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Understanding the role of energy consumption in human development through the use of saturation phenomena

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Abstract

A correlation is presented between the UN human development index and per capita energy consumption for 120 nations. A strong relationship between index values and energy consumption is observed for the majority of the world. Additionally, a distinct secondary trend emerges from the dataset, representing heavy energy exporters such as the Organization of the Petroleum Exporting Countries and some Former Soviet Union nations, among others. The preliminary observation is made that these two trends closely resemble saturation curves, exhibited by a variety of natural phenomena. For the primary trend, three regions are isolated: a steep rise in human development relative to energy consumption for energy-poor nations; a moderate rise for transitioning nations; and essentially no rise in human development for energy-advantaged nations, consuming large amounts of modern energy. These correlations suggest that tremendous gains in human development are possible for the world's poorest, with small incremental access to energy.

Keywords: HDI; Energy consumption; Sustainable development

1. Introduction

Current energy consumption patterns are both physically and socially unsustainable. While the industrialized world faces sweeping energy transitions imposed by an impending decline of petroleum production, much of the non-industrialized world already faces significant energy shortages. And although there is considerable discussion about the timing of 'peak oil,' there is little discussion about the nature of the overall transition to more sustainable energy systems. It seems unlikely that any single source will succeed in claiming a market share comparable to that currently owned by petroleum, let alone the collective fossil fuels. The transitions can be expected to be no more uniform than the current energy consumption patterns, and probably less so.

It will be critical in planning for the transition to understand the energy demand and potential production from various sources in terms of the value added by each source. In other words, real energy demands are not for quadrillion BTUs or kilograms of oil equivalent (kgoe), but for the work or services provided to the end-user. Fuel-wood use, for example, must be heavily discounted for a number of factors. Dependence on it contributes to deforestation in many urban areas of the developing world, crossing the threshold to unsustainable use. Beyond that, fuel-wood and other primary biomass sources only support bare subsistence requirements—showing no promise for supporting any plausible human development. For both environmental sustainability and human development purposes, then, direct consumption of traditional biomass offers very little real energy value added (REVA) (Ebenhack, 2007).

Part of the global energy transition challenge is to enhance REVA resources in the developing world. Even before evaluating the real value of specific energy alternatives, it is important to consider the total energy requirements of the global society. Energy consumption

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has been growing exponentially since recorded data are available. This growth is partially attributable to the needs of an exponentially growing population, but is also partially attributable to the energy demands of increasingly industrialized, urbanized, and mobile societies. The question of when an energy crisis will be manifested is practically moot — half of the world already faces a severe energy shortage. The UN estimates that 1.6 billion people lack any access to electricity. Even more people have limited and/or costly access. Most of these people also lack access to other modern combustion fuels, leaving them largely dependent on low REVA biomass fuels (wood, charcoal, and dung). In addition to the aforementioned impact on deforestation, its use contributes to a variety of respiratory disorders, especially amongst women and children (UNDP, 2005). It essentially prohibits any modern development projects.

It seems reasonable to assume that 'energy-poor' nations seeking to improve their quality of life will need increased access to cleaner, more reliable, and efficient energy sources. Thus, it follows that part of global energy transition planning entails reasonable evaluation of the goals society should set to address the imperative of increasing energy access to people seeking to improve their current conditions. Even if the argument is made that the energy consumption of some of the most affluent nations would be physically impossible to provide to all of humanity, recent consumption patterns by China and India suggest that a realistic energy transitions plan must include enhanced energy development and support the need for increased energy consumption from the developing world.

In this paper, we present recent per capita energy consumption (PCEC) patterns (IEA, 2006) compared with recent quality of life data (UNDP, 2004) from the UN human development index (HDI, a measure of human welfare as a function of a variety of factors) to isolate those nations that have a favorable HDI compared with moderate energy consumption at different stages of development. We also show that when including as large a dataset as possible, two distinct trends present themselves from the set and the character of these trends might be modeled after other saturation phenomena. Focusing on the primary trend, we establish different baselines to which energy-poor nations could strive in order to improve their HDI value. This should lay a foundation for beginning to understand the energy basis to development and what kinds of investments and technologies are necessary for a path to sustainable development.

2. The energy advantage relationship

At the most basic level, energy is required to cook our food, warm us from the cold, and light the dark. Without meeting these needs, survival is directly imperiled. Moving beyond survival, energy becomes an essential component to every aspect of enhanced development: providing motive force for industry; refrigerating medicines, lighting schools, preserving foods, transporting products, and communication.

The correlation between gross domestic product (GDP) and energy consumption has been noted elsewhere (Naseri, 2000). While the relationship is clearly real, it is not overwhelmingly compelling, especially if used as a significant indicator of human welfare or quality-of-life. However, as a handful of other researchers have shown (Smil, 2003; Goldemberg, 2001; Pasternak, 2000; Dias et al., 2006), comparing PCEC to HDI, the relationship becomes undeniable. Indeed, as depicted in Fig. 1, we find that if we isolate the consumption patterns of certain 'special-case' nations (i.e. Organization of the Petroleum Exporting Countries, or OPEC; the Former Soviet Union, or FSU; Trinidad and Tobago; Oman; and Gabon) from the rest of the world where data are available, this correlation is strengthened and two parallel development curves appear. Distinguishing these nations from the rest of the world seems to eliminate what previously has been perceived as 'noise' in the PCEC to HDI dataset in previous investigations and allows clarification to the nature of the two development curves.

2.1. The primary trend (energy advantage nations)

Fig. 2 depicts a recent trend representative of most of the world, which we refer to as the 'energy advantage' or EA. While a moderately satisfactory (and commonly applied) fit may be made using a single logarithmic trend, we propose that the most meaningful analyses of the EA data might be to compare it to a saturation curve, common to a variety of natural processes. Three examples of natural

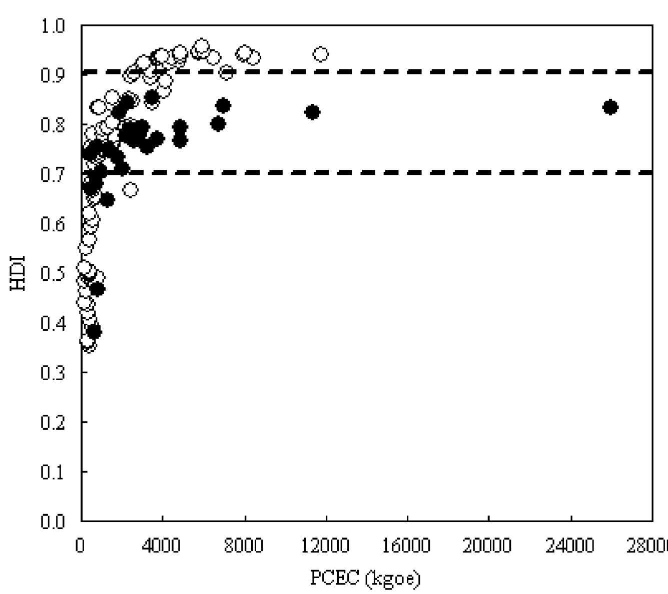

Fig. 1. 2004 UN HDI data versus 2001 PCEC for 120 nations. OPEC, FSU, Oman, Gabon, and Trinidad and Tobago are distinguished from the rest of the world by closed circles. PCEC and UN HDI data are available from the International Energy Agency and the Unite Nations Development Programme, respectively.

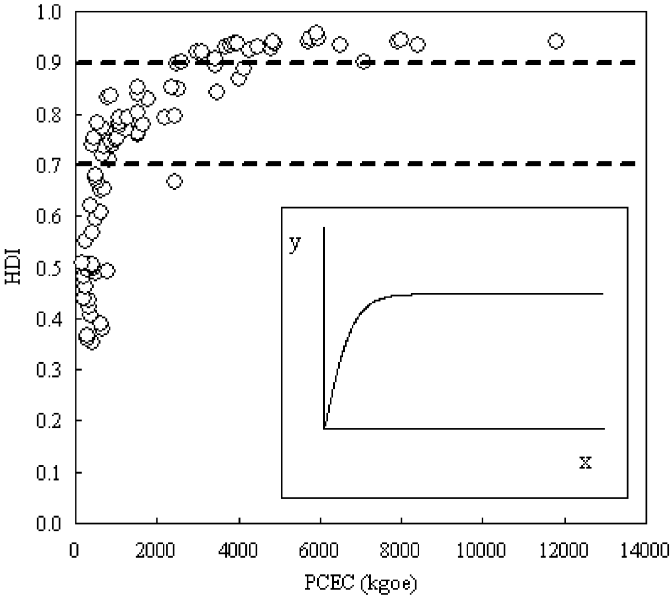

Fig. 2. Primary trend (the energy advantage), represented by UN HDI data versus per capita energy consumption for 90 nations. These data exclude OPEC and many FSU nations, as well as Oman, Gabon, and Trinidad and Tobago. A saturation curve is also presented to highlight the similarities between the simplified mathematical function and the dataset.

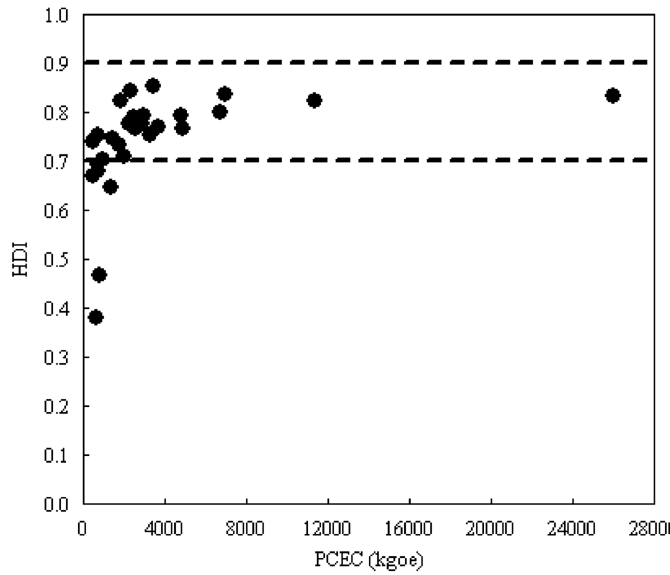

Fig. 3. Secondary trend (major energy export nations), represented by UN HDI data versus per capita energy consumption for 30 nations. The secondary trend includes OPEC and many FSU nations, as well as Oman, Gabon, and Trinidad and Tobago.

processes explained by saturation phenomena that might be analogized to the EA curve are molecular adsorption, ideal operation of a continuous flow stirred tank reactor with dead volume, and oxyhemoglobin dissociation. For the latter process, instead of temperature, pH, and partial pressure of carbon dioxide affecting the character of the curve, perhaps the EA curve is affected by factors such as type of primary energy used (e.g. firewood versus oil and gas), years since sovereignty, percent of resources exported, etc. If an adequate saturation model can be developed to explain this empirical relationship, it could have implications ranging from an explanation of the oil curse, to national energy planning, to informing international aid programs on the types of activities they should pursue in the developing world.

If one does assume saturation behavior of global energy consumption, then there is justification to isolate three regions within the EA. The first, steeply rising region (HDI 0.354–0.7) represents energy-poor nations, and indicates that there is a very strong dependence of human development on increased access to energy. The second region, located near the point of inflection (HDI 0.7–0.9), represents transitioning nations, and indicates a threshold from very poor human development to very high development. The third, leveling off or 'saturated' region (above 0.9) represents energy-advantaged nations residing in the industrialized world, and indicates that little improvement in human welfare can be achieved with greater energy consumption patterns at these very high HDI levels.

Of the many interesting features of the EA, it is striking how absolute the requirement for energy is and how much can be realized from relatively small increments of energy availability at the lowest levels. No country has extremely low HDI with PCEC above 800 kgoe and no country has an HDI above .7 with a PCEC below 400 kgoe. It is also striking how much excess energy is spent by the energy-advantaged nations for no real improvement in quality of life, as measured by HDI. While it is certain that some inefficiencies cannot be recouped as a result of infrastructures currently employed for ground and air transportation, for example, it is also certain that enhanced energy demands will not benefit the populace of these nations as a whole.

2.2. *The secondary trend (energy export nations)*

Fig. 3 shows the secondary saturation-like dataset lying below and to the right of the EA, corresponding to countries that are major net energy exporters (OPEC, Trinidad and Tobago, Oman, and Gabon) and many members of the FSU. Both of these groups represent special circumstances, thus we undertook to filter the data to separate members of the FSU and nations whose net energy exports represented a large share of their GDP. Note that several of the FSU nations also heavily export energy.

The major net energy exporters have an abundance of energy resources. They also tend to have extraordinarily large revenue streams that have, in some cases, been diverted into the private coffers of a few powerful individuals and less so into national development efforts. Indeed it has been shown that there is a strong disconnect between commercial petroleum development for export markets and internal development, dubbed "the oil curse" (O'Neill, 2007; Ross, 2001; Pegg, 2006). The nations of the FSU, on the other hand, have all emerged as independent states a mere 15 years ago. They are struggling, like any newly emergent nation, to develop their own socioeconomic and political structures. Furthermore, the production focus of Cold War Soviet industry contains notorious inefficiencies. We postulate that these factors contribute to depressed HDIs and exaggerated energy consumption in these early years of independence, making FSU nations a special case. Whether or not our causal analysis is accurate, it is clearly true that these nations have a number of factors in common, including a substantial departure from the trend established for the rest of the world. We expect that once an adequate saturation model is developed, this will help explain this observation.

Additionally, an inherent time lag undoubtedly must exist between new energy development for a nation's internal use and improved HDI. HDI can be superficially considered a snapshot of the current state of the nation for which it is measured, for GDP may respond within a year or two (quickly and positively affecting HDI) but infant mortality and literacy would require several years to be profoundly affected. Consider that, even after infrastructure has been built, and schools and hospitals electrified, it still takes some years to see the literacy gains from expanded educational opportunities and the improved lifespan from enhanced medical care. Thus, it may be meaningless to compare PCEC data with HDI data for the same calendar year. We believe that further analyses to characterize this time lag will be useful, both from a theoretical standpoint, to improve the correlation, but from a planning standpoint, to understand the time required to see the most profound benefits. This understanding may be essential for the populace of a developing nation to appreciate the evolving benefits of energy development programs initiated by their governments. Future work could look to the time lags seen in the United States for improvements in the factors contributing to HDI, following the extensive electrification programs of the Roosevelt administration as one example.

3. Factors affecting HDI and the need for modern energy

We see in the primary trend that there exist certain outliers to the bulk of the dataset. They represent nations that either have relatively high or relatively low HDI values compared with their energy consumption, or little improvement in HDI for more energy consumed. There are likely a number of factors affecting a nation's calculated HDI, and each nation's circumstances should be superimposed on any thorough analysis. But, due to the remarkably strong correlation presented here, those with unusually low HDI values relative to their energy consumption may reveal some internal problems. Unusually high HDI values relative to energy consumption may be artifacts of some fortuitous circumstances—or may offer some important guidance for development efforts around the world. Isolating measurable indicators for nations may be useful to assist energy-poor nations to transition to better standards of living. One obvious indicator likely affecting some of this variability is the type of energy used.

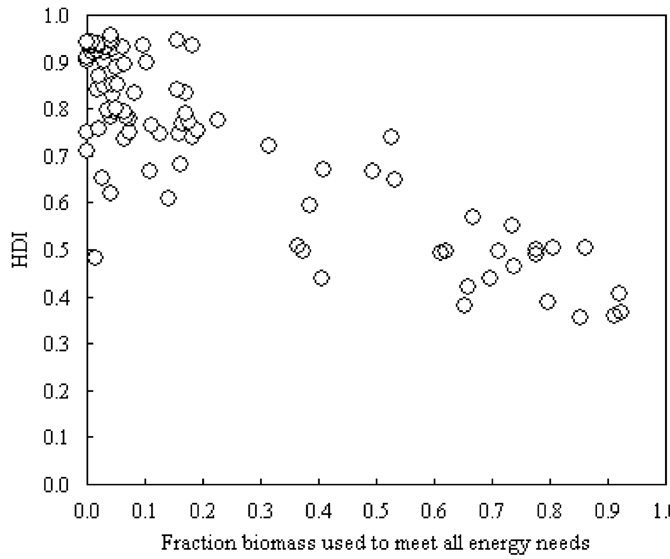

Fig. 4. HDI as a function of fraction biomass used to meet all energy needs for the primary trend. No country with more than 60% biomass dependence achieves better than .6 HDI. Note that a linear correlation trend line fits moderately well to the data ($R^2 = 0.73$). Biomass information available from World Resources Institute.

Fig. 4 shows that for the EA nations, a relatively strong correlation exists between HDI and fraction biomass used as a primary fuel source (World Resources Institute, 2003) Additionally, looking only at the energy-poor 'region' of the EA curve, if one compares HDI to PCEC using total energy versus energy just from modern sources, the correlation between the two becomes significantly improved, as seen in Fig. 5.[1] As the noted energy for development scholar Jose Goldemberg (2001) has stated elsewhere, the "… basic problem of the use of fuelwood for cooking is its dismally low efficiency". Of course, he also points to the significant localized air pollution and its impact on physical heath associated with this inefficiency (Goldemberg, 2001).

4. Modes to a transition

The energy-poor region of the EA is both quite linear and steep. This indicates that relatively small increases in energy availability for these least affluent nations can support very large increases in human welfare. Indeed, the addition of some 400 kg of oil equivalent (kgoe) per capita from modern energy for the people in the poorest nations (with current HDI values less than 0.4) could support a doubling of HDI — well into the transition region. To improve beyond that though, much more energy will be

[1]We have discounted South Africa since they consume enough energy to vault themselves well into the "transition" section of Fig. 3 and indicates other factors influencing their HDI values.

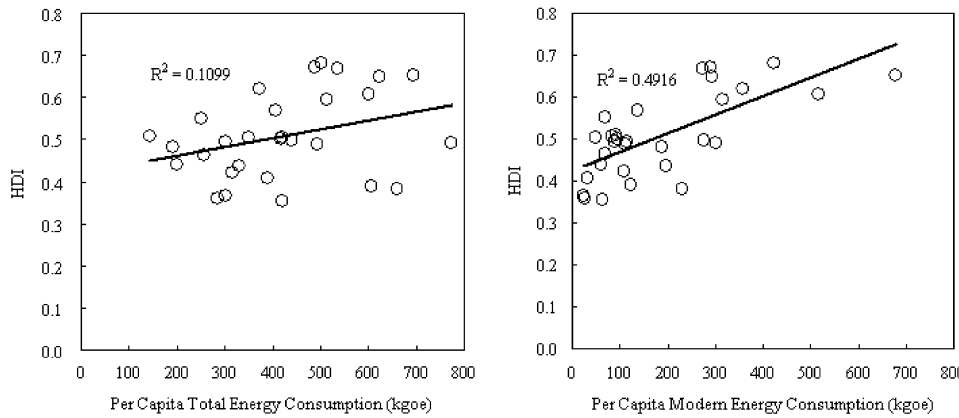

Fig. 5. HDI as a function of per capita total energy consumption and per capita modern energy consumption, respectively, for the energy poor. This is one major indicator for energy's role in human development.

necessary. For example, using the top five performers of the energy-advantaged region, energy-poor nations would require at least an additional 2500 kgoe (per capita) to potentially achieve HDI values near 0.9. Since this goal would require a massive global effort, we argue that focus should first be on securing enough energy access to first enhance human development to the Transition region. In and of itself, this could greatly reduce poverty everywhere. Note that it would only take roughly 7% of the world's modern energy consumption (easily achievable through efficiency improvements alone) for the 1.6 billion people living in the poorest nations (comprising a little less than 25% of the world's population) to have substantially improved quality of life.

Additionally, this extra energy cannot realistically come from traditional biomass. Thus, it seems clear that modern energy sources must be developed in the energy-poor nations to facilitate improved conditions for their people. Traditional biomass in the form of firewood, dung or charcoal will not support the elimination of poverty. To the extent that energy resources are available, the highest value to the people of energy-poor nations is achieved by using their energy resources locally. Fortunately, this meager increase and modern fuels are available to much of the energy poor (in the form of undeveloped fossil fuels and renewables).

4.1. *Preliminary resource evaluation for improved HDI in Moçambique*

Consider the example of Moçambique, which has the lowest HDI value of the 120 nations for which energy consumption data were found. As noted earlier, the populace is heavily dependant on traditional biomass (approximately 85% of total energy consumption). This is true despite possessing the energy resources to provide the basis for a rapid incremental step in development.

Taking 800 kgoe as the target PCEC to move into the transitioning nation region of the EA curve, it is possible to assess the various energy sources to which Moçambique has access. For about the next 50 years, Moçambique has identified coal reserves whose production could supply about 2080 kgoe, or 260% of their current total target per capita energy consumption (Swindells, 2004).[2] Their proved gas reserves could meet over 880 kgoe, or 110% for several decades (EIA, 2005).[3] Additionally, it appears that committing 0.1% of Moçambique's land area for solar power (i.e. photovoltaic) could produce as much as 80 kgoe, or another 10% of the target energy demand. Wind could readily contribute an additional 80 kgoe. While these estimates are very crude, and do not include Moçambique's large hydroelectric or biofuels capacity, they exemplify the opportunity to make large strides in the critical energy sector. This is especially true given their relatively small population.

5. Conclusions

The current study has demonstrated the richness of the information contained in the comparison of HDI to per capita energy consumption. With some simple screening criteria to filter out the OPEC and energy-exporting FSU nations (with known sets of differences from most of the world) the relationship of human development to energy access becomes undeniable. It offers considerable guidance in setting goals for international development. It also raises important questions about the individual nations and what characterizes their individual performance rating. Naturally, factors such as war and civil strife can be expected to play a role in exacerbating the demand for energy, with resulting losses in HDI, rather than gains. These factors

[2]Obviously, a national goal should be to limit coal use and maximize renewable use. However, if the resource is being developed for international markets anyway (it currently is), it is problematic to expect poor nations to not use it themselves.

[3]A significant portion of the current proved, producing gas reserves in Moçambique is committed to an export contract to South Africa. However, on-going exploration is continuing to expand the identified reserves, and the Mozambican government is dedicated to using as much of that gas as possible within the country.

should be further analyzed and will be the primary focus of modeling the transitioning curve to saturation phenomena.

We speculate that some reasons for the good performance in energy-poor nations include amounts and type of foreign aid, relatively stable governments, and/or a substantial reduction in firewood use for primary energy. Among the poor performers, extensive firewood use in Zambia and Moçambique likely inhibits good performance; while in South Africa, political factors (e.g. aftereffects of apartheid) and an extremely large population infected with HIV/AIDS might contribute to substantially low HDI compared with vast amounts of energy consumption (South Africa consumes more energy per capita than two-thirds of the Transition nations). For the energy-advantaged nations, we speculate that some reasons for the good performance include geographic location, cultural choices, and stable governments. Among the poor performers, transportation choices and climate are likely strong factors.

To the extent that energy also contributes to self-sufficiency and the ability to build other industry and social programming, such improvement may also catalyze continued growth and development in nations with reasonably good, responsible governance. It can be the building block for sustained development. The energy mix choices and planning for the future will be essential to making that sustained development *sustainable*, as will integrating the energy development with other key development programs.

The world is facing an increasingly difficult challenge to combat the spread of HIV/AIDS and other diseases, especially in energy-poor nations. While massive efforts have been and continue to be made to combat these illnesses, it is evident that the medicines necessary to defeat them cannot be reliably administered without reliable energy systems available for refrigeration, sterilization, and illumination in hospitals and clinics. Additionally, educational institutions cannot operate reliably at the current level of energy usage in these nations. Until the energy problems affecting over half of the world's population can be addressed, it is likely that these humanitarian efforts will continue to be limited in their success to combat disease and increase quality of life. Analyses such as this one suggest that the term 'energy poverty' is meaningful. Efforts to alleviate global poverty must not ignore the role of energy.

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