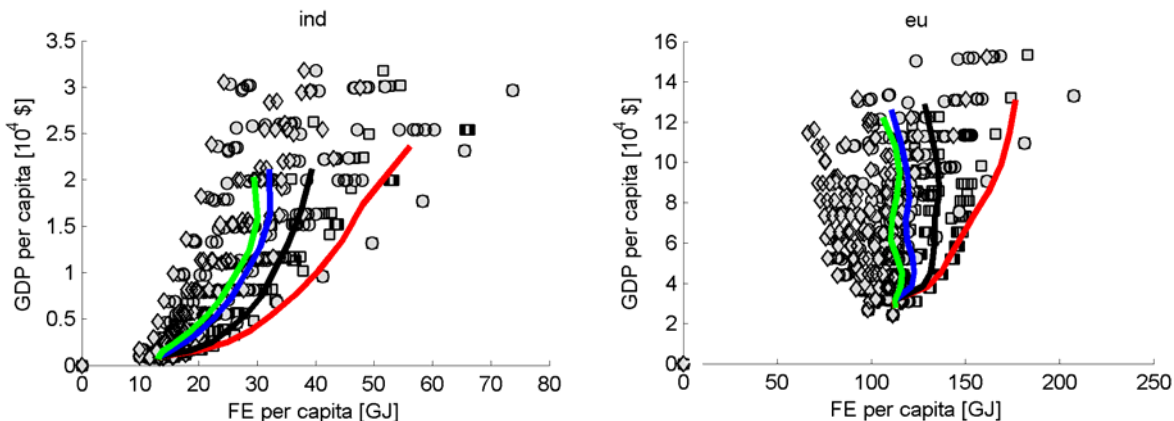
Figure B1: Comparison of ReMIND-R results with those of other models from the RECIPE and ADAM model comparison projects. Baseline scenarios are shown by squares, category 3&4 scenarios by circles and category 1&2 scenarios by diamonds. Different colors show differently ambitious ReMIND-R scenarios, i.e. 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.

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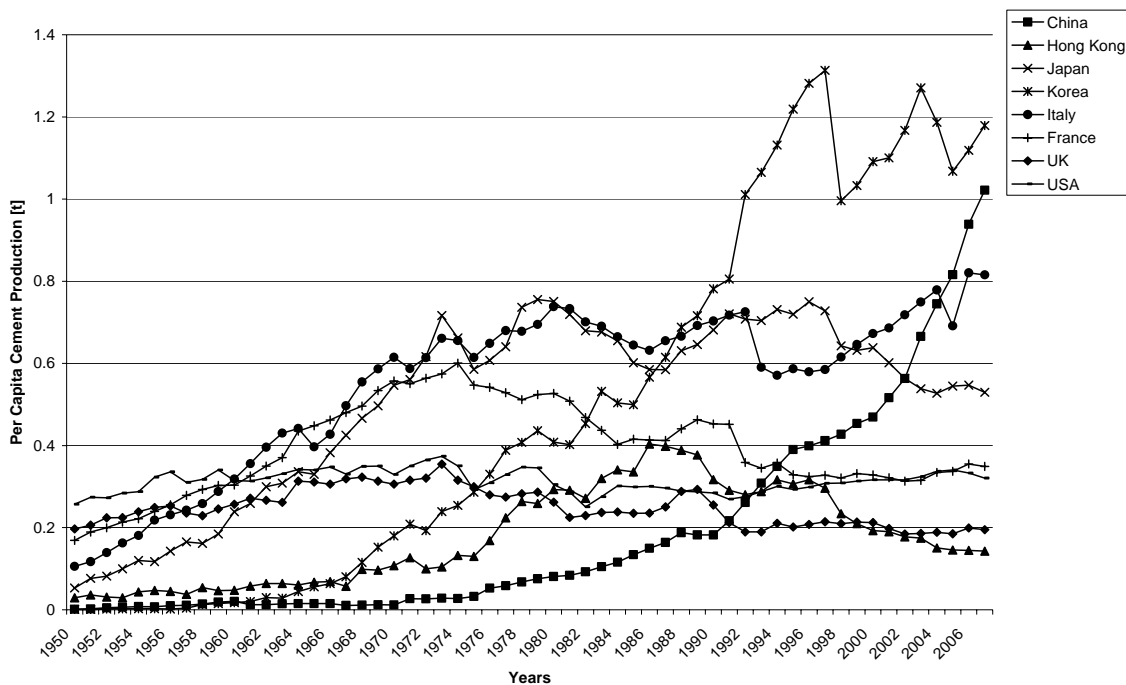Agénor, P-R and B. Moreno-Dodson (2006): Public infrastructure and growth: New channels and policy implications. Working paper, Available from http://ssrn.com/abstract=2005043

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