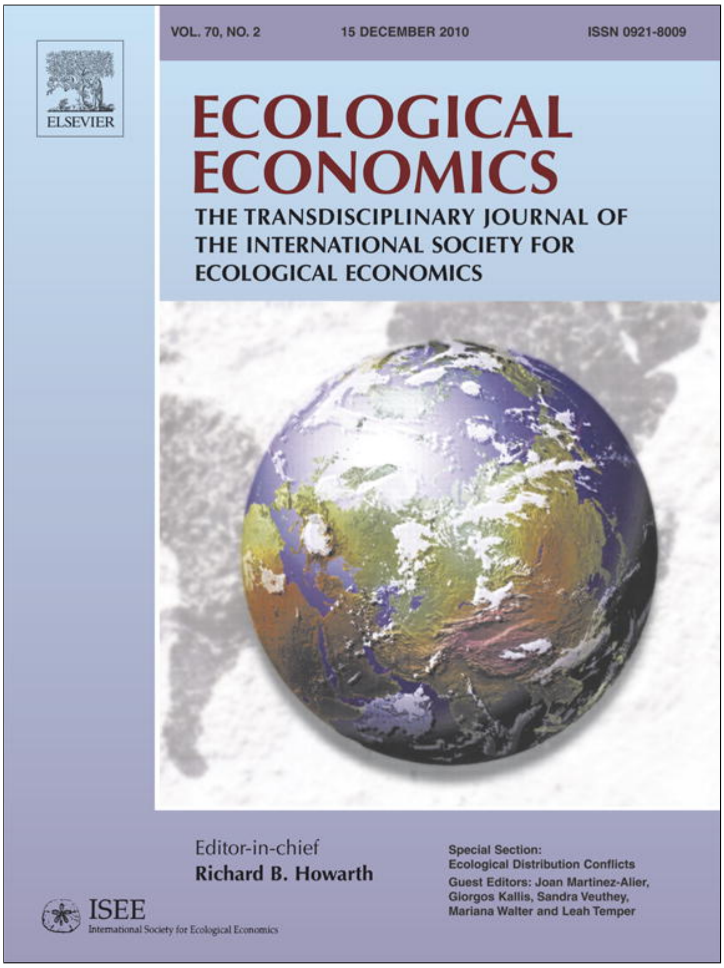
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Analysis

From constraint to sufficiency: The decoupling of energy and carbon from human needs, 1975–2005

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ABSTRACT

We investigate the relationship between human needs, energy consumption and carbon emissions for several indicators of human development: life expectancy, literacy, income and the Human Development Index. We find that high human development can be achieved at moderate energy and carbon levels; increasing energy and carbon past this level does not necessarily contribute to higher living standards. By conducting a novel longitudinal analysis from 1975 to 2005, we observe a previously undetected decoupling of the per capita energy and carbon required for human needs. If resources were equally distributed, current energy and carbon levels would be more than sufficient to satisfy global human needs at high levels of human development. By projecting current trends to 2030, we demonstrate that the global energy consumption and carbon emissions required to satisfy human needs will decrease with time, despite growth in population.

1. Introduction

What levels of energy use and greenhouse gas emissions are required in order for nations to attain high levels of human development? The devastating impacts of anthropogenic climate change and the irreversible depletion of fossil resources motivate the urgency of determining whether adequate human development can occur with significantly less energy use and carbon emissions. Most previous research focuses on technical improvements and how these affect the GDP generated per unit energy input or carbon output, with economic growth projections forming the backbone of IPCC scenarios (Nakicenovic and Swart, 2000). However, more researchers are questioning the necessity and adequacy of economic growth for ameliorating the human condition (Latouche, 2007; Jackson, 2009), and human well-being is arguably a more central measure of social progress than economic growth. In this article, we examine the evolving relationships between energy, carbon and indicators of human development. By conducting a novel longitudinal analysis, we find evidence of previously undescribed secular trends; we project these trends to 2030 and consider their implications.

We find that high human development (as defined by the United Nations' Human Development Index combining life expectancy, literacy and income) can be achieved at moderate energy and carbon levels. Increasing energy and carbon past this level does not necessarily contribute to higher living standards. This research goes beyond previous studies by conducting a novel longitudinal analysis from 1975 to 2005, which reveals when and how this previously undetected decoupling of the per capita energy and carbon required for human needs has occurred. By extending current trends to 2030, we demonstrate that the global energy consumption and carbon emissions required to satisfy human needs will decrease with time, despite growth in population. The analysis also shows that if resources were equally distributed, current energy and carbon levels would be more than sufficient to satisfy global human needs at high levels of human development.

The article is structured as follows: in the next section, we review the literature and past interest in the topic. In Section 3, we describe the data and methodology of analysis. The results are presented in Section 4 and discussed in Section 5; ending with conclusions in Section 6.

2. New and Old Interest in Human Well-being and Resource Use

The goal of development is to improve human well-being. To begin, we need a working definition of well-being and how can it be measured. This is by itself an immense topic. In this article, we interpret human well-being according to Amartya Sen's “capability approach”, which led him to conceive the Human Development Index: capabilities to function, in one's personal life, family and society (Sen, 1990). Since capabilities cannot be measured directly, other indicators serve as proxies: life expectancy (since our ability to do anything is

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limited by the time our time on earth), literacy, and income (both necessary for full participation in modern societies).

Over the past half century, a surprisingly modest number of researchers have examined the links between indicators of living standards, energy consumption and carbon emissions (Cottrell, 1955; Mazur and Rosa, 1974; Alam et al., 1991; Olsen, 1992; Suarez, 1995; Rosa, 1997; Alam et al., 1998; Pasternak, 2000; Smil, 2003; Dias et al., 2006; Martinez and Ebenhack, 2008). Most studies have found strong correlations between energy and/or carbon and living standards at lower consumption levels (developing countries), and decoupling at higher levels (industrialized countries). The correlation and decoupling features can be clearly seen in Fig. 1 for national Human Development Index, or HDI, vs. a country's energy consumption and carbon dioxide emissions. National levels of energy and carbon are often expressed through the IPAT and Kaya identities as multiplications of population, affluence and technological factors, but human development appears to be more complex. The human development decoupling at high consumption levels is referred to as a “plateau” by Pasternak (2000) or “saturation” by Martinez and Ebenhack (2008). As early as 1974, Mazur and Rosa (1974) concluded their study of 55 countries by describing this pattern and stating that “so long as America's per capita energy consumption does not go below that of other developed nations, we can sustain a reduction in energy use without long-term deterioration of our [non-economic] indicators.” Recently, Dietz et al. (2008) suggested that the environmental efficiency of human well-being should be studied systematically.

Already in 1974, Mazur and Rosa (1974) recommended a longitudinal analysis of these phenomena, but few efforts have been made. Suarez (1995) compared energy and HDI from 1960–65 to 1991–2, and found an improvement in average HDI at lower energy levels in the later data set. Pasternak (2000) noted an increase of the highest values of HDI between 1980 and 1997. Most recently, the ecological footprint (Wackernagel and Rees, 1996), which is mainly driven by fossil carbon emissions, is contrasted at the country-level with HDI for the years 1975 and 2003 (Moran et al., 2008). In the majority of cases, the HDI and ecological footprint increase together. To our knowledge, these are the only studies in which more than one point in time was considered. In this article, we cover the period 1975–2005 at 5 year intervals.

The question of energy consumption for human needs immediately raises the issue of a minimum threshold energy: one above which human needs can reasonably be met. In 1985, Goldemberg et al. (1985) estimated that we could attain “basic needs and much more

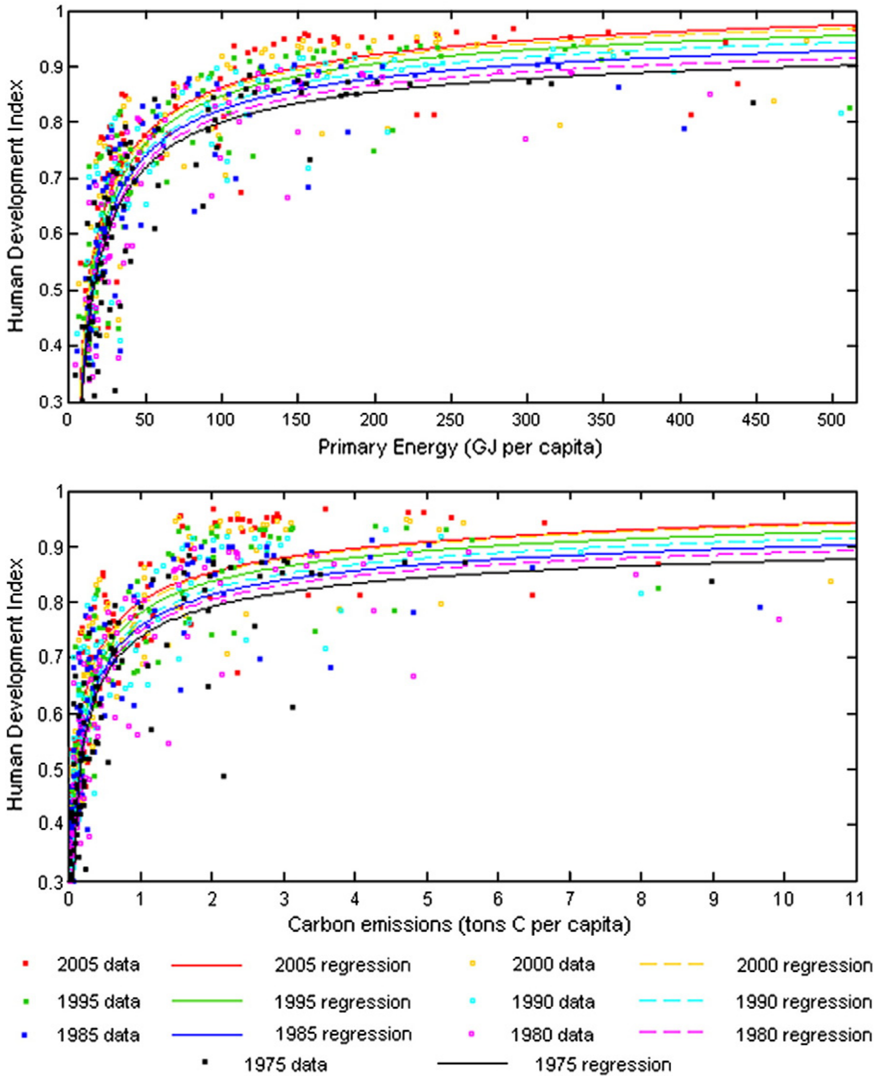

Fig. 1. Data and regressions of HDI and energy consumption (upper plot, 80 countries), carbon emissions (lower plot, 93 countries) from 1975 to 2005. The lower plot doesn't show the United Arab Emirates carbon emissions of 16 tons per capita (due to gas flaring) in 1975. CO_2 emissions can be obtained from the carbon values by multiplying these by 3.664.

for one kilowatt per capita" primary energy. Two decades later, Spreng (2005) put forward the Swiss "2000 Watt Society" proposal, which advocates a global convergence to a fairly low per capita energy consumption of 2 kW (or 63 GJ yr^{-1}) of primary energy. Under the assumptions of the 2000 Watt society, this corresponds to 1 ton of CO_2 emissions per capita (or 0.27 tons carbon). This is also the level that Chakravarty et al. (2009) recently indicated as an individual emissions "floor" which would enable the Millennium Development Goals to be met in 2030. The Global Commons Institute's famous proposal calls for a "Contraction and Convergence" (GCI, 2003) to a global mean of carbon emissions per capita far below a ton, which would be needed for atmospheric CO_2 concentrations to stay within 450 ppm. However if an energy or carbon threshold for human needs can be estimated, there is no reason to believe it remains constant over time: our goal is to question the immutability of this relationship.

3. Data and Methodology

The goal of this work is the investigation of the changing relationship between various measures of human development, on the one hand, and energy consumption and carbon emissions on the other. We do not assume a causal relationship, beyond the obvious fact that physical resources are required for life, although compelling specific linkages have been suggested, for instance to achieve the UN Millennium Development Goals (Wilkinson et al., 2007). In order to model the relationship, we take energy and carbon as explanatory variables, and human development indicators as dependent variables in a linear regression. The resulting fit parameters characterize the energy/carbon and human development relationship at the year of observation.

We investigate changes over time in this relationship by performing another series of linear regressions: of the fit parameters of the energy/carbon and human development relationship with time. The final result consists of energy and carbon *thresholds* for given human development levels, as a function of time. Our analysis is similar to that of Preston's seminal work testing the changing links between income and life expectancy (Preston, 2007).

3.1. Data Sources

The human development indicators are taken from the database maintained by the United Nations Development Programme used for compiling the Human Development Index (HDI). This publicly-available database has comparable international data over long a time-series and covers a large numbers of nations. It consists of life expectancy, literacy rate, gross enrollment ratio (the fraction of children of school age attending schools), and income (GDP per capita in constant 2000 purchasing power parity dollars). This spans the years 1975–2005, with most data available at 5 year intervals (UNDP, 2007). Given the scarcity of quality data from the world's smallest and poorest nations, especially for earlier years in our time period, we chose life expectancy, literacy, income and the HDI itself as human development indicators. The global level of these human development indicators has steadily increased: between 1975 and 2005, the span of our study: life expectancy rose from 62 to 69 years, literacy rates from 79% to 87%, income from 16,000 to 23,000 dollars per capita, and HDI from 0.66 to 0.76.

We provide more information on the structure, history and interpretation of the HDI in the supplementary materials. We prefer the HDI components to subjective measures of well-being, such as the Happy Life Expectancy (Veenhoven, 1996), because they compare the state of human development between countries, rather than the perception of that human development, which may depend on factors as diverse as social inequalities, government propaganda or advertising. HDI is also far more available and reliable over time, national income, and country size.

Our explanatory variables are primary energy per capita (Total Primary Energy Supply, TPES in GJ, from the International Energy Agency (IEA) (IEA, 2007a,b); population data from the United Nations (UN, 2007)) and total carbon emissions from fossil energy, gas flaring and cement manufacture (carbon data in metric tons from the CDIAC (Boden et al., 2009)).

We choose total primary energy (such as crude oil, coal, nuclear and hydraulic power), not final energy (like gasoline or electricity), because we are interested in the total energy input to human societies. The evolution of primary energy in relation to human development includes technical improvements in the transformation of primary sources to final energy forms: we are interested in capturing these technical efficiencies as a global trend. We expect a future study of final energy forms to yield complementary insights.

The primary energy category of the IEA data includes estimates for non-commercial energy such as combusted biomass and waste. This is an important category of energy, but as the data quality for this category may not be reliable before 2000, we repeated the analysis with only the commercial energy categories. We found almost identical results.

Likewise, the carbon emissions data do not include any other greenhouse gas emissions, or carbon emissions from land-use change, both of which we see as valuable areas for future research. The carbon emissions are thus very closely related to primary energy use; any differences between the two results from cement production and gas flaring contributions and changes in the carbon content of the energy carriers (the transitions from coal to gas, for example).

3.2. Selection of Country Sample

In order for the measured trend not to be affected by the changes in the country sample, we use the maximum number of countries for which the data exists for all years for each of the relations under consideration. As is common with cross-national time-series studies, we were forced to exclude the former USSR republics and Germany, for which consistent data was not available across the time span. Many small and developing countries are also missing from the sample. Overall, 81–91% of the global population is included in the models. We explore the impact of having these country exclusions in individual year analyses, described in the Results section.

3.3. Population Weighting

The data points correspond to individual countries, which are weighted by population number in order for the regression to be representative of the global population. Small countries such as Trinidad & Tobago thus have a far smaller weight than China or India. The rationale for this weighting is that large countries are more indicative of global patterns of efficiency in resource use than smaller ones: small countries may outsource their resource intensive activities, leading to interpretation mistakes such as the Netherlands fallacy, according to which every country in the world could achieve the population density and prosperity of the Netherlands. We explore the impacts of weighting and not weighting the sample–these findings are discussed in the Results section.

3.4. Functional Form

We consider several functional forms which have been suggested or used in the literature, as well as a new one we derived for the purpose of this work. For simplicity, in this section we denote the dependent variable as HD (for human development) and explanatory variable as EC (for energy or carbon per capita). Throughout the text, we use the goodness-of-fit R^2, along with graphical examination of the residuals for quadratic behavior to assess the model fit, because of the widespread use and ease of interpretation of R^2.

The most commonly employed function, used for instance by Pasternak (2000), describes the relationship between energy and human development as *semi-logarithmic*:

$$\mathrm{HD} = \mathrm{A} + \mathrm{B}\cdot\log(\mathrm{EC}). \tag{1}$$

This semi-logarithmic form is unsatisfactory, however. Its residuals are quadratic, indicating a systematic distortion of the fit curve compared to the data, and it yields somewhat lower goodness-of-fit parameter R^2 than alternative functional forms.

In his analysis of income and life expectancy, Preston used a *logistic* function to fit what are now known as "Preston curves" (Preston, 2007), which can be formulated for linear regression thus:

$$\mathrm{HD} = \frac{\mathrm{HD}_{sat}}{1+\exp(\mathrm{A})\cdot\mathrm{EC}^{\mathrm{B}}} \Leftrightarrow \log(\mathrm{HD}_{sat}/\mathrm{HD}-1) = \mathrm{A} + \mathrm{B}\cdot\log(\mathrm{EC}) \tag{2}$$

$\mathrm{HD}_{\mathrm{SAT}}$ is the saturation value of the human development variable, and is discussed further below. The logistic curve goodness-of-fit is better than the logarithm, but it exhibits quadratic residuals at lower EC values: simply put, the slope of the rise from low to high EC is too steep to be fit by this function.

Martinez and Ebenhack (2008) suggest a saturation curve is appropriate for the HDI-energy relationship, without however expressing it or fitting it mathematically. A saturation curve could also be approximated by adding a *quadratic* term to the semi-logarithmic form:

$$\mathrm{HD} = \mathrm{A} + \mathrm{B}\cdot\log(\mathrm{EC}) + \mathrm{C}\cdot\left(\log(\mathrm{EC}) - \overline{\log(EC)}\right)^2. \tag{3}$$

This approach has been used by Dietz, Rosa and York (Dietz and Rosa, 1997; York et al., 2003; Rosa et al., 2004) to search for turnover behavior in the relation between income and environmental impacts. This functional form yields better results in terms of goodness-of-fit and residuals than the simple logarithm, but also entails more complexity. The third fit parameter, C, requires a multiple linear regression, prohibiting population weighting. The functional form is no longer analytically invertible (an important feature for the interpretation of our results).

Mathematically, a saturation curve is *hyperbolic*. The hyperbolic form for our data is the following:

$$\mathrm{HD} = \mathrm{HD}_{\mathrm{SAT}} - \exp(\mathrm{A})\cdot(\mathrm{EC})^{\mathrm{B}} \Leftrightarrow \log(\mathrm{HD}_{\mathrm{SAT}} - \mathrm{HD}) = \mathrm{A} + \mathrm{B}\cdot\log(\mathrm{EC}), \tag{4}$$

where the coefficient B is expected to be negative. This form has both advantages and disadvantages. It fits the data slightly better than the semi-logarithmic and logistic forms, does not yield quadratic residuals, is invertible, and the simple linear regression allows data weighting. On the minus side, the asymptote, or saturation value of the human development variable, $\mathrm{HD}_{\mathrm{SAT}}$, has to be determined from the data: we use $\mathrm{HD}_{\mathrm{SAT}} = 1.1\cdot\max(\mathrm{HD})$. However, changing this asymptotical value (by changing the 1.1 factor to other values) does not change the fit or results significantly.

For our purposes, the hyperbolic form has definite advantages over the simple or quadratic semi-logarithmic forms: it is invertible, allows data weighting, and has no quadratic residuals.

3.5. Energy and Carbon Threshold Functions

The results from the hyperbolic regression are the fit parameters A and B, and the asymptote $\mathrm{HD}_{\mathrm{SAT}}$, for each year for which the data exists. The goal of this work is to identify any systematic trends in the evolution of these parameters, and to interpret the implications of these trends. We do this by yet another set of linear regressions to model A, B and $\mathrm{HD}_{\mathrm{SAT}}$ over time. Our final result is in some sense built on a pyramid of linear regressions: first of the human development vs. energy/carbon relationship for several separate years, then of the resulting fit parameters vs. time.

We thus obtain energy and carbon *threshold functions*. These are expressed as:

$$\mathrm{EC}(\mathrm{HD},t) = \left(\frac{\mathrm{HD}_{\mathrm{SAT}}(t) - \mathrm{HD}}{\exp(\mathrm{A}(t))}\right)^{1/\mathrm{B}(t)} \tag{5}$$

The threshold functions not only reproduce the results from the regressions for the years for which data exists: their analytic form enables them to be projected into the future.

4. Results

Our principal results are in the form of threshold values of energy and carbon: the amount of energy and carbon required to reach a given level of human development. In order to obtain the threshold functions, we analyze 8 relations, between 4 measures of human development: (1) life expectancy, (2) literacy, (3) GDP per capita and (4) the Human Development Index, on one hand, and 2 measures of resource use and environmental impact: (1) primary energy use and (2) carbon emissions, on the other.

4.1. Energy/Carbon and Human Development Indicators

The fit results for the hyperbolic form (Eq. (4)) are shown in Table 1, with high goodness-of-fit values for single explanatory variable regressions, given the heterogeneous global sample. Interestingly, the quality of the regressions tends to decrease with time, with the exception of GDP, where it increases. This would imply that economic activity is becoming more tightly coupled to energy and carbon emissions, while human development parameters like life expectancy and literacy are becoming more decoupled.

The derived saturation values of the human development parameters are shown in Table 1. For GDP, the regression is performed on the log of the parameter, but anti-log of the saturation value (in income units) is displayed. The high values of the GDP per capita saturation values are due to the log form of this variable.

The analysis ranges between encompassing 81% and 91% of the global population, while the energy fraction ranges between 70% and 88%, and the carbon between 62% and 81%. The energy and carbon fractions are probably lower than the population fractions because of the absence of the fossil-intensive former Soviet Union from our sample.

4.2. Steady Decoupling and Energy/Carbon Thresholds

The regression curves in Fig. 1 show that for constant energy and carbon levels, the HDI is increasing with time. Seen from the other perspective, a given HDI value is attainable at lower and lower energy and carbon emissions: human development is decoupling from energy and carbon. Moreover, this decoupling is remarkably steady, and can be described through the energy and carbon threshold functions in Eq. (5). The use of threshold functions is preferable to a simple increasing ratio, analogous to technical or economic efficiency, because the energy-human development relationship, seen in Fig. 1, is so non-linear that a ratio (slope) is most likely not meaningful. The figures for the other explanatory variables show similar trends and are available in the supplementary material (Figs. S1–S3).

The threshold functions for energy and carbon derived from our analysis in Figs. 2a and 3a, as a function of time, for each of the human development variables, show these steady secular trends over time. We chose values corresponding or close to those required for "high human development" by the UNDP: a life expectancy of 70 years at birth, a GDP of 10,000 USD, a literacy rate of 80%, and an

Table 1
Regression results for energy and carbon vs. life expectancy, GDP per capita, literacy and HDI for the years 1975 to 2005. The countries are listed in Table S1 of the supplementary materials.

	Life expectancy		GDP per capita		Literacy		HDI	
	R^2	Saturation value (years)	R^2	Saturation value (USD per capita)	R^2	Saturation value (literacy rate)	R^2	Saturation value (HDI)
Energy	110 country sample		85 country sample		103 country sample		80 country sample	
1975	0.743	82.8	0.828	147 355	0.826	109%	0.895	0.97
1980	0.751	84.3	0.838	148 747	0.809	109%	0.888	0.98
1985	0.745	85.4	0.858	94 155	0.777	109%	0.879	1.00
1990	0.744	86.8	0.857	107 441	0.781	109%	0.889	1.02
1995	0.716	88.0	0.879	123 143	0.770	109%	0.889	1.03
2000	0.663	89.3	0.899	158 641	0.747	109%	0.879	1.05
2005	0.652	90.5	0.871	181 045	0.750	109%	0.856	1.06
Carbon	156 country sample		105 country sample		105 country sample		93 country sample	
1975	0.762	82.8	0.687	147 355	0.703	109%	0.805	0.97
1980	0.756	84.3	0.688	148 747	0.699	109%	0.788	0.98
1985	0.735	85.4	0.662	94 155	0.647	109%	0.741	1.00
1990	0.739	86.8	0.666	107 441	0.624	109%	0.748	1.02
1995	0.732	88.0	0.702	123 143	0.610	109%	0.751	1.03
2000	0.707	89.3	0.741	158 641	0.580	109%	0.748	1.05
2005	0.672	90.5	0.722	181 045	0.618	109%	0.718	1.06

Note: R^2 is the goodness-of-fit parameter for linear least squares: R^2 ranges from 0 to 1, with 1 signifying a perfect fit, corresponding to 100% of the data being explained by the regression curve.

HDI of 0.8. The threshold functions are extended into the future until 2030, along with projected energy and carbon levels (OECD and IEA, 2008).

The threshold functions can be seen as a global quantification of the concept of environmentally efficient well-being presented by Dietz et al. (2008), estimating how much energy and carbon were needed in the past, are needed in the present, or will be needed in the future, to reach a certain level of average global human development. For all the human development indicators we considered, the energy and carbon thresholds for high levels of human development are decreasing functions of time (Figs. 2a and 3a). We thus observe a gradual decoupling of the energy and carbon necessary to fulfill human needs; in other words, achieving human well-being is becoming steadily more efficient.

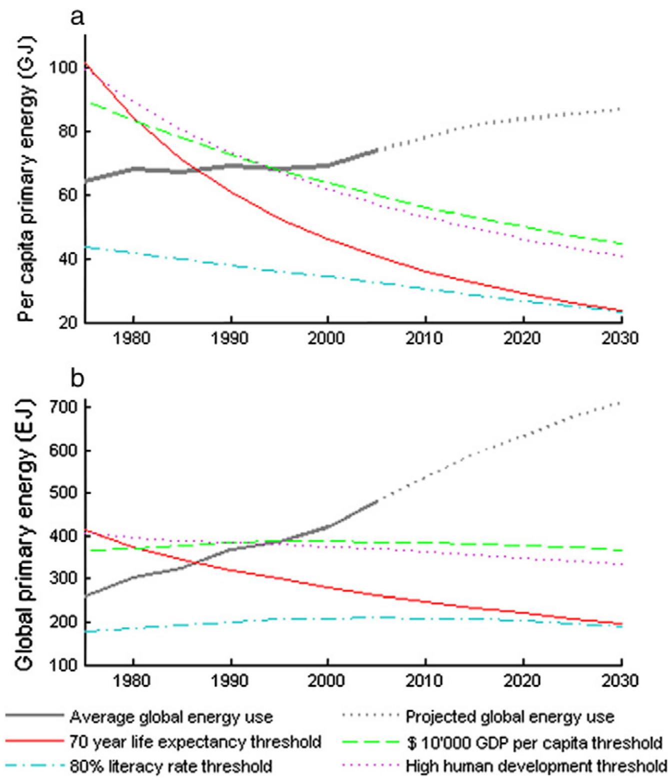

Fig. 2. Primary energy thresholds for several human development indicators, compared to energy consumption, past (continuous) and projected (dotted), both from the IEA. Upper plot (a): per capita; lower plot (b): global.

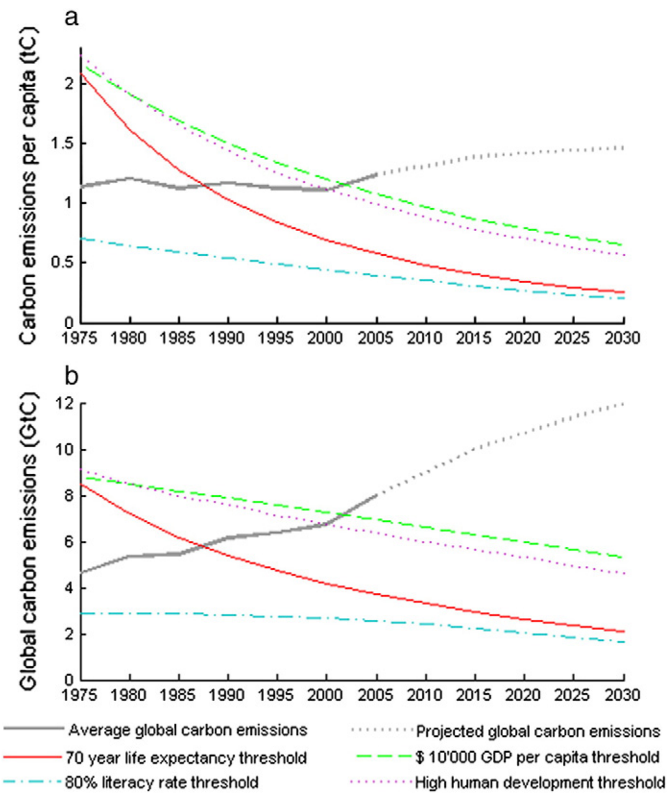

Fig. 3. Carbon emissions thresholds for human development indicators, compared to energy consumption, past (continuous) and projected (dotted), both from the IEA. Upper plot (a): per capita; lower plot (b): global.

4.3. Differences between Human Development Indicators

The values of the energy and carbon thresholds are quite distinct for the different human development indicators. Literacy stands out as having the lowest threshold values, hinting that high literacy rates are attainable at very low resource use levels. In 1975, the threshold values for the other indicators were fairly close, grouped around 100 GJ per capita and 2.2 tons of carbon per capita. While the GDP and HDI thresholds remained close together, decreasing to roughly 60 GJ and 1 ton of carbon in 2005, the life expectancy threshold dropped dramatically, to 40 GJ and 0.6 tons in 2005, and if these trends continue, is projected to decrease further to 25 GJ and 0.25 tons of carbon in 2030. The GDP and HDI thresholds are also projected to continue their decline, to 45 GJ and 0.7 tons of carbon by 2030.

All the human development thresholds decrease over time, but there are stark differences between their rates of decrease: life expectancy's threshold dropped the fastest, by 60% in energy and 73% in carbon between 1975 and 2005, while literacy's threshold only decreased by 26% for energy and 44% for carbon. The threshold decreases for GDP and HDI are somewhere in the middle: 34% and 43%, respectively, for energy, and 51% and 56% for carbon. In contrast, since 1975, carbon emissions per capita have remained steady, and energy use has only increased by 15%. The rate of decoupling of energy and carbon from human needs is thus much faster than the change in global consumption levels.

The rates of decrease of the thresholds are always larger for carbon than for energy, since energy itself has been steadily decarbonizing over the time span covered by the data. This trend is not immutable, however, since recent work has shown that decarbonization rates may be slowing or even reversing themselves as coal's cheapness and abundance leads it to be reconsidered in national development planning (Raupach et al., 2007; Pielke et al., 2008). In contrast, others are more optimistic in calling for a low carbon energy transition (Hoffert et al., 2002). In either case, our carbon projections are dependent both on the level of energy demand and the carbon content of the energy supply, and thus even more uncertain than the energy projections.

4.4. Country Pathways

The trajectories of several industrialized and developing countries for carbon and energy are shown in Fig. 4. All the countries show steady increases in HDI, but different trajectories in energy/carbon. Spain and Japan dramatically increase their energy/carbon, while the USA remains fairly steady at a high consumption level. Developing India and China have slow but steady increases in carbon/energy per capita, whereas Costa-Rica seemingly is increasing its HDI at very little energy/carbon cost.

4.5. Results without Country Selection and Population Weighting

An identical analysis was performed with all the available countries for each individual year (rather than a uniform sample). The inclusion of all countries tends to bring down the goodness of fit (from 0.76 to 0.67 on average), and raise the energy and carbon thresholds by approximately 10%, but does not affect the relations significantly, and we are thus confident that the selection of a uniform country sample does not distort the trends we are measuring. To assess the influence of individual countries on regression outcomes an outlier analysis (or robustness check) could be conducted.

When the full analysis is performed without the population weighting, the goodness-of-fit parameter decreases considerably (from 0.76 to 0.65 on average), indicating that many smaller countries deviate from the global trend of the larger ones. The decreasing trend of the thresholds remains, but there are some interesting differences with the population weighted case.

For energy, the unweighted thresholds for life expectancy and literacy are larger than those shown in Fig. 2a, but only before 1990, after which the results are similar. The HDI energy threshold is virtually unchanged, but for GDP, the unweighted energy threshold is systematically and significantly lower than shown in Fig. 2a. These discrepancies between the population weighted and unweighted results can be explained by the cluster of fossil-exporting countries: these countries typically have small populations, high energy consumption and high GDP per capita, and, in many cases, not terribly high life expectancies compared to other, larger countries

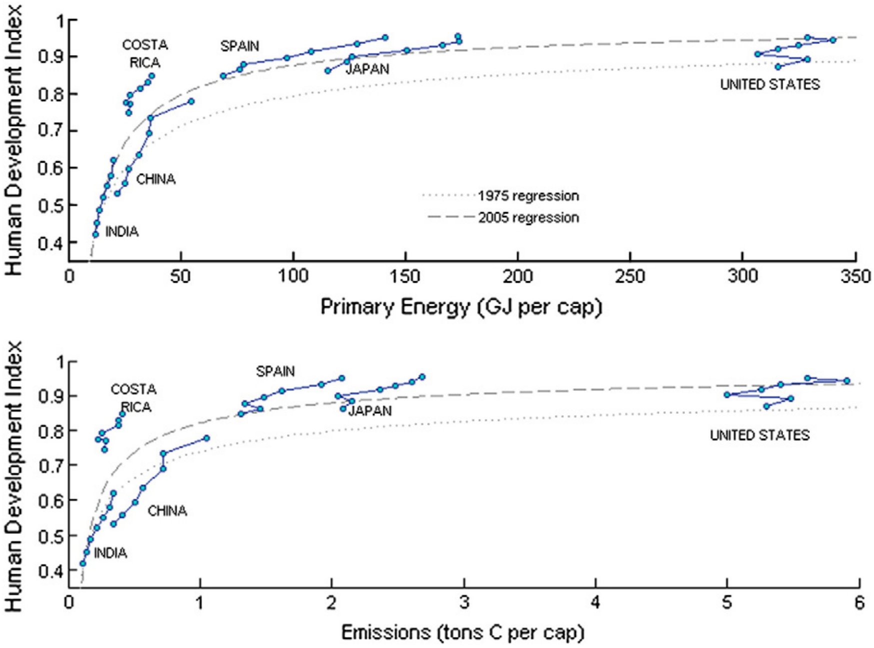

Fig. 4. Development trajectories of China, Costa-Rica, India, Japan, Spain and the USA for HDI vs. energy and carbon emissions, from 1975 to 2005, at 5 year intervals. The regression curves from Fig. 1 for 1975 and 2005 are also shown for reference.

with similar energy and GDP levels. Indeed, Martinez and Ebenhack (2008) already noted that OPEC and fossil-exporting countries follow a distinct trend.

Interestingly, without population weighting, the carbon thresholds are systematically lower than in the weighted analysis shown in Fig. 3a. The change in the carbon-to-energy levels could be explained by the fact that several large population countries are also very coal intensive: China, India and the USA. Smaller population countries may also have less domestic extractive activities, and thus import refined lower-carbon fuels and energy-intensive manufactured goods produced elsewhere.

5. Analysis and Implications

What do we learn from the differences in human development indicators in their relation to energy and carbon over time? The relationship is highly non-linear: for the poorest nations, great benefits tend to come with relatively slight increases in energy consumption and carbon emissions. At a certain threshold, the improvements level off very sharply. But more, the curves themselves are steadily changing over the thirty years we examined: we found that the Human Development Index is increasing steadily with time, even if energy and carbon emissions levels are held constant. That is, high human development can be generated at lower and lower energy and carbon emissions costs, and the quality of life is steadily decoupling from its material underpinnings.

In 1975, a life expectancy of 70 years of age was correlated with an energy use of 100 GJ and carbon emissions of 2.1 tons per capita, almost twice as much as the per capita levels of energy and carbon. By 2005, the situation had changed dramatically. The average person consumed 74 GJ and emitted 1.2 tons of carbon, almost twice the levels correlated with a life expectancy of 70 years. If these trends continue, by 2030, a life expectancy of 70 will be correlated with only 24 GJ and 0.25 tons of carbon, a factor of more than three below the projected consumption levels (OECD and IEA, 2008). The exact values of the energy and carbon depend on the sample of countries included in the study–and could thus be somewhat higher–but the crucial fact of a declining trend remains.

Different aspects of human development have fundamentally different behaviors, and each merits investigation. In particular, in energy and carbon terms, literacy is fairly “cheap:” high literacy rates have apparently always been possible at fairly low energy and carbon levels, and these levels are still decreasing. For the HDI of 0.8 and a GDP of 10,000 USD per capita, although the decreases in energy and carbon thresholds are not as dramatic, they still drop far below the current and projected levels. Most dramatic, however, are the falls in the energy and carbon “cost” of high life expectancy: thirty years ago, higher life expectancy and economic activity used to be far more expensive than they are today. The energy required for high life expectancy is rapidly becoming easily accessible, while economic wealth follows a slower trend.

One might argue that these human development indicators are simply following their own trajectories, and are, if anything, more likely to be closely linked to each other than to have any causal relation with fossil energy use. However, Preston found a similar decoupling between life expectancy and income (Preston, 2007). Preston demonstrated that longer life expectancy is due to other factors than income increases. It is true that these development indicators are influenced by much more than fossil consumption: for instance advances in basic medicine and hygiene, education or governmental health programs have clear and direct impacts. However, these indicators remain closely coupled to energy and carbon emissions, as can be seen from the high level of correlation in every year in this study. The phenomenon under observation is thus twofold: the decoupling of human needs from energy and carbon, on the one hand, and the reality that human needs cannot be met below minimum levels of carbon and energy, on the other.

How does population growth affect the results? Does population growth overwhelm the decline in energy and carbon thresholds at a global level? The global energy and carbon levels corresponding to the per capita values in Figs. 2a and 3a are shown in Figs. 2b and 3b, using the UN medium-variant population projections (UN, 2007). Except for literacy, the decline in the energy and carbon thresholds for human development is so large that it outpaces the growth in population. The result of this dropping threshold is an absolute decrease in the total energy required for a high global level of human development.

A few countries, mostly Latin American, exist in the upper left-hand “Goldemberg Corner” of Fig. 1, with primary energy below 50 GJ and high human development. We show the trajectory of one of these countries, Costa Rica, compared to the China, India, Japan, Spain and the USA in Fig. 4. All of the countries in Fig. 4 improve their HDI significantly, with Costa-Rica, India and the USA maintaining relatively stable energy per capita. The fluctuations in the USA's per capita energy use demonstrate that consumption decreases are possible while still increasing HDI. It should be noted that taking international trade into account may change these country pathways significantly: from a consumption perspective, in 2000, China exported 24.4% and imported 6.6% of its emissions, leading to 17.8% net exports (Peters and Hertwich, 2008).

What are the implications of these results? One interpretation is that, unsurprisingly, there are significant energy efficiency gains in human development. Technological improvements have certainly allowed more energy services to be delivered per unit input energy, as well as access to energy services to be more widely available (Lovins, 1976; Jochem, 2000; Johansson and Goldemberg, 2004). Technical advances and improvements in knowledge are bound to have repercussions on basic living standards as well as on luxuries, so these results should be expected as business-as-usual. This is not only true for primary energy: preliminary analysis regarding total electricity consumption (high quality final energy) shows very similar behavior. Progress independent of technical efficiency may also play a role: for instance, the maximum life expectancies have been increasing past all projections at a remarkably steady rate (Oeppen and Vaupel, 2002).

The efficiency of the delivery of essential energy services is growing steadily, but, as with other types of energy efficiency, this efficiency cannot be expected to lead to absolute decreases in energy use. Historically, the growth of energy efficiency is more than matched by growth in energy consumption, through the rebound effect (Jevon's Paradox) (Hertwich, 2005; Ayres et al., 2007). Further measures are required for the necessary reductions in total consumption and emissions–but our results show that these do not necessarily come at a cost in human development.

The human development indicators we have considered cover basic aspects of existence (life expectancy, income), but is it possible that other, less tangible, properties continue to increase with higher energy use. This brings us to the challenge of accurately measuring “happiness” or “life satisfaction.” Recent studies show that happiness exhibits saturation behavior income (Jackson, 2009), very similar to the saturation behavior we see for human development indicators, but further research into the various human well-being indicators should be pursued.

From another perspective, our results show a fundamental shift, from one of absolute resource constraint in 1975 (average energy use is below what is correlated with high development) to apparent resource sufficiency in 2005 and beyond. Rather than drastic supply shortages or mitigation-driven cutbacks, in this perspective the twin challenges of energy supply and carbon emissions become issues of consumption restraint and global distribution. Moreover, the systematic and steady declines in energy and carbon thresholds happened in the absence of widespread deliberate energy efficiency or decarbonization policies, suggesting that far greater progress may be possible with targeted government efforts and appropriate market incentive structures.

The need for such a dramatic shift is seen in assessments of total carbon emissions above which the global climate system is expected to become unpredictable, and destabilize the basic natural support systems for human society (IPCC, 2007; Richardson et al., 2009). There is no consensus on whether 550, 450 or 350 ppm of carbon dioxide equivalents from all greenhouse gases would constitute a "safe" level of increased pollutants in the atmosphere. Since 280 ppm is the pre-industrial concentration at which human society developed for most of its history, and since the massive injections of carbon in the last half century is largely cumulative, it may be that we simply do not have the time for secular trends such as those we have documented here to have their effect. Getting onto a pathway to keep global atmospheric greenhouse gas concentrations at a safe level is bound to put extreme pressure on the international political system. (The same, of course, could be said about adapting to the climate crises that lay in store if we do not get on these pathways Hamilton, 2010.)

Finally, in terms of the previous estimations on minimum levels of energy and carbon for human needs, this work first of all shows that this minimum level cannot be seen as constant: it decreases with time. The minimum level also depends on which human development indicator is chosen, so great care must be taken to explain which human need goals one is seeking to meet. In 1985, the 1 kW per capita (31.6 GJ) level put forward by Goldemberg et al. (1985) was in fact optimistic, and below all the threshold functions in Fig. 3a. By 2005, the 2000 Watt society (63 GJ) of Spreng (2005) may already have been on the high side, since it is above all the thresholds in Fig. 2a. The 1.0 ton of CO2 goal, or 0.27 tons C, suggested by some (GCI, 2003; Spreng, 2005; Chakravarty et al., 2009), in contrast, is still far below the 2005 thresholds. Moreover, the carbon threshold values projected through 2030 are entirely dependent on the carbon content of energy, which, as we mentioned, may lamentably be reversing the trend of more than a century towards decarbonization (Raupach et al., 2007; Pielke et al., 2008). The projected carbon thresholds may thus be too modest, making the 1 ton of CO2 per capita level unrealistically low for meeting human needs without a transition to predominantly renewable energy sources. Clearly a shift away from fossil fuels could change the carbon content of the energy supply, and alter these thresholds substantially.

6. Conclusion and Future Steps

The finding of the continuously decoupling levels of energy and carbon required for human needs is of crucial importance to researchers and policy makers. Rather than insisting that a high level of energy and carbon are a prerequisite for high living standards, as assumed by the Energy Development Index of the International Energy Agency (IEA and OECD, 2004), it would seem that they are ever less necessary. The social equity and sufficiency goals of sustainable energy development may be within reach at bearable environmental costs: *globally, the total amount of primary energy currently consumed is now more than sufficient to attain high human development for all.* The issue of carbon levels depends on trends in the carbonization of energy, and the share of low-carbon sources.

Rather than biophysical or technical limits, then, the solutions to energy over-use and under-development now are mostly constrained by economic and political structures; these constraints include pressures for relentless economic growth and the struggle for competitiveness. The falling energy and carbon thresholds for development will not automatically solve looming climate change, energy supply problems or human development shortfalls. Indeed, truly sustainable social and environmental progress is only possible if the industrialized nations, which are currently using far more energy and emitting far more carbon dioxide per capita than they need for high standards of living, substantially reduce their consumption and emissions. If coupled with effective sustainable development programs and low-carbon energy, such a reduction would allow nations with lower living standards to move up the steep slope to high development, which can be achieved from very small increases in energy use and carbon emissions.

The analysis also supports the observation that with thoughtful restructuring, highly developed countries could use a fraction of their current energy without any measurable loss in human development. Such large voluntary reduction in energy and carbon from the world's richest countries will not happen automatically or easily, since it goes against the main driver of higher consumption and emissions: a growth-driven economic system, which requires higher and higher consumption levels to support production and employment, to compensate for resource and labor productivities increases (Jackson, 2009; Ayres et al., 2007).

National development pathways and international trade may be key factors, with some countries locked in to energy-intensive extractive, processing and manufacturing industries, supplying others with higher quality goods while deriving relatively low economic or human development benefits (Roberts and Parks, 2007). Peters and Hertwich (2008) have recently shown that a consumption perspective significantly changes national emissions. Repeating our present analysis from both production and consumption perspectives would yield further insights into the role of international trade. Such a differentiated analysis may be useful to guiding progress for both national and international climate and energy policy negotiations.

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Appendix A. Supplementary Data

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