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Across a Moving Threshold: energy, carbon and the efficiency of meeting global human development needs

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Contents

Abstract

We approach the twin challenges of global warming and finite fossil fuel reserves from the perspective of human development rather than economic or technical performance. Human development depends strongly on energy use. Rather than remaining static, however, the crucial relationship between energy consumption and human development is shifting steadily. We derive time-dependent threshold functions of energy and carbon emissions required for human development. From these threshold functions, we show that higher national values of the Human Development Index (HDI) are now attained at half the energy use and carbon emissions than they were three decades ago. An important result from this analysis is that, starting in the 1990s, the total amount of energy consumed was large enough to raise all nations to high living standards. Globally, despite population growth, the energy required to meet human development needs is decreasing with time. Projections of the threshold functions show a continuing global decrease of energy and carbon required for high human development until at least 2020.

1 Introduction

What thresholds of energy use and greenhouse gas emissions are required in order for nations to attain decent levels of human development? Most previous research on the relation between energy use and human progress has focused on technical improvements and how these affect the GDP generated per unit energy input. In this work, we take a different direction, investigating energy use in terms of human well-being as a goal in itself. We find a crucial and largely unremarked secular trend with sweeping implications.

Over the past decades, a few researchers have examined the links between living standard indicators, 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), but have largely assumed that these links were unchanging. Anthropogenic climate change and the irreversible depletion of fossil resources make clear the importance of investigating the changing links between energy use, carbon emissions and human development, but the topic remains remarkably under-researched.

In a 1985 article, (Goldemberg et al., 1985) estimated that we could attain “basic needs and much more 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 kilowatts (or 63 GJ per year) of primary energy, corresponding to 1 ton of CO_2 emissions per capita (or 0.27 tons carbon). Similarly, the Global Commons Institute’s famous proposal calls for a “Contraction and Convergence” (GCI, 2003) to a global mean of carbon emissions per capita below a ton, which would be needed for atmospheric CO_2 concentrations to stay within 450 ppm. These constant thresholds are designed to either satisfy human needs, prevent dangerous climate change, or both. If an energy threshold for human needs can be defined, why do we expect it to be constant?

Previous analyses of the relationship between energy use/carbon emissions and GDP growth have failed to capture the more basic outcome of development: human well-being. The goal here is to understand the ongoing shift in the crucial relationship between human society and its principal resource: energy. We find that, far from being stable, the relationship between energy use and human development is shifting steadily. We derive an energy threshold for human development and show that this threshold has dropped by more than fifty percent over the past three decades. This study first characterizes the relationship between human development, energy use and carbon dioxide emissions at a national level for a large sample of countries. Human development is measured by the United Nations Development Programme’s widely used Human Development Index (UNDP, 1990; Anand and Sen, 1994). We then examine how these relationships have changed over three decades and how they are likely to continue evolving through 2020.

2 Data and methodology

To investigate the dependency of human development on energy use and its impact in terms of carbon emissions, we conduct two separate regression analyses. Our dependent variable is the HDI, the Human Development Index from United Nations Development Programme (UNDP) (UNDP, 2007). The HDI is an aggregate indicator which captures the following features of human wellbeing: life expectancy, education and income. The HDI is the equally weighted average of three distinct sub-indicators: (Life expectancy indicator + Education indicator + Income indicator)/3 and ranges from 0 to 1. Above an HDI of 0.8, a country is considered by the UNDP as “highly developed;” “low development” is defined as below 0.5. Above an HDI of 0.8, the average life expectancy is 75 years old; it drops to 50 years in the low development category.

The HDI has been criticized, especially in its initial form (Lüchters and Menkhoff, 1996; Sagar and Najam, 1998), and some have suggested that economic growth alone remains a better indicator of human development (Ravallion, 1997). Many of the critical suggestions have been incorporated in the current form of the HDI. Specificially, the inclusion of income is uniform across nations and the index is now consistently derived over time, allowing cross-country and longitudinal analysis. We find for current purposes that the HDI is a simple, compelling measure of human welfare encompassing both means (economic) and ends (life expectancy and education), making good use of some of the only internationally comparable and available data over long time-series and large numbers of nations. Some may argue that the components of the HDI are closely correlated (they are), and that an economic analysis alone is thus sufficient. We believe this represents an extremely narrow view of human well-being. We prefer an index which includes both economic and social aspects, and future analyses should utilize the best ones for which data is available. Moreover, we have replicated our analysis for the single components of the HDI as well, with the overall findings valid for each. The HDI thus functions as a summary of welfare indicators. More information regarding the construction of the HDI and the implications of its value ranges can be found in Appendix A. The most recently calculated 1975-2005 HDI dataset is assembled using a comparable methodology (UNDP, 2007).

Our explanatory variables are primary energy per capita (Total Primary Energy Supply, TPES in GJ, from the International Energy Agency (IEA) (IEA, 2007b; IEA, 2007a); 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 (Marland et al., 2007)). Since the carbon emissions data for 2005 were not yet available, we used 2004 values.

We use total primary energy (such as crude oil and coal), 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 analogous study of final energy forms and carbon emissions to yield complementary insights.

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 result from the cement production and gas flaring contributions and changes in the carbon content of the energy carriers (the transitions from coal to gas, for example).

The intriguing correlation between HDI and energy use has been noted previously (Suarez, 1995; Pasternak, 2000; Dias et al., 2006; Martinez and Ebenhack, 2008), as well as the relation between Physical Quality of Life (an indicator combining literacy, infant mortality and life expectancy) and electricity consumption (Alam et al., 1991; Alam et al., 1998). In general, a strong correlation exists for low HDI and energy values (developing countries), where more energy input appears necessary for improvements in HDI. Contrarily, very little correlation is seen at higher energy values (industrialized countries): a large range of energy inputs can create the same high HDI

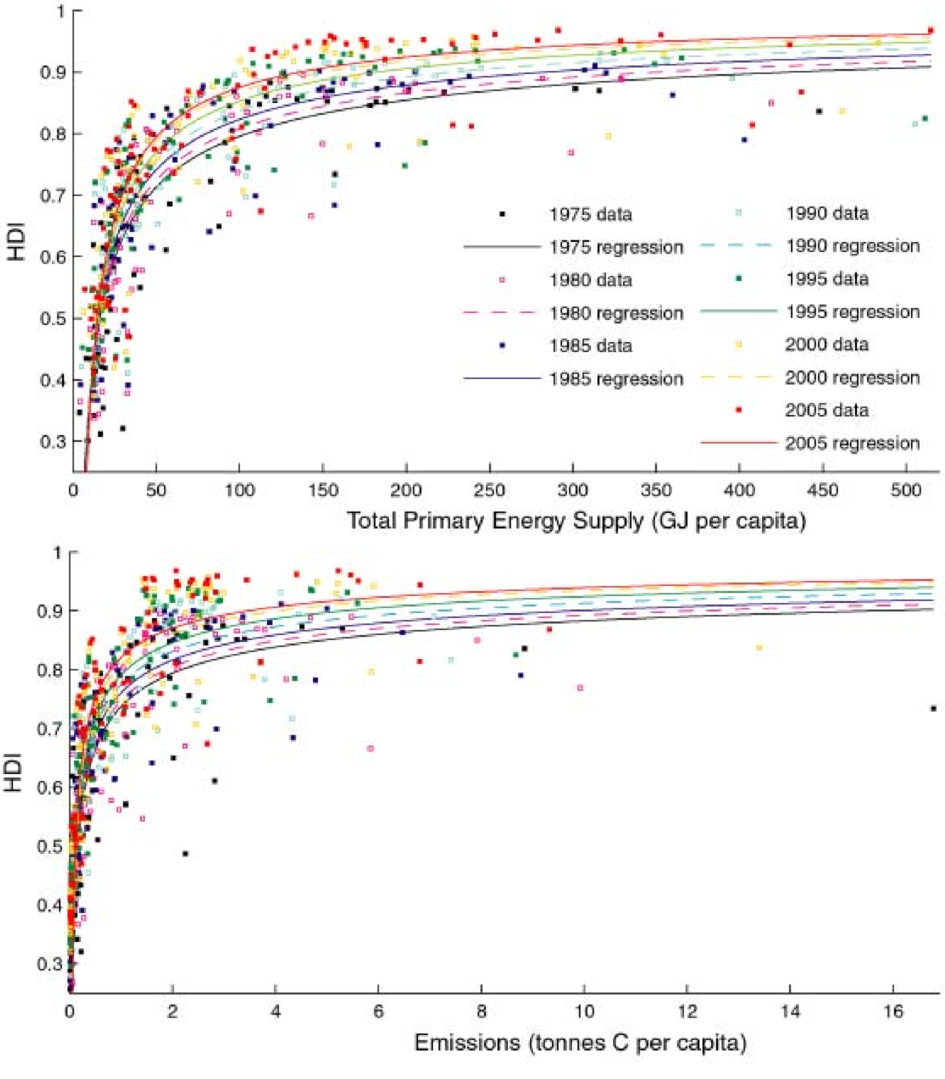
levels. This is termed the HDI “plateau” by (Pasternak, 2000) or “saturation” by (Martinez and Ebenhack, 2008). These features can be clearly seen in Figure 1.
Suarez (1995) compared energy and HDI data from 1960-65 and 1991-2 and found an improvement in average HDI at lower energy levels in the later data set, whereas Pasternak (2000) noted an increase of the highest values of HDI between 1980 and 1997. Most recently, the ecological footprint, 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. In this article, we investigate the change in the HDI-energy and HDI-carbon relationships, from 1975 to 2005, at 5 year intervals.

Our sample consists of the set of countries for which all data (HDI, energy, carbon emissions, population) were available for all years. These 74 countries, listed in Table C-3, comprise between 78% and 79% of the global population, between 61% and 74% of global carbon emissions, and between 66% and 75% of the world’s total energy use (the fractions increase with the year of observation). Significant missing countries include 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. To assess how the missing countries might bias the results, the fitting analysis was repeated for the year 2005, where the most data was available, and compared with the other results. The 2005 sample comprised 126 countries, 91% of the carbon emissions and 93% of the global population and energy consumption.

3 Results: energy and carbon thresholds for human development

We use population-weighted Linear Least Squares fitting to yield the regression curves shown in Figure 1. The quality of the fit for each year is given by the parameter R^2, which is 1 for a perfect fit, corresponding to 100% of the data being explained by the regression curve. R^2 ranges between 0.85 and 0.9 for the energy data and between 0.75 and 0.85 for the carbon data. The quality of the fits is remarkably high, considering the heterogeneous global sample. The details of our analysis and fit results are presented in Appendices B and C.

Fig. 1: HDI, energy use and carbon emissions



Data and regressions of HDI and energy consumption (upper plot), carbon emissions (lower plot) for 74 countries from 1975 to 2005. CO_2 emissions can be obtained from the carbon values by multiplying these by 3.664.

The enlarged 2005 sample regression results are quite close to those of the reduced sample. The enlarged 2005 fit values are closer to the 1995 or 2000 results for the reduced sample, which suggests that the missing countries have a lower overall performance (lower HDI for same energy and carbon values). This can be expected to affect the constant term in our results, but not the overall trend.

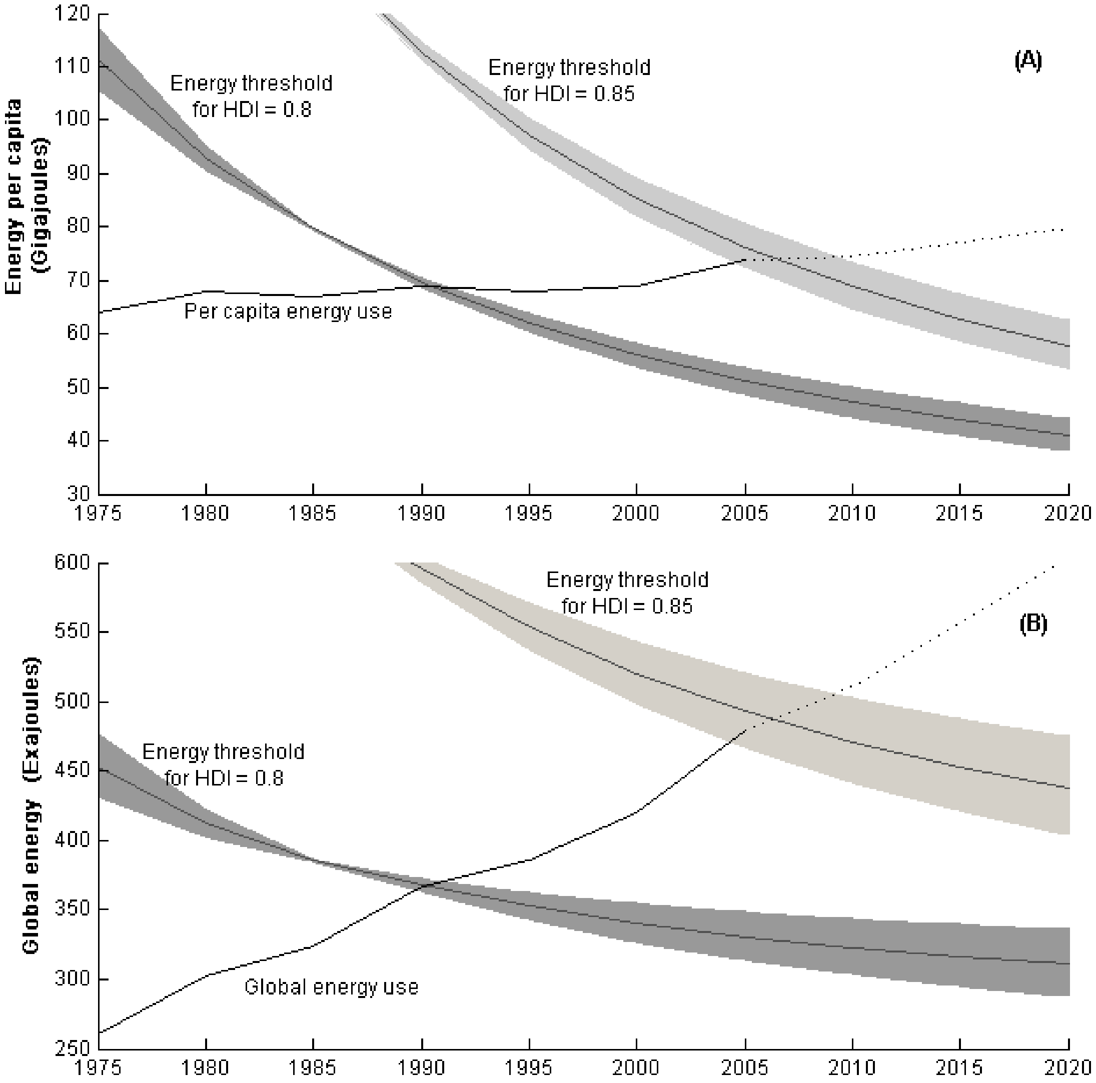
It is clear from the regression curves in Figure 1 that for constant energy use and carbon dioxide emission levels, the human development index is increasing with time. Seen from the other perspective, a given HDI value is attainable at lower and lower energy and carbon emissions. Moreover, this progress is remarkably steady. However, since the HDI does not focus solely on physical health and social human well-being, but also includes an economic component, we had to rule out whether we are only witnessing the well-known increase in economic efficiency, in GDP per unit of energy. We repeated the analysis with the economic component removed from the HDI, as well as for the other HDI sub-indicators, life expectancy and education, separately. The results reproduce the trend seen in Figure 1. This implies that the well-known relationship between GDP and energy consumption exists in similar forms for other social goods, like education and health. Although the causation pattern is far from clear, the high level of correlation between energy consumption, carbon emissions and these crucial social indicators validates the assumption that energy use is vital to society. The characterization of these relationships thus informs the debate on possible pathways for sustainable development.

The TPES energy category of the IEA data includes estimates for non-commercial energy such as combusted biomass and waste. As the data quality for this category may not be reliable before 2000, we repeated the analysis with only the commercial energy categories, with almost identical results.

In Figure 1, we see that a given HDI value, say 0.8 for high development, is attainable at lower and lower energy and carbon values. From our regression results, we can derive *energy and carbon threshold functions*: they express the energy and carbon per capita needed, from our global sample average, to reach a certain level of human development, as a function of time. The threshold functions can thus be used to estimate how much energy and carbon were needed in the past, or will be needed in the future, to reach a certain level of average global human development. The use of threshold functions is preferable to a simple increasing ratio, analogous to technical or economic efficiency, because the energy-HDI relationship is so non-linear that a ratio (slope) is not meaningful. The derivation of these functions is given in Appendix D.

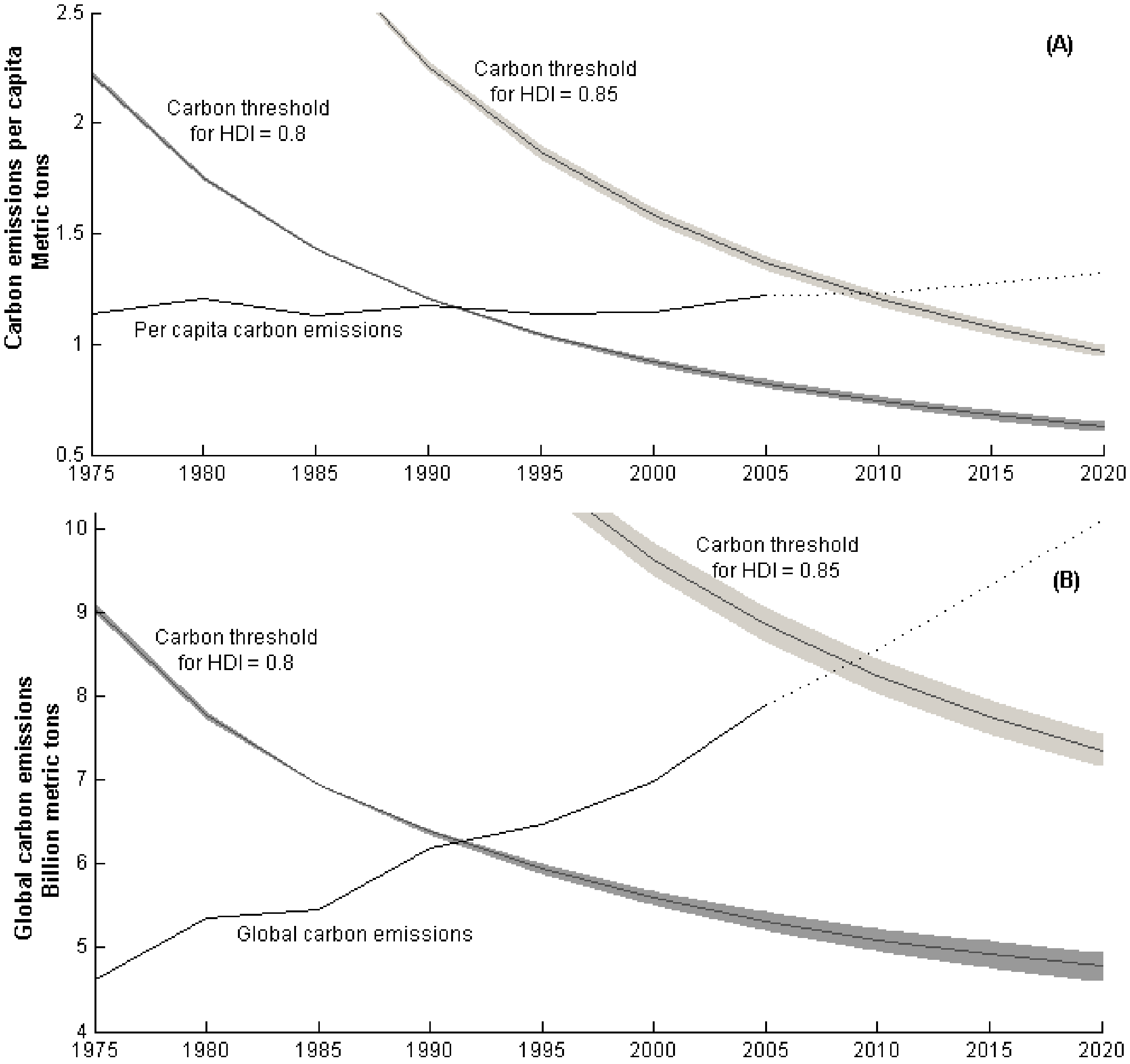
The threshold functions for energy and carbon are plotted A of Figures 2 and 3, for HDI values 0.8 (minimum for “high development”) and 0.85, projected until 2020. Because of the strong non-linearity of the relation between HDI, energy and carbon shown in Figure 1, attaining an HDI of 0.85 requires, on average, significantly more energy than for an HDI of 0.8, which in turn requires significantly more energy than an HDI of 0.75 (not shown). However, the dramatic decrease in the energy and carbon threshold functions over time is common to all medium-to-high human development HDI values. The uncertainty in the threshold function estimation is given by the standard error in the fit parameters. Due to the increase of the uncertainty with time, we only extend the projections to 2020.

Fig. 2: Energy threshold for high human development



Primary energy thresholds for a Human Development Index of 0.8 and 0.85, compared to energy consumption, past (continuous) and projected (dotted), both from the IEA. Plot A: per capita; plot B: total

Fig. 3: Carbon threshold for high human development



Carbon thresholds for a Human Development Index of 0.8 and 0.85, compared to carbon emissions, past (continuous line, from CDIAC) and projected (dotted, from the IEA, adjusted to the CDIAC level). Plot A: per capita; plot B: total.

4 Analysis and implications

The energy threshold required to reach a "high" level of human development is a steeply decreasing function of time, both for HDI of 0.8 and 0.85 (Figure 2A). We focus our discussion on HDI of 0.8, which is the lower limit for high human development as defined by the United Nations Development Programme. This choice is somewhat arbitrary – however the exact results are less important than the trend, which is true for all medium-to-high HDI values. In 1975 the average person required a primary energy consumption of 110 GJ and carbon emissions of 2.2 tons to attain an HDI of 0.8, corresponding to the lower limit of high development. By 2005, the required energy consumption was only 50 GJ, while carbon emissions had dropped to 0.8 tons: both reductions of more than a factor of 2. It is clear that the relationship between human development, energy consumption and carbon emissions is far from immutable, but is instead progressing with time, allowing higher living standards for lower energy consumption and emissions.

How does the average global per capita energy consumption compare to the energy threshold for human development? The average consumption is displayed in as a bold line in Figures 2A. In 1975, the global average per capita energy use was 60% of the threshold amount for high human development. The two values cross in 1990, mostly due to the steep decline of the threshold function, and in 2005 energy consumption was 150% of the energy threshold for high development. The comparison of energy consumption and threshold functions yield an important new insight: in 1990, or a few years later, the per capita energy consumed globally would theoretically have been enough to bring the entire global population to a high level of development. Since then, the total amount of energy consumed exceeds that required for human development needs.

How does population growth affect the results? Does population growth overwhelm the decline in energy threshold at a global level? Plot B in Figure 2 utilizes UN medium-variant population projections (UN, 2007) and shows that the decline in the energy threshold 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 result which contradicts the shrinking carrying capacity predictions of Malthus and Ehrlich. The IEA projections for global energy use through 2020 (IEA and OECD, 2004) are shown as dotted line, both in the upper and lower Figure 2. By 2020, the projected energy use is roughly twice the threshold energy for a global average HDI of 0.8.

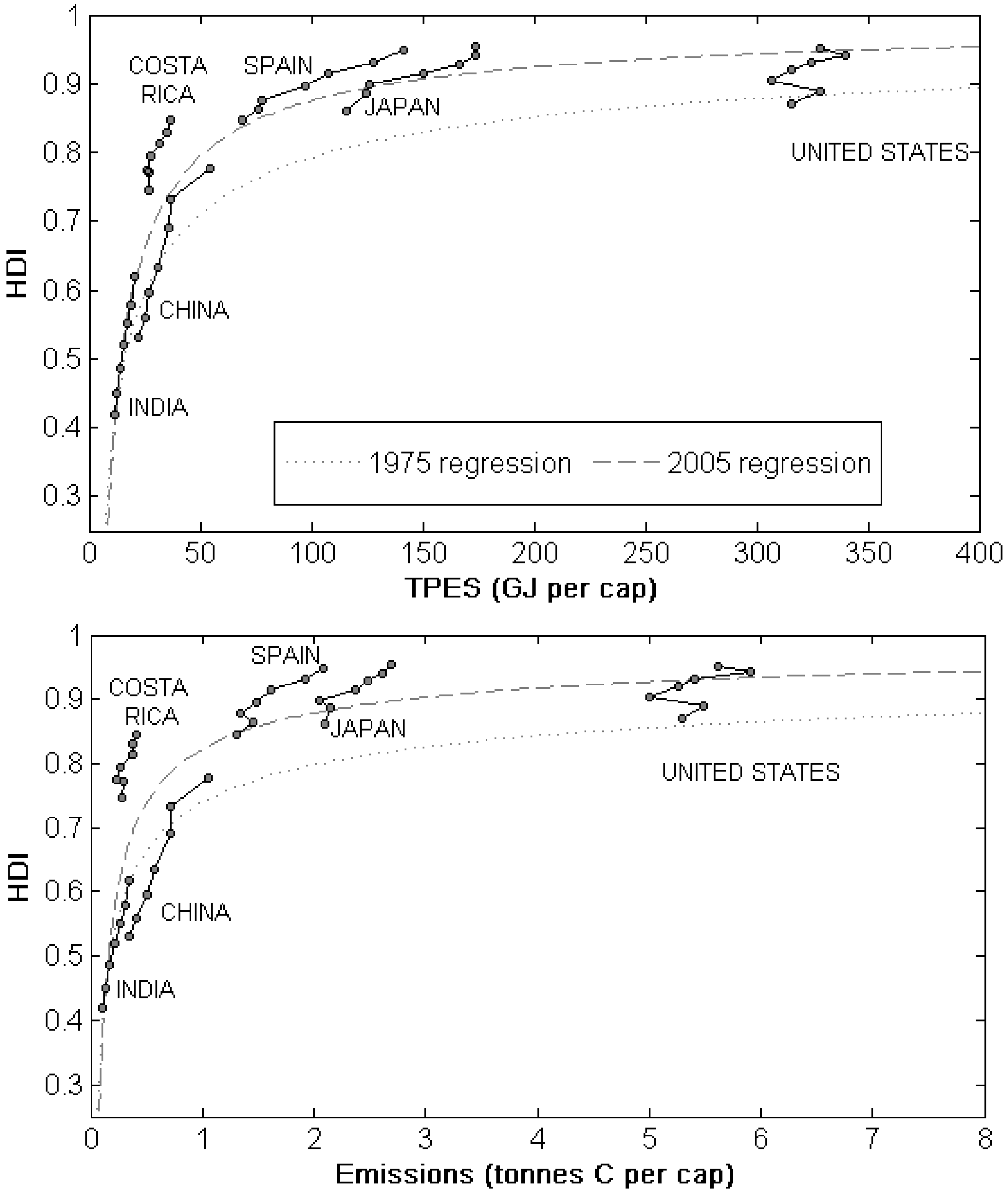
An identical analysis for carbon emissions threshold for human development is shown in Figure 3. Unsurprisingly, the principle features are the same for carbon and energy, despite important national differences in the carbon intensity of energy production. However, the decline in the carbon threshold for high development is even steeper than for energy, a factor of 2.75 rather than 2 in 30 years. This steeper decline is due to a gradual increase in the global energy-to-carbon ratio. Although the steep decline shows signs of slowing, by 2020, the projected carbon emissions are twice the carbon threshold for high development. This systematic decline even without widespread conscious efforts at “decarbonizing the economy” suggests that greater progress may be possible with targeted government efforts and market incentive structures.

Some countries, mostly Latin American, exist in the upper left-hand “Goldemberg Corner” of Figure 1, with primary energy consumption 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 Figure 4. All of the countries improve their HDI significantly, with Cost-Rica, India and the USA maintaining relatively stable energy consumption per capita. The fluctuations in the USA's per capita energy use demonstrate that consumption decreases are possible while still increasing HDI.

There are many candidates for the causes explaining the increase in the energy and carbon thresholds for human development, but some stand out as obvious: efficiency and other 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 (Jochem, 2000). 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). These findings suggest that projections about long-term global improvements of energy and emissions efficiency incorporated in the greenhouse emissions scenarios should not be based purely economic and technical trends of carbon emissions (Pielke et al., 2008).

We anticipate the study of individual countries or country clusters to yield clues as to the above average performance of some, and the under-performance of others. 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).

Fig. 4: Development trajectories of selected countries



Development trajectories of China, Costa-Rica, India, Japan, Spain and the USA in terms of HDI (increasing with time), energy and carbon emissions. The regression curves from Figure 1 for 1975 and 2005 are also shown for reference.

5 Conclusion

The finding of a decreasing energy and carbon threshold for human development is of crucial importance to researchers and policy makers. Rather than insisting that a high level of energy use and carbon emissions are a prerequisite for high living standards, as assumed by the Energy Development Index of the IEA (IEA and OECD, 2004), it would seem that they are ever less necessary, even with continued reliance on fossil fuels. 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 more than sufficient to attain high human development for all.

Rather than biophysical or technical, then, the solutions to energy over-use and under-development now are mostly constrained by economic and political structures; these constraints include pressures for economic growth and competitiveness. The falling energy and carbon thresholds for development will not automatically solve looming climate change, energy supply problems or human development shortfalls. Indeed, 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, such a reduction would allow nations with low HDI 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.

Moreover, further research considering the pathways of individual countries which perform better and worse than the global average, may yield insights into the underlying causes of progress or wastefulness, so that the trend towards higher living standards for lower resource use may be purposefully accelerated by judicious economic and political efforts. Such analysis may be key to guiding progress for both national and international climate and energy policy negotiations, and for strategies to reach the UN's Millennium Development Goals, many of which are dependent on energy service delivery (Wilkinson et al., 2007).

6 Acknowledgements

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7 Appendix A: The Human Development Index

The Human Development Index, or HDI, is the equally weighted combination of three sub-indices, each constructed to go between 0 and 1. The three sub-indices represent life expectancy at birth (LEX), education (EDU) and income (GDP).

$$\textit{(Eq. 1)} \qquad \mathrm{HDI} = \frac{\mathrm{LEX} + \mathrm{EDU} + \mathrm{GDP}}{3}$$

The sub-indices are constructed as follows. LEX is a linear function of the life expectancy at birth, in years. LEX = 1 if the average life expectancy of a country is 85 (or above) and 0 if it is 25 or below.

$$\textit{(Eq. 2)} \qquad \mathrm{LEX} = \frac{\text{Life expanctancy at birth - 25}}{85 - 25}$$

EDU is a combination of two thirds adult literacy rate and one third gross school enrolment ratio, both in percentage.

$$\textit{(Eq. 3)} \qquad \mathrm{EDU} = \frac{2}{3}(\text{Adult literacy rate}) + \frac{1}{3}(\text{Enrolment rate})$$

The GDP sub-index is a logarithmic function of income, defined as GDP per capita, in constant PPP USD, in order to discount higher incomes.

$$\textit{(Eq. 4)} \qquad \mathrm{GDP} = \frac{\log(\mathrm{GDP\ per\ capita}) - \log(100)}{\log(40'000) - \log(100)}$$

With an HDI above 0.8, a country is considered to have high human development, whereas low human development defined to be below 0.5. Table A-1 shows averages and ranges of the life expectancy, literacy, enrolment and income for different HDI value brackets.

For more details on the HDI, see (UNDP, 1990; Anand and Sen, 1994). For information regarding the dataset we used, see (UNDP, 2007).

Table 1: HDI ranges and sub-indicator values, for high, medium and low human development.

		High human development	**Medium human development**	**Low human development**
HDI value		>0.8	0.5-0.8	<0.5
Life expectancy (years)	Mean	75	65	50
	Range	65 - 82	41 - 76	28 - 62
Literacy rate (%)	Mean	97	78	39
	Range	71 - 99	28 - 99	Jul-78
Enrollment rate (%)	Mean	80	63	36
	Range	54 - 100	25 - 94	7 - 78
Average income (2005 PPP$ per capita)	Mean	20,732	5,246	1,347
	Range	5,316 - 40,000	679 - 40'000	366 - 7,843

8 Appendix B: Functional form of energy-HDI relation

The functional form corresponding to “high correlation at low energy and low correlation high energy” is a *hyperbola*, with one asymptote at energy or carbon = 0 and another at HDI = 1. This can be expressed as

$$\textit{(Eq. 5)} \qquad \mathrm{HDI} = 1 - \exp(A_E) \cdot (\mathrm{Energy})^{B_E} \ \text{ and } \ \mathrm{HDI} = 1 - \exp(A_C) \cdot (\mathrm{Carbon})^{B_C}$$

where the “E” subscript on A_E and B_E denotes “Energy”, to distinguish them from the equivalent parameters for carbon emissions, A_C and B_C. Equation 5 can be transformed to a linear fit for the parameters $A_{E,C}$ and $B_{E,C}$ as follows, where log is the natural logarithm:

(Eq. 6) $$\log(1-\mathrm{HDI}) = A_E + B_E \cdot \log(\mathrm{Energy}) \text{ and } \log(1-\mathrm{HDI}) = A_C + B_C \cdot \log(\mathrm{Carbon})$$

Martinez and Ebenhack (2008) suggest a saturation curve is appropriate for the HDI-energy relationship, without however expressing it or fitting it mathematically. Perhaps the most commonly employed function, used by Pasternak (2000), describes the relationship as a *logarithm*:

(Eq. 7) $$\mathrm{HDI} = A_E + B_E \cdot \log(\mathrm{Energy}) \text{ and } \mathrm{HDI} = A_C + B_C \cdot \log(\mathrm{Carbon}).$$

Although the goodness-of-fit parameter R^2 is comparable for the logarithmic and hyperbolic regressions, the logarithm does not respect the absolute maximum of the HDI at 1 and has quadratic residuals. The hyperbolic form is thus superior.

9 Appendix C: Results of energy-HDI and carbon-HDI linear regression

The results of our analysis are the four parameters $A_{E,C}$ and $B_{E,C}$ from 1975 to 2005 at 5 year intervals (see Table C-2). They are determined by Linear Least Squares regression, weighted by country population size, in order for the analysis to be representative of the global system. We thereby avoid giving small countries like Trinidad & Tobago the same weight as China and other large nations.

R2 is the goodness-of-fit parameter for linear least squares: R2 goes from 0 to 1, with 1 signifying a perfect fit. The goodness-of-fit parameter R^2 decreases modestly but continuously over time for both the energy and carbon fits. A potential explanation is that increasing numbers of countries have development pathways which are different from the global average, causing an increasing diversion or even a change in overall functional form.

Table C-2: Regression results for the hyperbolic functional form of HDI vs. energy use and carbon emissions.

Energy	A_E		B_E		R^2
	Value	standard error	Value	standard error	
1975	0.66	(0.07)	-0.48	(0.02)	0.90
1980	0.74	(0.08)	-0.52	(0.02)	0.89
1985	0.79	(0.09)	-0.55	(0.03)	0.89
1990	0.93	(0.10)	-0.59	(0.03)	0.89
1995	1.05	(0.11)	-0.64	(0.03)	0.89
2000	1.12	(0.12)	-0.68	(0.03)	0.89
2005	1.24	(0.15)	-0.72	(0.04)	0.85
2005 only	1.03	(0.13)	-0.66	(0.03)	0.79

Carbon	A_C		B_C		R^2
	Value	standard error	Value	standard error	
1975	-1.34	(0.03)	-0.37	(0.02)	0.85
1980	-1.38	(0.04)	-0.39	(0.02)	0.82
1985	-1.44	(0.04)	-0.41	(0.03)	0.78
1990	-1.51	(0.04)	-0.45	(0.03)	0.78
1995	-1.58	(0.04)	-0.50	(0.03)	0.78
2000	-1.67	(0.04)	-0.55	(0.04)	0.79
2005	-1.72	(0.05)	-0.56	(0.04)	0.75
2005 only	-1.69	(0.04)	-0.46	(0.03)	0.67

The 74 countries for which all data was available for all years are shown in Table C-3.

Table C-3: List of 74 countries for which the data was available for all observation years.

1. ALGERIA
2. ARGENTINA
3. AUSTRALIA
4. AUSTRIA
5. BANGLADESH
6. BELGIUM
7. BENIN
8. BOLIVIA
9. BRAZIL
10. CAMEROON
11. CANADA
12. CHILE
13. CHINA
14. COLOMBIA
15. CONGO
16. COSTA RICA
17. CÔTE D'IVOIRE
18. DENMARK
19. DOMINICAN REPUBLIC
20. EGYPT
21. EL SALVADOR
22. FINLAND
23. FRANCE
24. GHANA
25. GREECE
26. GUATEMALA
27. HONDURAS
28. HUNGARY
29. ICELAND
30. INDIA
31. INDONESIA
32. IRAN, ISLAMIC REPUBLIC OF
33. IRELAND
34. ISRAEL
35. JAMAICA
36. JAPAN
37. KENYA
38. LUXEMBOURG
39. MALAYSIA
40. MALTA
41. MEXICO
42. MOROCCO
43. NEPAL
44. NETHERLANDS
45. NEW ZEALAND
46. NICARAGUA
47. NIGERIA
48. NORWAY
49. OMAN
50. PAKISTAN
51. PANAMA
52. PARAGUAY
53. PERU
54. PHILIPPINES
55. PORTUGAL
56. SENEGAL
57. SOUTH AFRICA
58. SPAIN
59. SRI LANKA
60. SUDAN
61. SWEDEN
62. SWITZERLAND
63. SYRIAN ARAB REPUBLIC
64. THAILAND
65. TOGO
66. TRINIDAD AND TOBAGO
67. TUNISIA
68. TURKEY
69. UNITED ARAB EMIRATES
70. UNITED KINGDOM
71. UNITED STATES
72. VENEZUELA
73. ZAMBIA
74. ZIMBABWE

10 Appendix D: Energy and carbon threshold functions

The results in Table C-2 show an impressively steady trend for the fit parameters A and B, both for energy and carbon. Indeed, the evolution of A_E, B_E, A_C and B_C is extremely well fit with a linear trend: the final result is thus the comprehensive and invertible functions

$$\begin{aligned} \mathrm{HDI}(E,t) &= 1 - \exp[\mathrm{A}_{\mathrm{E},1} + \mathrm{A}_{\mathrm{E},2} \cdot (t - 2000)] \cdot \mathrm{E}^{\mathrm{B}_{\mathrm{E},1} + \mathrm{B}_{\mathrm{E},2} \cdot (t - 2000)} \\ \mathrm{HDI}(C,t) &= 1 - \exp[\mathrm{A}_{\mathrm{C},1} + \mathrm{A}_{\mathrm{C},2} \cdot (t - 2000)] \cdot \mathrm{C}^{\mathrm{B}_{\mathrm{C},1} + \mathrm{B}_{\mathrm{C},2} \cdot (t - 2000)} \end{aligned} \qquad \textit{(Eq. 8)}$$

The time is entered with respect to the year 2000. The eight parameters $A_{(E,C),(1,2)}$ and $B_{(E,C),(1,2)}$ fully and concisely capture the systematic evolution of the relationship between HDI, energy and carbon emissions. These parameters are shown in Table D-4.

Table D-4: Time series regression results for energy and carbon threshold function parameters A and B: $A = A_1 + A_2 * (t\text{-}2000)$ and $B = B_1 + B_2 * (t\text{-}2000)$.

Energy threshold function parameters

$A_{E,1}$		$B_{E,1}$	
1.126	(0.013)	-0.680	(0.004)
$A_{E,2}$		$B_{E,2}$	
0.0197	(0.0009)	-0.0081	(0.0003)
R^2		R^2	
0.99		0.99	

Carbon threshold function parameters

$A_{C,1}$		$B_{C,1}$	
-1.653	(0.008)	-0.529	(0.006)
$A_{C,2}$		$B_{C,2}$	
-0.0132	(0.0005)	-0.0069	(0.0004)
R^2		R^2	
0.99		0.98	

By inverting the HDI expressions in Eq. (8), the following functions for energy and carbon as a function of time and HDI are obtained:

(Eq. 9)

$$\mathrm{E}\,(HDI,t)=\left(\frac{1-HDI}{\exp\left[\mathrm{A}_{\mathrm{E},1}+\ \mathrm{A}_{\mathrm{E},2}\cdot(t-2000)\right]}\right)^{1/\left[\mathrm{B}_{\mathrm{E},1}+\mathrm{B}_{\mathrm{E},2}\cdot(t-2000)\right]}$$

$$\mathrm{C}\,(HDI,t)=\left(\frac{1-HDI}{\exp\left[\mathrm{A}_{\mathrm{C},1}+\ \mathrm{A}_{\mathrm{C},2}\cdot(t-2000)\right]}\right)^{1/\left[\mathrm{B}_{\mathrm{C},1}+\mathrm{B}_{\mathrm{C},2}\cdot(t-2000)\right]}$$

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