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Human development in a climate-constrained world: What the past says about the future

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ABSTRACT

Energy consumption is necessary for the delivery of human development by supporting access to basic needs, services and infrastructure. Given prevailing technologies and the high degree of inertia in practical rates of decarbonisation, growth in energy consumption from rising global living standards may drive consequent greenhouse gas emissions (GHG). In this paper the 'development as usual' GHG emissions impact of achieving high levels of life expectancy, access to basic needs and continued economic growth are projected to the mid-century using historical elasticities of development and energy consumption in 3 regions – Africa, Centrally Planned Asia, and South Asia. The results suggest that long life expectancy and high levels of access to basic needs are achievable at lower levels of emissions than continued economic growth, but will consume a substantial share of the global budget associated with a 2 °C climate goal.

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1. Introduction

A defining feature of industrial development since the 1950s has been a rapid increase in the extraction and consumption of energy (Krausmann et al., 2008). Energy use is a prerequisite for modern lifestyles (Mazur and Rosa, 1974), economic activity more broadly (Stern, 2011), as well as the underlying infrastructures that support human development (Rao et al., 2014). Energy production, along with land-use change and agriculture, in turn generates greenhouse gas (GHG), ultimately leading to climate change impacts. In a world of persistent poverty, with continued inequalities in health, education, nutrition and sanitation (UN, 2014), what will be the GHG emissions impact of raising all to an adequate standard of living? How do these 'development' emissions compare to the emissions budget available if we are to stabilise climate change at levels related to the 2 °C target? These questions are the focus of this paper.

There has been much elaboration in the literature on equity proposals and the 'fair burden-sharing' of emissions rights between industrial and developing nations (Baer, 2013; Baer et al., 2009), but very little research on the actual energy use *necessary* for development and likely arising emissions. This is a prescient issue in the context of on-going international negotiations, where it is now recognised that the participation of all major emitters, including key developing countries such as India and China, is required to break the climate impasse (Grasso and Roberts, 2014). Technology transfer offers one means to 'leapfrog' development to a less emissions-intensive pathway, but has unfortunately failed to manifest in time for low and middle income countries to avoid highly polluting infrastructures (Unruh and Carrillo-Hermosilla, 2006). Instead it appears that systems of energy production and consumption embody a high degree of inertia in their practical rates of decarbonisation (Anderson and Bows, 2011; Loftus et al., 2014; Raupach et al., 2014), with almost certain near term emissions growth in most developing countries (Davis and Socolow, 2014). Our approach thus focuses on extrapolating existing trends in energy growth, emissions and development, highlighting the level of policy ambition that will be necessary to meet the twin challenges of climate change and poverty alleviation.

The patterns by which greenhouse gas emissions facilitate human development have been the focus of much recent research (Costa et al., 2011; Dietz et al., 2009; Jorgenson, 2014; Lamb et al.,

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2014; Pretty, 2013; Rao and Baer, 2012; Steinberger et al., 2012, 2010). The central premise of this work is the need to measure development outcomes directly, rather than as a function of increasing per capita incomes. The resulting human development and energy or carbon relationship is noted for its non-linearity: increasing resource and energy consumption (and hence economic development) improve human well-being, but only up to a point (Mazur and Rosa, 1974; Rao et al., 2014). Diverse groups of countries have followed relatively efficient pathways of development (Steinberger and Roberts, 2010), achieving high well-being outcomes at moderate levels of energy consumption and emissions (Lamb et al., 2014). The relationship between human well-being and it's environmental impacts is also known to be temporally dynamic, becoming progressively more efficient over the past several decades (Steinberger and Roberts, 2010), with important regional differences (Jorgenson, 2014). Few studies have attempted to shape these factors into a quantity of emissions necessary for development: Costa et al. (2011) employed elasticities of the Human Development Index (HDI) and per capita CO_2 emissions to project the climate impact of reaching particular HDI thresholds; while Rao and Baer (2012) lay out a conceptual roadmap for assessing the energy requirements for specific development needs and activities in a bottom-up approach.

In this study we make a number of advances. First we design an indicator for 'basic needs', capturing a high level of detail on material living standards that is missing from previous studies. Pairing this indicator with average life expectancy and income, we generate historical elasticities of energy consumption using 20 years of data (1990–2010) in order to project energy growth scenarios to 2050 for three developing regions. This method allows us to compare the energy requirements of reaching thresholds in two dimensions of human development, as well as that of economic growth more generally. Finally, these are translated into GHG emissions scenarios via GHG intensities from the LIMITS integrated assessment study. By employing these intensities we are able to directly compare our own development based (no policy) allocation of emissions rights to widely employed least cost IAM mitigation scenarios, assessing the likely conflict that may arise between addressing climate change and poverty eradication.

2. Materials and methods

2.1. Human development

In acknowledging the narrow focus of gross domestic product (GDP) per capita (Stiglitz et al., 2009), alternative indicators of development must be theoretically sound, empirically quantifiable and policy relevant (Reinert, 2009). The literature to date linking well-being to environmental impact has been predominantly guided by Sen's 'Capabilities Approach', employing the human development index (Costa et al., 2011; Martínez and Ebenhack, 2008; Moran et al., 2008; Pasternak, 2000; Steinberger and Roberts, 2010) and its constituents, income, life expectancy and educational achievement (Dietz et al., 2009; Jorgenson, 2014; Lamb et al., 2014; Steinberger et al., 2012). In this paper we follow Doyal and Gough's (1991) theory of human need, wherein they define well-being as physical health and personal autonomy, i.e. the avoidance of serious harm, the ability to participate in society, and the freedom to choose that form of participation. In particular, and in contrast to previous literature, we operationalise cross-cultural 'intermediate' indicators, i.e. a set of preconditions for achieving human well-being. These 'basic needs' constitute a minimum baseline of access to material and infrastructural services, and is able to provide a defensible 'moral minimum' of energy and emissions requirements for development (Doyal and Gough, 1991; Rao and Baer, 2012; Reinert, 2009; Reusser et al., 2013). Such a baseline exists firmly within the policy space for intervention, and can be commonly established across all societies. To contrast our approach to previous conceptualizations of human development, we also conduct our analysis for life expectancy. Similarly, GDP per capita is included in order to compare the well-being approach to a purely economic perspective. Our analysis does not incorporate other components of basic well-being, such as physical, economic and childhood security, due to a lack of appropriate time-series international data. In addition, while there are clear links (as described below) between meeting basic needs and greenhouse gases, improvements in personal autonomy are likely to take the form of social and institutional developments, with less obvious impacts on GHG emissions.

We describe basic needs access as a composite of six factors related to food, shelter, basic health and hygiene, and education. We select suitable indicators based on available data. They include: (1) access to improved sanitation facilities (flushed latrine, ventilated improved pit latrine, pit latrine with a slab or a composting toilet); (2) access to household electricity; (3) access to an improved water source (piped household water, public tap, tube well/borehole, protected dug wells, protected springs, rainwater collection); (4) adequate nourishment (where average dietary energy consumption is above an energy intake adequacy rate for that population); (5) access to education (at least one year of primary school for all persons over 15 years of age); (6) a survival rate to 5 years of age. Factors (1–3) are sourced from the World Bank Development Indicators (2014), (4) from FAOSTAT (2014), (5) from Samir et al. (2010), (6) from the UN (2013) life tables. Life expectancy data is sourced from the UN (2013) and GDP per capita (expenditure side purchasing power parity) from Feenstra et al. (2014).

The composite basic needs indicator is calculated as an unweighted geometric mean of these six dimensions, scaled from 0% (no access) to 100%, where all persons in a country have access to basic needs (in fact it is possible get close to, but not reach full access, as there will never be a perfect 100% survival rate). A potential alternative methodology would simply take the minimum level of achievement across all six indicators, however this would lead to systemic bias as in the majority of cases sanitation is the poorest performing criteria of development. Following the Multidimensional Poverty Index we do not assign weights to the individual dimensions of basic needs, avoiding normative judgments of their relative importance, but also rendering them substitutable – an important drawback of our study (Decancq and Lugo, 2013). Follow-up work may assign weights to poorer performing dimensions (such as sanitation).

2.2. Climate impact via energy consumption

Human development is known to share strong links with energy consumption (Karekezi et al., 2012). For instance, access to electricity and clean cooking fuels in households has well documented benefits for women and children's health, education and livelihoods. More broadly, energy is a prerequisite for adequately functioning hospitals, schools, transportation and other productive activities that support basic human needs. We measure this energy use at the point of consumption, using the International Energy Agency (2014) indicator for 'final energy consumption'.

In defining climate impact, researchers have typically focused their attention on CO_2 emissions, from both territorial (Costa et al., 2011; Jorgenson, 2014; Steinberger and Roberts, 2010) and consumption-based approaches (Lamb et al., 2014; Steinberger et al., 2012), as well as ecological footprinting (Dietz et al., 2012, 2009, 2007). To our knowledge, only Rao et al. (2014) have explored overall GHG emissions and their implications for development – an important point, as non-CO_2 emissions tend to be proportionally higher in developing countries (Smith et al., 2013). In this paper we calculate GHG emissions as the sum of carbon dioxide equivalents of CO_2, CH_4, N_2O and F-gases for each region, assuming 100 year global warming potentials (WRI, 2014). We exclude the GHG emissions associated with land-use change, as there is not to our knowledge a well-established systematic relationship to human development, in part because the impacts on human development are highly context-dependent, and confounded by export-driven land use.

For both of these indicators we focus on their per capita (intensive) values, to allow for comparability between nations, as well to scale our results with population projections in the final stage of analysis. A consistent data set of population was used across all intensive values, sourced from the Penn World Table (Feenstra et al., 2014).

2.3. Climate stabilisation scenario

Integrated assessment models (IAMs) constitute the predominant framing of the technological and economic characteristics of climate change mitigation (Krey, 2014); as such they provide a useful point of reference for understanding the level of emissions reduction required in different regions to achieve climate stabilisation under different scenarios of climate policy. In this paper we illustrate two scenarios from the energy-economy IAM MESSAGE model used in the LIMITS project (Kriegler et al., 2013; Tavoni et al., 2014b): a baseline business as usual scenario and a stringent climate policy scenario that stabilises climate at 450 ppm ("The IAM Scenario"). These scenarios are described in full in Kriegler et al. (2013). While these are only two of dozens of comparable scenarios, they provide a reasonable example of the range of emissions budgets for developing regions with and without stringent climate stabilisation. The baseline scenario reflects development and emissions pathways unconstrained by mitigation actions, while the IAM scenario reflects climate actions after 2020 based on a least cost allocation of mitigation effort to achieve 450 ppm by 2100. Negative emissions technologies (e.g. bioenergy with carbon capture and storage) are allowed in the IAM mitigation scenario. The difference between the regional emissions pathways for this scenario and the ones we estimate for human development provide insight into the potential conflict between climate mitigation and development.

The IAM defines 10 regions based on economic and geographic characteristics. We follow this definition in order to easily compare our results, but focus on three developing regions only: Africa (which includes sub-Saharan countries only); Centrally Planned Asia (CPA, which includes China, Mongolia, Laos, Cambodia and Vietnam); South Asia (India, Pakistan, Bangladesh, Nepal and Sri Lanka). See Table 3 in the Appendix for a complete list of countries. Using these regions allows us to borrow population projections, GDP growth rates and GHG intensities from the IAM. This ensures a consistent comparison of results, but in all other respects the following analysis remains independent from the IAM scenario.

2.4. Scenario calculations

The scenarios are calculated in four stages. First we correlate the human development indicators with energy consumption for every year from 1990 to 2010 at a national level, generating global elasticities and their evolution over time. Second, we aggregate developing countries into three regions and calculate their current state and rate of change in human development achievement, projecting it forward to 2050. Third, the annual energy consumption required for projected development outcomes is estimated using the global elasticities. Finally, we apply a population projection and no-policy GHG intensities (of energy) from the integrated assessment model to arrive at the climate impact of development as usual. The full scenario assumptions are summarised in Table 2 (Appendix).

2.4.1. Correlating human development and climate impact

Fig. 1 plots each human development indicator against final energy consumption per capita for the year 2000. In general we observe a strong decoupling trend for basic needs access and life expectancy; at low levels of energy use and emissions they remain linearly correlated, but beyond a threshold area (approximately 30 GJ/capita) a change in one indicator is no longer related to a change in the other. By contrast, GDP per capita, plotted here in log–log space, has no such decoupling trend and tends to scale continuously with energy consumption. These observations are consistent with previous studies (Lamb et al., 2014; Rao et al., 2014; Steinberger and Roberts, 2010; Steinberger et al., 2012).

Several functions can be used to describe the non-linear relationship between the first two pairs of indicators: semi-logarithmic (Pasternak, 2000), logistic (Costa et al., 2011) and hyperbolic (Steinberger and Roberts, 2010). We tested all three functions, discarding the first two as they yielded lower R^2 goodness of fits and poorer residual distribution. The hyperbolic saturation function is described in full as:

$$\mathrm{HD} = \mathrm{HD}_{\mathrm{SAT}} - \exp(A)\cdot(\mathrm{EC})^{B} \Leftrightarrow \log(\mathrm{HD}_{\mathrm{SAT}} - \mathrm{HD}) = A + B\cdot\log(\mathrm{EC}) \qquad (1)$$

where HD is the human development indicator, EC is the energy or GHG indicator and $\mathrm{HD}_{\mathrm{SAT}}$ is a saturation value. Following Steinberger and Roberts (2010), the saturation value for life expectancy is calculated as $\mathrm{HD}_{\mathrm{SAT}} = 1.1\cdot \max(\mathrm{HD})$; this value is linked to the data rather than determined a priori due to the highly consistent trend of year on year increases in the maximum value of life expectancy (Oeppen and Vaupel, 2002). Basic needs, on the

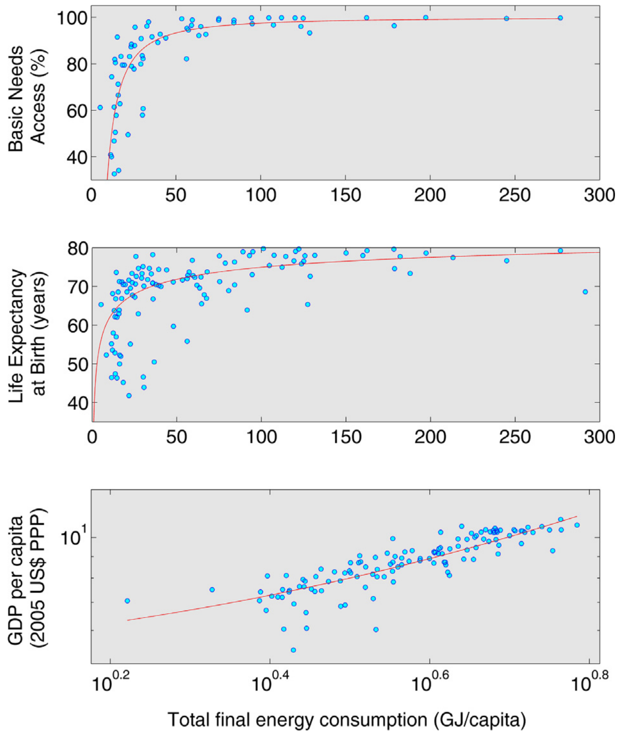

Fig. 1. Correlations of human development indicators and final energy consumption. Data is from the year 2000.

other hand has a maximum upper bound of 100%, which we set as its saturation value.

Recognising the substantial body of literature critiquing the "Environmental Kuznets Curve" and the log-linear functional form for GDP per capita and energy consumption (or emissions) (Galeotti et al., 2009; Stern, 2004), we employ a linear model in log–log form:

$$\mathrm{GDP} = \exp(A)\cdot(\mathrm{EC})^{B} \Leftrightarrow \log(\mathrm{GDP}) = A + B\cdot\log(\mathrm{EC}) \qquad (2)$$

The results from these regressions for a single year (2000) are detailed in Table 1. Generally high goodness of fits are found for each indicator pair, comparable with ranges found in the literature. We do note however that limited data availability reduces our sample of countries to 67 in the case of basic needs access. Indeed, the lower R^2s for life expectancy compared to this indicator are likely an artefact of a larger sample size which in particular includes the low-performing (in health terms) former soviet countries (Martínez and Ebenhack, 2008). These differences in sample size are a source of some uncertainty in our results. Nevertheless Eqs. (1) and (2) are weighted by total population, taking advantage of the relatively high proportion of global population represented even in the smaller samples.

Much recent research has highlighted the time-variant nature of the relationship between human development and environmental impact (Jorgenson and Clark, 2012; York, 2012). Income and Human development are known to be steadily decoupling from emissions, life expectancy at a particularly rapid rate (Steinberger and Roberts, 2010). In order to capture these dynamics, we perform regressions for every year between 1990 and 2010 (a time period that maximises data availability, but is still sufficiently long to reflect broad trends), obtaining the dynamic change in the fit parameters for each development variable. These fit parameters may be regressed vs. time and linearly projected to generate future elasticities, but as noted in Steinberger and Roberts (2010), this constitutes a surprisingly aggressive decoupling rate for life expectancy in the absence of policy. Instead, for this scenario, we develop a sensitivity range for the decoupling rate using the lower bound of a constant 2010 elasticity and an upper bound of progressively decoupling elasticities until 2020 and constant thereafter.

2.4.2. Extrapolating human development

An important step in the analysis is to project the achievement of future human development in each region under study, as these will inform the estimates of climate impact arising from these activities. Our analysis reveals a startling trend (Fig. 2) of a consistent linear historical (2000–2010) improvement in human development, but at different rates in different regions. We extrapolate these trends to 2050, using population weighted average value of basic needs and life expectancy in each region in 2010. Fig. 2 depicts these results for three developing regions, revealing diverging trends of development achievement, with CPA expected to reach 100% basic needs access within 10 years, South Asia in 30 years, while Africa does not reach this level before 2050. A more ambitious projection of development achievement is plausible for the latter regions, which would increase their near-term emissions, but is not explored in this analysis.

Systemic shocks over the past decade render the projection of GDP growth using the same method problematic. Instead we refer to the GDP growth projection for these regions in the baseline scenario of IAM model run described in Section 2.3. This projection results in rates of economic growth between 2% and 4.5% for the developing regions and persistent inter-regional differences through to 2050.

2.4.3. Projecting energy use for human development

The non-linearity of life expectancy and basic needs access with climate impact presents a challenge in this top down analysis: beyond a threshold area the relationship no longer holds. To address this issue we define specific threshold points for each indicator, beyond which it is assumed that further energy and emissions are superfluous for the purposes of human development. Following the human development reports (UNDP, 2011), 'high development' might be defined as the upper quartile of a 10 year average life expectancy. But since the threshold lies on an inflection point of steeply increasing energy consumption, the results will be highly sensitive to such a value. Consequently we choose a sensitivity range of the median HD in 2000 (70.4 years life expectancy, 83.5% basic needs access) to that in 2010 (72.8 years and 89.9% access). These thresholds correspond to the approximate level of middle-income countries such as China, Indonesia and Sri Lanka in 2010 (see Table 3 in the Appendix for a full list); and as of the same year, 47% of the world's population had exceeded the 83.5% threshold for basic needs access (not including countries for which we have no data). There is no threshold for income, which, unlike the HD indicators, is not bounded and does not have a saturation effect.

A second challenge of this analysis is to match the historical regression samples to the integrated assessment model scenario space, with likely dissimilarities in data sources, region boundaries and other assumptions. As such the per capita energy projections for each indicator and region are normalised to that of the start of the IAM scenario space in 2010. Thus while all regions follow a global pathway of development described by the HD-EC elasticity, the method 'calibrates' each region according to its relative efficiency in delivering HD – taking account of persistent regional differences in the underlying energy systems and infrastructures of nations (Lamb et al., 2014).

Finally, the energy projections for each region are scaled by population and then converted into GHG emissions, using a population projection and intensities from the baseline IAM scenario already discussed. This allows for a reasonable approximation of regional changes in energy generation technology to 2050 in the absence of climate policy, including very limited rates of decoupling (less than 1% compounded in all regions). It also allows us to directly compare the results to a mitigation scenario from the same model.

3. Results and discussion

Figs. 3–5 depict the annual energy and GHG emissions for achieving and maintaining human development in Africa, CPA and South Asia (Figs. 7–9 in the supplementary materials also reproduce these results in per capita terms). Broadly, it seems

Table 1
Regression results from scatter plots in Fig. 1.

	R^2	n	% world pop	A	B	$\mathrm{HD}_{\mathrm{SAT}}$
Basic needs access	0.93	67	77	7.42	−1.41	100
Life expectancy	0.71	120	92	3.97	−0.29	89.18
GDP per capita	0.89	121	92	4.51	1.10	

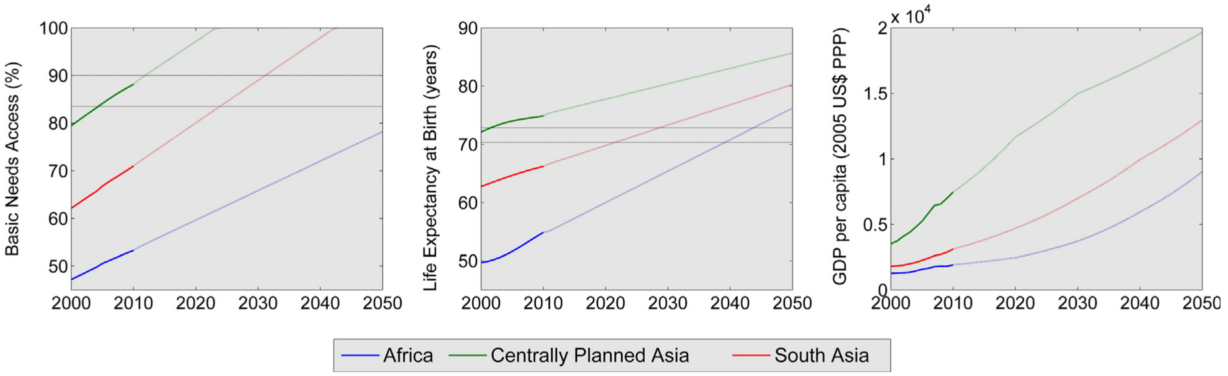

Fig. 2. Trends and projections of human development. Horizontal lines denote threshold values of 70.4 years and 72.8 years for life expectancy and 83.5% and 89.9% for basic needs access.

that when HD is defined in terms of basic needs, the emissions budget required to achieve the threshold is lowest among the three indicators, and when HD is defined in terms of life expectancy, emissions requirements match or exceed those associated with GDP – at least in the medium term. One exception is CPA, where the threshold is already met for life expectancy, but not for basic needs, so the latter has a higher emissions requirement, but only marginally.

The dashed line in each plot represents the level of energy consumption and emissions for each region in the IAM scenario. In general, the energy and emissions requirements for meeting HD thresholds exceed the available budget in this mitigation scenario. They offer evidence that in the absence of international cooperation on mitigation, despite strong assumptions of energy efficiency improvements, there indeed may be a conflict between human development and climate mitigation on a least cost basis. There are, however, important regional differences, due to variation in levels and rates of change in development achievement, relative GHG efficiencies in delivering goods and services, and rates of population growth to 2050.

3.1. Regional trends in energy and emissions

In terms of final energy consumption, Africa has a steadily increasing requirement for all three indicators – continuing to raise basic needs access (but not reaching the threshold before 2050) would require up to 40 exajoules (EJ) per year (or 25 GJ/capita/year) by 2050 for 78% access; life expectancy requires a far higher expenditure of energy, between 55 and 90 EJ/year (32–53 GJ/capita/year) for reaching 70.4 and 72.8 years respectively; while income growth continues to steadily scale up to between 75 and 90 EJ/year (45–54 GJ/capita/year) by 2050. By comparison, the IAM mitigation scenario has a far shallower rate of energy growth in Africa over the same period. Similar dynamics are evident with GHG emissions, with emissions in the IAM scenario decreasing to 2 $GtCO_2e$ by 2050, in contrast to the extreme upper range of 12 $GtCO_2e$ associated with 'development as usual'.

Similarly, the results also predict an increasing energy and GHG demand for meeting human development in South Asia, but with important differences. This region's very rapid progress in life expectancy achievement and basic needs access result in it reaching both thresholds between 2020 and 2030, with between 50 EJ and 100 EJ/year (22–44 GJ/capita/year) by 2050 necessary to maintain them. In contrast to Africa, the basic needs projection scales with the approximate mid to lower range of life expectancy, due to the more optimistic growth rate of this indicator in this region. For all indicators high levels of growth in energy use are required in the mid-term, contrary to the mitigation scenario from LIMITS. This is also the case with GHG emissions, with a minimum shortfall of up to 2 $GtCO_2e$/year by 2050 between the mitigation scenario and the lower range of life expectancy and basic needs.

The remaining region, CPA has very dissimilar results. As the life expectancy and lower basic needs access thresholds are just below the current level of achievement in this region, only a small level of growth in emissions is required to meet the upper threshold for basic needs, and a constant level thereafter (remember: due to the non-linearity of these relationships, it would not be reasonable to use the elasticity method to estimate the emissions impact of higher levels of human development in more advanced regions). Nevertheless, CPA's energy budget for maintaining basic needs access and life expectancy is more or less consistent with the mitigation scenario for energy, between 55 and 70 EJ/year (35–45 GJ/capita/year) through to 2050. As expected, the energy growth for GDP continues to a higher range of approximately 140–160 EJ/year (82–100 GJ/capita/year) due to the linear functional form used in this projection. However, in all regions, the emissions budget in the IAM mitigation scenarios falls sharply by the mid-century, well below levels required to maintain HD in the absence of any climate policy.

3.2. Reconciling human development and mitigation

The results presented here demonstrate that in the absence of policy intervention, human development will continue to require growth in energy and emissions until at least 2030 in South Asia and likely the mid-century in Africa. CPA, having reached our normatively defined thresholds of development, face a separate challenge in decoupling the emissions associated with higher and improving levels of HD. As there is no evidence in the historical data that further increases in energy consumption will deliver additional years of life expectancy, or greater access to basic needs, the challenge here shifts to sustaining improvements that have already been achieved, involving more nuanced issues such as distribution, inequality and prevailing expectations of 'the good life' (Druckman and Jackson, 2010).

The autonomous decoupling rate of energy consumption and development appears to have a substantial effect on projections of emissions – consider for example the wide sensitivity range of income at the end of the mid-century in all three regions. However, by far the greatest source of uncertainty in these projections is the threshold level of human development. When combined with the decoupling range, this can lead to a factor of two difference in the projection, as is the case for life expectancy in South Asia, an issue not generally addressed in similar studies (Costa et al., 2011). Nonetheless, in most cases these decoupling trends prove

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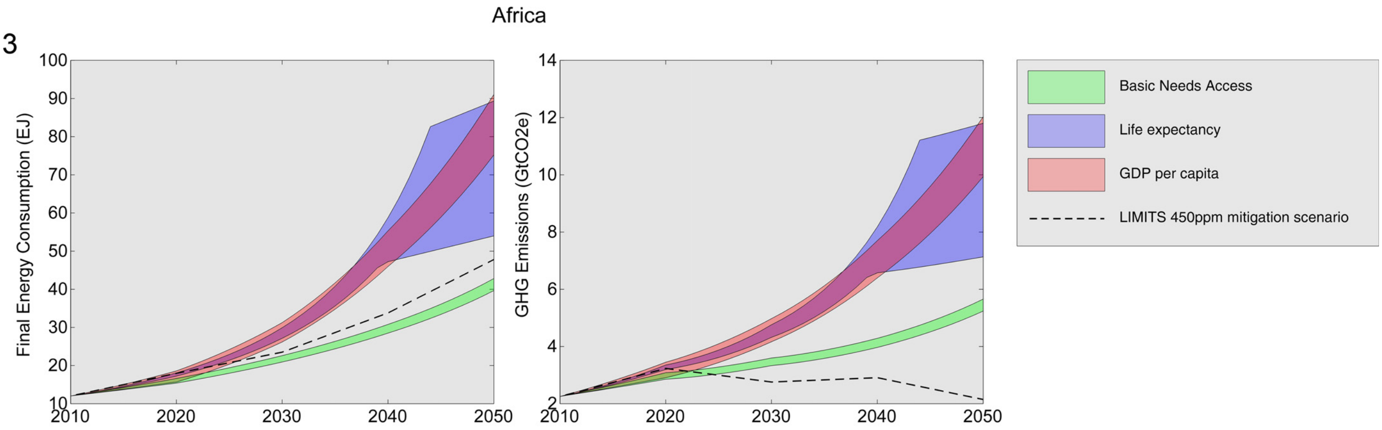

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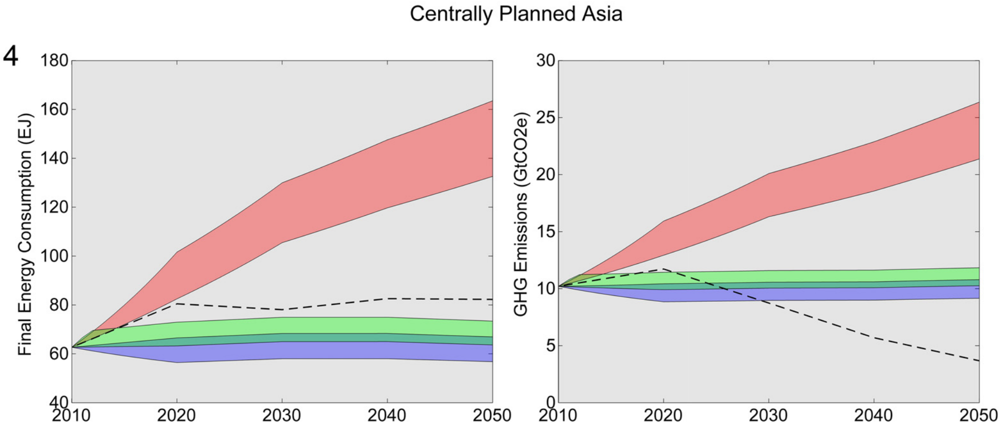

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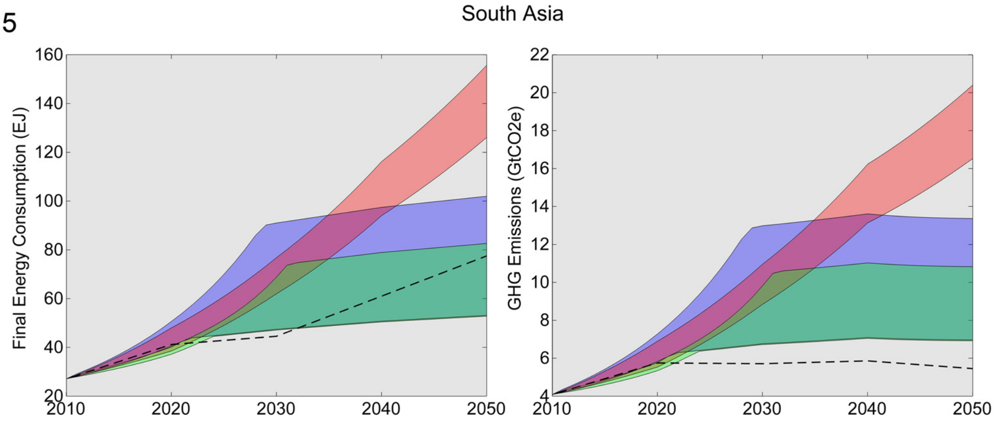

Figs. 3–5. Projections of energy and GHG emissions for human development. Final energy consumption and greenhouse gas emissions required to meet three dimensions of development from 2010 to 2050, contrasted with the LIMITS 450 ppm mitigation scenario. Each coloured area represents a sensitivity range: the upper bound consisting of a higher human development threshold (72.8 years, 89.9% access) and a low decoupling rate (a constant level from 2010); the lower bound consisting of low human development thresholds (70.4 years, 83.5% access) and a higher decoupling rate projected to 2020 and constant thereafter. (For interpretation of the references to color in figure legend, the reader is referred to the web version of the article.)

insufficient in themselves to achieve the emissions reductions required for climate stabilisation – either a greater rate of policy-induced decoupling is required, or the allocation of emissions rights is fundamentally insufficient for these regions.

Considering a faster decoupling effort, there is evidence to suggest that significant savings may be made in the delivery of basic services, particularly in areas such as heating and cooling, appliances and transportation (Cullen et al., 2011). A region's supply-side energy mix will of course account for the majority of emissions, although geographic constraints and the long lead-time of infrastructural investments renders renewable energy deployment a non-trivial strategy fraught with inertia (Davis and Socolow, 2014; Unruh and Carrillo-Hermosilla, 2006). There are strong differences in the efficiency at which regions deliver human development. Fig. 6 depicts the cumulative per capita energy consumption required to meet development needs from 2010 to 2050; in comparison to CPA, Africa and South Asia are likely to consume significantly less energy as they progress towards meeting basic needs (approximately 28 and 29 GJ/capita/year, respectively, compared to 40 GJ/capita/year in CPA). Of course,

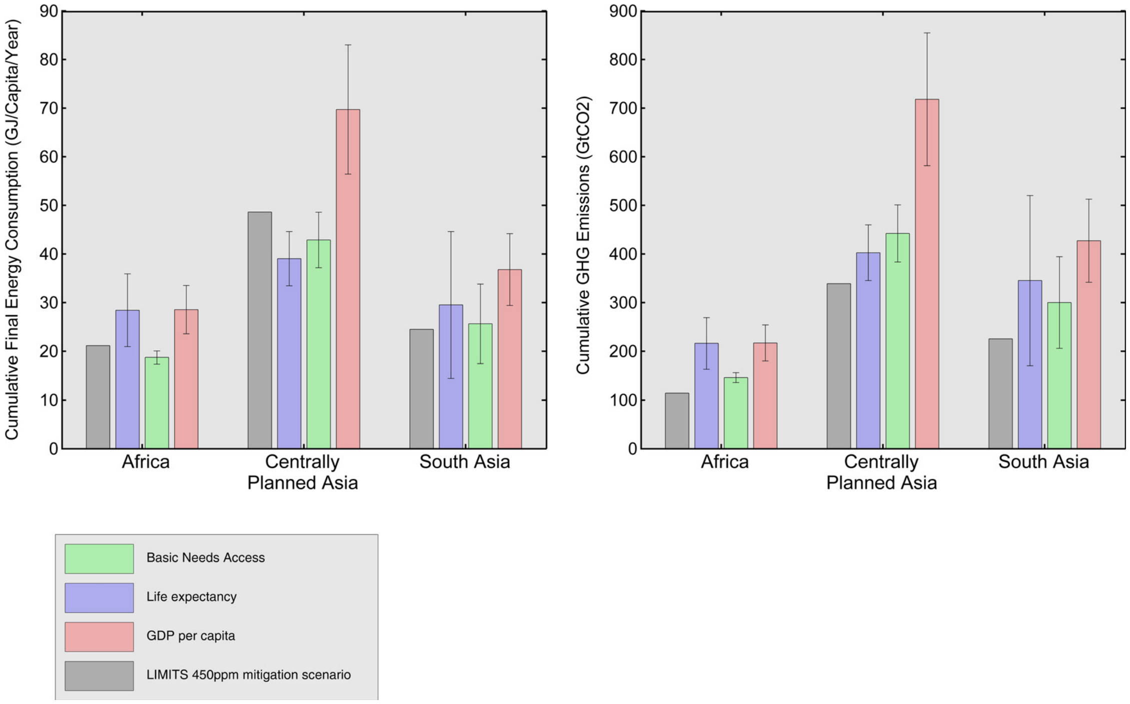

Fig. 6. Cumulative projections of per capita final energy consumption and total GHG emissions for human development. Cumulative per capita final energy and cumulative total greenhouse gas emissions required for human development in three regions in 2010–2050. The bar whiskers represent a sensitivity range: the upper bound consisting of a higher human development threshold (72.8 years, 89.9% access) and no future decoupling; the lower bound consisting of low human development thresholds (70.4 years, 83.5% access) and an extrapolated decoupling rate projected to 2020 and constant thereafter.

these regions reach their maximum energy expenditure corresponding to the development threshold at a much later stage, but this does allow time for interventions to be made. At a country level, many examples can be found of nations achieving high well-being outcomes with concomitant low levels of impact, offering some prospect of adapting existing strategies to soften the growth in energy consumption and emissions that may be needed for development (Lamb et al., 2014).

The fair allocation of emissions rights and the role of development has emerged as one of the most important considerations in climate change mitigation, most clearly articulated in Greenhouse Development Rights Framework (Baer, 2013; Baer et al., 2009). While it remains to be established what rates of change, and plausible interventions, would deliver sufficient decoupling to maximise human development *and* reduce emissions on a cost-based allocation, an alternative strategy might set a floor of ‘development emissions’ which is excluded from obligations to mitigate. In absolute cumulative terms between 2011 and 2050, focusing on the most expensive indicator from basic needs and life expectancy in each region, a baseline floor would constitute approximately 216 $GtCO_2e$ for Africa (4.2 tCO_2e/capita), 442 $GtCO_2e$ for CPA (6.7 tCO_2e/capita) and 345 $GtCO_2e$ for South Asia (4.1 tCO_2e/capita) (Fig. 6). Note that these figures are derived from these regions’ respective starting points and historical rates of progression, and include both the emissions for achieving *and* maintaining the chosen human development thresholds. As such, these estimates represent emissions associated with basic human development that these regions are *likely* to generate by 2050 at historical progress rates. Thus, Africa would occupy the least carbon space even though the region has the highest shortfall in human development, because of its slow rate of progress.

Compared to the global carbon budget in the chosen 450 ppm stabilisation scenario (1581 $GtCO_2e$), development requirements in these regions constitute 63% of total global emissions by 2050. This high figure underlines the importance of early interventions to improve the efficiency of human development. It also suggests that a development floor of emissions may be larger than currently appreciated in integrated assessment models and policy circles, particularly those that are formed on the basis of a least-cost allocation. These results provide an empirical basis to justify directing emissions towards enhancing well-being in the global South, but not without consequences for the speed at which mitigation must proceed in developed regions. Since it is the cumulative emissions that matter, the later developed countries peak in their emissions, the greater the risk that development aspirations may conflict with climate change goals (Anderson and Bows, 2011, 2008) and the higher our reliance on unproven negative emissions technologies (Fuss et al., 2014).

4. Conclusions

This research opens up a number of important avenues for investigation. The dynamics of human development progress and decoupling appear to be particularly important for achieving annual as well as cumulative budget constraints. Reconciling these dynamics with technology portfolios and potential social and behavioural change from a bottom-up approach may deliver further insight into the actual drivers of human development, and indeed how their costs may be estimated in more advanced regions. If a development emissions exemption is to be taken seriously as a guiding principle of allocating mitigation, it is likely that unprecedented rates of change may be necessary in developed regions – yet the means to achieve these radical transitions are unfortunately lacking in the literature. Adapting integrated assessment models with development-constraints in this way could provide useful insights into the technological pathways that may still avoid dangerous climate change. It would also be a natural extension of this work to assess and compare the distributive implications of fair mitigation regimes based on the definitions of development floor employed here in comparison to previous efforts, such as income-based threshold by Baer et al. (2009), or an 'equal effort' allocation of emissions rights (calculated as the same proportional loss of GDP in each region) used in the LIMITS project (Tavoni et al., 2014a). For this purpose, the analysis can be conceivably scaled down to individual countries, or alternative regional groupings (rather than the IAM-oriented regional definitions used in this paper).

The results presented here serve as a reminder that mitigation costs embodied in a global carbon market can ignore the real energy and emissions that is required for certain infrastructures and services. However they do suggest that a broader, non-income definition of human development is cheaper to satisfy in energy and emissions terms than unabated economic growth. Our findings reveal the extraordinarily steady improvements that have been made in basic needs access over the past two decades – as has also been found with life expectancy (Oeppen and Vaupel, 2002). But with at least half of the world's population still lacking a suitable level of access to these services, it is imperative to avoid accelerating this long term linear trend. Ultimately these considerations are highly relevant in the context of international climate change negotiations. Understanding the diverse ways in which human development might be enabled while reducing its impact on the environment is a key task in the making of global climate change policy.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2015.03.010.

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