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Energy, EROI and quality of life

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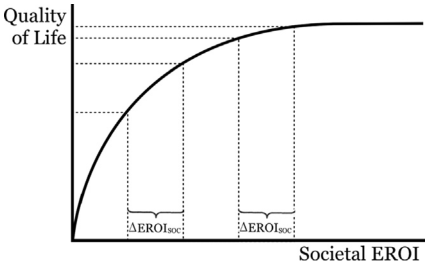
HIGHLIGHTS

- Large quantities of high quality energy appears to contribute to social well-being.
- LEI examines the quantity, efficiency and distribution of energy within the system.
- EROI$_{SOC}$ of $<25{:}1$, <100 GJ/capita and LEI <0.2 point to poor/moderate quality of life.
- A threshold of well-being is: EROI$_{SOC}$ of 20–30:1, 100–200 GJ/capita and LEI 0.2–0.4.
- Improvement in well-being levels off at: EROI$_{SOC}$ $>30{:}1$, >200 GJ/capita and LEI >0.4.

GRAPHICAL ABSTRACT



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ABSTRACT

The near- and long-term societal effects of declining EROI are uncertain, but probably adverse. A major obstacle to examining social implications of declining EROI is that we do not have adequate empirical understanding of how EROI is linked, directly or indirectly, to an average citizen's ability to achieve well-being. To evaluate the possible linkages between societal well-being and net energy availability, we compare these preliminary estimates of energy availability: (1) EROI at a societal level, (2) energy use per capita, (3) multiple regression analyses and (4) a new composite energy index (Lambert Energy Index), to select indicators of quality of life (HDI, percent children under weight, health expenditures, Gender Inequality Index, literacy rate and access to improved water). Our results suggest that energy indices are highly correlated with a higher standard of living. We also find a saturation point at which increases in per capita energy availability (greater than 150 GJ) or EROI (above 20:1) are not associated with further improvement to society.

1. Introduction

Humans, as well as our complex societies, require food energy and now massive amounts of external energy to survive and reproduce. For all organisms it is the net energy, or the energy available to an organism or a society after investments to obtain that energy, that is important, indeed that may be the most important factor in determining the long-term survival and well-being of humans and society (Tainter, 1988; Hall and Klitgaard, 2012). The history of human cultural advancement can be examined from the perspective of the development of energy resources and the evolution of energy conversion technologies. Energy provided by the burning of fossil fuels has fostered the expansion of economic, social and environmental development (Munasinghe, 2002; Ayres and Warr, 2009). The availability of energy and the increased efficacy with which it is used has enabled humans to enhance their comfort, live longer and increase their numbers.

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Top-down macroeconomic analysis suggests that a shift to higher quality fuels, improvements in fuel efficiency driven by higher fuel prices and structural changes in national economies usually result in a decrease in the ratio of energy to gross domestic product (GDP) (at least in conventional terms/units) (Kaufmann, 2004; Hall et al., 2003). Kaufmann (1994) validates this assumption that over time, market signals (prices) tend to reflect the perceived economic usefulness of a fuel (Kaufmann, 1994). Because energy is used directly and indirectly in the production of all goods and services, energy prices have a significant impact on nearly every facet of economic performance. Economic growth models and analyses indicate that decline in the rate of increase in energy availability is likely to have serious effects (Smulders and de Nooij, 2003). In fact, there is a strong correlation between per capita energy use (i.e. energy quantity) and social indicators such as the UN′s Human Development Index (Smil, 2003). However, there has been little work on the relation between energy quality and generally accepted indicators of societal well-being.

1.1. *Quality of energy*

The quality of a unit of energy is essentially the usefulness of that unit of energy to society. The amount of work that can be performed by an available unit of energy (not used directly or indirectly in the acquisition of the next unit of energy) influences the perception of quality but is not the only factor in ascertaining that unit of energy′s usefulness. For example, hydropower creates electricity that has greater economic utility than a similar amount of heat energy (Berndt, 1990). However, electricity is less useful for smelting ore as it would need to be translated into thermal energy for this task and would lose a good deal of its special properties in this process. Energy return on investment (EROI) is one measure for establishing the quality, in this case the net energy available to an organism or society to achieve that organism′s or society′s various ends. EROI is, simply put, the energy gained from a unit of energy spent in the process of obtaining energy (Hall et al., 1979; Cleveland et al., 1984; Murphy et al., 2011). We use EROI as a gauge of the effectiveness of human activity intended to satisfy fundamental physical needs, assist in achieving a sense of mental and psychological well-being, and accomplish the higher aspirations associated with the best of what the human species has to offer. Studies of early human culture (e.g. Lee′s (1969) study of the ! Kung) suggest that hunter gatherers have a relatively large energy surplus (i.e. an EROI of 10:1), which allows them to spend a great deal of time in leisure activities. Just as with the !Kung, the larger the surplus, i.e. the higher the EROI, the greater the societal welfare that can be generated. Hence the higher the EROI of a society, the greater the contributions possible to quality of life.

1.2. *Quantity of energy*

Quantity of energy refers to the total amount of energy that flows into a system (society or nation). Quantity does not take into account the quality of this energy, rather it focuses on the sheer amount of energy available to perform work within that society. Anthropologist White (1959) was among the first to recognize the importance of surplus energy for art, culture, progress and indeed all the trappings of modern civilization. Others, such as sociologist Cottrell (1955) and ecologist Odum (1971, 1973) continued work on the analysis of the relation of energy to societal affluence and well-being. Modern humans invest their own energy plus an enormously larger quantity of fossil fuel to produce food, to generate leisure and to do the plethora of activities and attributes we associate with modern society. Whether increased GDP is required is implicit but not proven: one can imagine a causative chain: higher EROI$\geqslant$higher GDP$\geqslant$higher social well-being.

1.3. *Obtaining energy through trade*

Societies that are net energy producers may be able to supply their own energy needs through using that energy directly. An economy without sufficient domestic fuels of a type that it needs, such as oil for transport, must import these fuels and pay for them using an externally-accepted currency via some kind of surplus economic activity. This is especially the case if and as the nation develops industrially. Oil is usually the fuel of choice. The ability to purchase the oil used to maintain or grow an economy depends upon what an economy can generate to sell to the world, the oil required to grow or produce those products and their relative prices. Assume an economy that depends 100 percent on imported oil (e.g. for agriculture and transportation). Costa Rica is an example. It has no domestic fossil fuels (although considerable hydroelectric power) but has a fairly energy-intensive economy, and to a large degree pays for its imported oil with exported agricultural products e.g. bananas and coffee (Hall, 2000; Leclerc and Hall, 2007). These are commodities highly valued in the world and hence readily sold. They are also quite energy-intensive to produce, especially when produced of the quality that sells in rich countries. Costa Rica′s bananas, for example, require an amount of money equivalent to about half of their dockside purchase price to pay for the oil and petrochemicals required for their production and cosmetic quality (Hall, 2000). These production expenses consume a large portion of the economic "surplus" necessary to generate hard currency to pay for imported petroleum.

1.4. *EROI and the net energy cliff*

Fig. 1 illustrates the possible distribution of energy employed to produce energy (light grey) and the outcome of this process, the energy available to society (dark grey) for various fuel sources ranked according to their EROI values (Murphy and Hall, 2010). As EROI approaches 1:1 the ratio of the energy gained (dark gray) to the energy used (light gray) from various energy sources decreases exponentially (Murphy and Hall, 2010). High EROI fuels allow a greater proportion of that fuel′s energy to be delivered to society, e.g. a fuel with an EROI of 100:1 (horizontal axis) will delivers 99 percent of the useful energy (vertical axis) from that fuel to society (Murphy and Hall, 2010). Conversely, lower EROI fuels delivers substantially less useful energy to society (e.g. a fuel with an EROI of 2:1 will deliver only 50 percent of the energy from that fuel to society). Therefore, large shifts in high EROI values (e.g. from 100 to 50:1) may have little or no impact on society while small variations in low EROI values (e.g. from 5 to 2.5:1) may

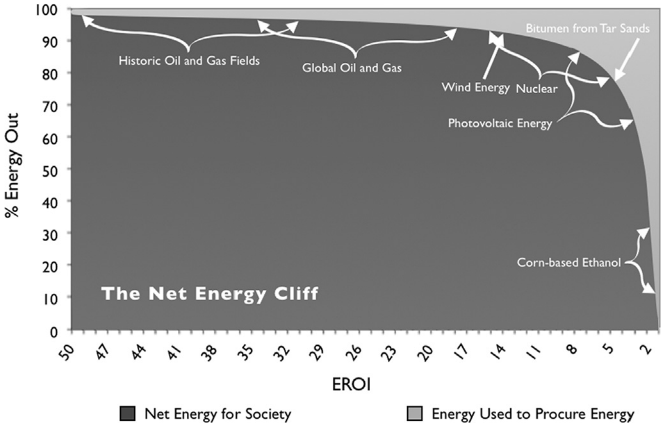

Fig. 1. The "Net Energy Cliff" with EROI expressed as the number of the horizontal axis to one, i.e. 20:1 (figure from Lambert and Lambert (in preparation), adapted from Murphy and Hall (2010)). Concept courtesy of Euan Mearns.

have a far greater and potentially more "negative" impact on society (Murphy and Hall, 2010).

The oil, gas and coal that dominate energy use today probably had EROI values greater than 30:1 to 100:1 in the past (Guilford et al., 2011). Therefore, we did not need to be concerned with their EROIs or the potential political, economic and social ramifications of decreasing EROI values. Recently, we have become aware that the EROI and hence the amount of net energy available to society are in a general decline as the highest grade fossil fuel deposits are depleted (cf. Hall, Lambert and Balogh, this issue). Society has employed Ricardo's "best first principle" and used our highest EROI fuels in the past because they were cheapest to exploit. We are now facing the distinct possibility that the energy from these traditionally high EROI deposits may need to be supplemented or rapidly replaced by new lower-quality deposits or alternative energy sources to avoid future energy constraints and the potential effects of climate change. These "new" energy sources must be sufficiently abundant and have a large enough EROI value to power society, or much more time, effort, and attention must be paid to securing the next year's supply of energy, leaving less money, energy, and labor available for discretionary purposes (Hall et al., 2008). The general decline in EROI for our most important fuels implies that depletion is a more powerful force than technological innovation (Hall et al., this issue).

Because of its relatively high EROI, wind power might be a viable energy source but we must consider also the cost of backup systems. Low EROI synthetic fuels produced from tar sands appear to be economically viable (since most of the investment energy comes from the abundant resource itself) but have high environmental impact (Hall et al., 1986; Smil, 2008). Temperate latitude corn-based ethanol appears to have insufficient EROI to be considered a viable source of net energy without subsidy (Hall et al., 2011). Carbon capture and sequestration (CCS) and the use of hydrogen fuel cells are topics of interest to the energy community but are not considered within this discussion as neither are methods of source energy production (Tainter and Patzek, 2012). The former, CCS, is perceived as a potential method of reducing carbon emissions. The latter is a method for storing and transferring energy. Use of either would, in all likelihood, decrease EROI values.

If the EROI values of traditional fossil fuel energy sources (e.g. oil) continue to decline and non-conventional energy resources fail to provide sufficient quantities of high EROI alternatives, we may be moving toward the "net energy cliff." If EROI continues to decline over time, the surplus wealth that is used to perform valuable but perhaps less essential activities in a society (e.g. higher education, the arts, technologically advanced health care, etc.) will probably decline (Hall et al., 2009; Hall and Klitgaard, 2012). Given this, we believe that declining EROI will play an increasingly important role in our future economy and quality of life (Hall et al., 2008).

1.5. *Quality of life indices*

We hypothesize that access to cheap and abundant fuel is related to an individual's and a society's ability to attain a "higher quality of life." A quantitative assessment of a nation's "average quality of life" requires the use of multidimensional metrics that gauge quantifiable facets of physical and mental well-being. To accomplish this we employ some commonly used indicators of a society's performance—the Human Development Index (HDI), percent of children under weight, average health expenditures per capita, percent of female literacy, Gender Inequality Index (GII), and improved access to clean water for rural communities. These values impart an array of environmental and social features that assist in defining the "quality of life" of the citizens of a nation. Although many scientists, including Cottrell (1955), Odum (1971, 1973), White (1959), and Smil (2003) have clearly developed the importance of net energy to societies, to date, there has been little quantification of the potential impact of EROI levels and per capita energy availability on economies and their likely effects on the "quality of life" in societies other than any number of studies that have found a strong correlation between energy use and GDP (e.g. Cleveland et al., 1984; Smil, 2003).

The human development index (HDI) is a commonly used composite index of well-being and is calculated using four measures of societal well-being: life expectancy at birth, adult literacy, combined educational enrollment, and per capita GDP (FAO, 2012). It has a possible range of 0 to 1. The world's most affluent countries in 2009 had HDI values above 0.7; these include Norway (0.876), with the highest value, followed by Australia (0.864), Sweden (0.824), the Netherlands (0.818), and Germany (0.814). The lowest HDI values, below 0.35, tend to belong to the world's least affluent countries (e.g. Ethiopia (0.216), Malawi (0.261), Mozambique (0.155)).

Two indices of the physical quality of life are percent of children under the age of 5 underweight and per capita health expenditures. Both reflect the impact of various environmental issues (e.g. nutrition). The first is a static value that evaluates current nutrition and overall health while the second represents a nation's access to medical services. Health expenditures per capita, measured in USD, is an index of a population's access to medical treatment. This metric does not measure specifically the benefits received by this medical treatment (e.g. average life expectancy) but can be used as a measure of a society's level of development. Female literacy statistics are considered one measure of gender equality within a society, although it is not sufficiently sensitive to distinguish between women that can read but remain functionally illiterate and those who achieve a greater level of literacy (FAO, 2012; Smil, 2003). Many developing nations fall into the former category. The Gender Inequality Index (GII) is calculated using three measures of gender disparity (reproductive health, employment and labor market participation) and ranges from 0 to 1 (FAO, 2012). The more affluent countries in 2009 had GII values below 0.4. The higher GII values, above 0.4, tend to be found in the world's less affluent countries. The FAO describes access to and control of clean water as one of the most influential for economic asset production and as key to enhancing livelihoods (FAO, 2012). Limited access to clean water for consumption and productive uses exacerbates poverty and negatively impacts quality of life.

Some scientists believe that energy scarcity is associated with constrained food production, poverty, limited production and conveyance of essential goods and services, and also generates strain on other limited environmental resources (e.g. Homer-Dixon, 1999). Although energy and economic assessments provide essential components to our understanding of the implications of reductions in energy flow, they have, thus far, failed to quantify the link between EROI and "quality of life." In this paper, we examine and quantify these linkages and provide a rudimentary paradigm for discussing possible constraints on societal development in a world characterized by a growing population and increasingly constrained availability of our traditional energy resources.

2. Methodology

Energy return on investment (EROI) is the ratio of energy gained from an "energy-gathering" activity compared with the energy invested in that process.

$$\mathrm{EROI} = \frac{ER}{EI} \text{ or } \mathrm{EROI} = \frac{\text{energy returned to society}}{\text{energy invested to get that energy}}$$

In this equation, the units of measure within the numerator and the denominator are the same so that the resulting ratio is dimensionless. The output is expressed as a ratio of units of energy returned for one unit of energy invested. This equation, although appearing simple and straight forward, has many sources of uncertainty (or often more accurately sensitivity) including: variations in the boundaries of the analysis, assumptions regarding the quality of different energy types, and slippage in accuracy and precision that sometimes results when sufficiently comprehensive energy data are not available and it is necessary to translate financial data into energy values. Each of these may influence the calculated output energy resulting in sometimes large variations in the actual operation of the system when compared to theoretical values (Murphy et al., 2011).

2.1. EROI for domestic oil

For oil-producing countries such as the U.S. or Norway (see Hall et al., this issue), or, in principle Nigeria and Yemen, the EROI for an oil field or all industries at the national level can be derived if the cost of production is known: the energy invested in exploration, drilling, pumping, field pressurization and so on, as well as the energy embodied in the purchase of required items such as drill bits, steel pipes and forms, cement and so on (Murphy et al., 2011). Unfortunately that kind of information is almost never available for developing countries (China is an exception: see Hu et al., 2011, 2013).

2.2. EROI for imported oil

We live in a global market and as such most countries are dependent upon imported oil, which must be paid for via foreign exchange derived from exports (or debt). Since such financial data is usually available, the EROI for imported oil ($\mathrm{EROI_{IO}}$) can be derived with a moderate degree of accuracy. The EROI for imported oil is the ratio between the energy value of the amount of fuel purchased with a US dollar relative to the amount of oil required to generate a US dollar's worth of goods and services (GDP). US Dollars (or Euros) are necessary since most oil companies do not accept local currencies. The quantity of the goods or services that must be generated to attain a unit's worth of oil (e.g. barrels for oil) depends upon the relative price of the oil versus those of exported commodities.

We begin our analysis with Kaufmann (in Hall et al., 1986), who derived an explicit method to assess quantitatively the EROI of imported oil (see Eq. (1)). The concept is that the EROI for imported oil depends upon what proportion of the energy content of an imported dollar's worth of oil is needed to generate a dollar from the export of commodities generated domestically. King (2010) developed a metric similar to Kaufmann's $\mathrm{EROI_{IO}}$ called the energy intensity ratio (EIR) and calculated it for various industrial fuels in the US over time. The results of his 2010 study support his contention that the EIR is able to act as a proxy for the EROI for individual fuels.

Pakistan, for example, imported an estimated 126.4 million barrels of oil in 2009 (CIA, 2012), which cost the country (i.e. its various buyers) some 7.5 billion USD (EIA, 2012a). To get these dollars, Pakistan exported 20.1 billion dollars' worth of various commodities (The World Bank, 2012), such as textiles and clothing. That year, the economy of Pakistan used on average about 24 MJ of energy from all sources per dollar of economic production as a nation. We assume that it exports a range of products that require an average amount of energy per dollar to produce. Thus to get 7.5 billion dollars to buy its oil, Pakistan had to use some 180 million GJ of energy (7.5 billion dollars times 24 MJ/dollar) to run its farms, factories and so on, an amount equal to some 30 million barrels of oil. Thus it took about one barrel of oil, used in Pakistan's general economy, to generate enough dollars from external sales to buy about 4 barrels of oil. Hence the EROI for imported oil for Pakistan in 2009 was about 4:1.

Table 1
Price per unit of fuel (E_P) in 2009.

Fuel	Price per unit of fuel	Source
Coal	10 to 150 USD/t	EIA (2012b)
Oil	59 USD/bbl	The World Bank (2012)
Natural gas	4.19 USD/tcf	EIA (2012c)
Combustable renewables	52 USD/t (Green wood)	USDA (2012)
Primary energy	0.1 USD/kW	BP (2012)

2.3. EROI for a society

To test our hypothesis, that EROI is correlated with quality of life, we compare the EROI of a society ($\mathrm{EROI_{SOC}}$) at a national level for imported and domestically produced fuels with indices of human development. We also compare per capita energy consumption with these indices. Since there is no existing method for determining the EROI at the national or societal level, we have developed a proxy method by extending Kaufmann's theory to include all fuel sources, domestic and imported that a nation uses. This method relies in part on King and Hall's (2011) finding that there is a relation between EROI and fuel prices: the lower the EROI the higher the fuel price. We expand Kaufmann's methods for imported fuels (discussed above) to include the energy delivered to society from the use of all fuels: domestic and imported coal, oil, natural gas, combustible renewables and waste, and primary electricity generated by hydropower, nuclear and other alternative energy sources.

We assume for this initial analysis an open competitive energy market, available to all economic actors and equal opportunity for entry into that market. Hence the price of fuel (e.g. US dollars per unit of energy) is assumed to be about the same for each country examined (Table 1). For energy producing nations, energy invested in the extraction of future energy is assumed to be included within the price of the fuel. Financial benefits associated with the sale of fuels produced are assumed to be included in that country's GDP.

In a sense what we are doing is examining the ratio of the useful chemical or electrical energy in a fuel to its embodied energy, or energy required to make it. For example, for a Gigajoule of coal (at an EROI of 50:1) roughly 0.02 GJ of energy is required to produce it. For oil (at an EROI of 10:1) it would be about 0.1 GJ, five times more. The price we pay for fuel appears to reflect basically the embodied energy in a fuel, not the chemical or electrical energy content (e.g. for crude oil at EROI of 10:1: 0.61 GJ embodied per barrel=610 MJ, divided by \$100 per barrel=6.1 MJ/USD). Basically we pay for the energy required to produce or supply a dollar's worth of fuel at about the same rate as for commodities in general. Thus in the US in 2012 we use about 7 MJ to generate an average dollar's worth of GDP, and use roughly the same quantity of energy to generate a dollar's worth of coal (12.7 MJ/\$) or oil (6.1 MJ/\$). Hence we use roughly the same amount of energy to generate a dollar's worth of fuel as to generate an average dollar's worth of all goods and services.

In the case of $\mathrm{EROI_{SOC}}$, the numerator (ER) is composed of a nation's GDP (in USD) multiplied by the MJ per unit of energy used in the generation of that GDP, which is the output energy that society is described as having. The denominator (EI), the energy invested in order to produce the energy output, is composed of the total energy consumed by that nation in a given year (in MJ) multiplied by dollars per unit spent in the acquisition of that fuel. Thus our model for the EROI of all thermal fuels used in the

Table 2
Energy (MJ) per unit of fuel (E_T).

Fuel	Energy per unit of fuel	Source
Coal	4,882 to 29,107 MJ/t	EIA (2012a)
Oil	5,455 to 6,521 MJ/bbl	EIA (2012a)
Natural gas	945 to 1372 MJ/cf	EIA (2012a)
Combustable renewables	5,702 MJ/t (Green wood)	USDA (2012)
Primary energy	3.6 MJ/kW	BP (2012)

Table 3
Variables identified in Eqs. (1)–(3).

Variables	Meaning	Unit
E_T	Total energy consumed by a society	MJ
GDP	Gross domestic product	USD
E_U	Energy per unit of fuel	MJ
P	Price per unit of fuel	USD
η	Ratio of net energy contribution	n.a.

production of GDP for a given national economy is similar to Kaufmann's model for the EROI of imported fuels but includes all fuels in relation to the efficacy of the entire economy. We use a modified version of the specification described in Section 2.1 to express the societal EROI ($\mathrm{EROI_{SOC}}$). We start with Kaufmann's (1986) equation:

$$\mathrm{EROI_{IO}} = \frac{E_{U\,\mathrm{(Oil)}}}{(E_T/\mathrm{GDP}) \times E_{P\,\mathrm{(Oil)}}} = \frac{ER}{EI} \tag{1}$$

where: $\mathrm{EROI_{IO}}$ is equal to the energy content of a barrel of oil divided by the economic intensity of an economy (E_T divided by GDP, in which E_T is total energy, GDP is in 2009 USD (The World Bank, 2012)) multiplied by the price per barrel of oil.

$$\mathrm{EROI_{IO}} = \frac{\mathrm{GDP} \times E_{U\,\mathrm{(Oil)}}}{E_T \times E_{P\,\mathrm{(Oil)}}} = \frac{ER}{EI}$$

$$\mathrm{EROI_{IO}} = \frac{\mathrm{GDP}}{E_T} \times \frac{E_{U\,\mathrm{(Oil)}}}{E_{P\,\mathrm{(Oil)}}} = \frac{ER}{EI} \tag{2}$$

Next we further delineate Kaufmann's (1986) equation into economic efficiency (GDP divided by E_T) and the energy content price differential for oil (E_U divided by E_P).

$$= \frac{\mathrm{GDP}}{E_T} \times \frac{E_{U1} + E_{U2} + E_{Un}}{E_{P1} + E_{P2} + E_{Pn}} = \frac{ER}{EI}$$

$$\mathrm{EROI_{SOC}} = \frac{\mathrm{GDP}}{E_T} \times \frac{\eta_1 E_{U1} + \eta_2 E_{U2} + \eta_\eta E_{Un}}{\eta_1 E_{P1} + \eta_2 E_{P2} + \eta_\eta E_{Pn}} = \frac{ER}{EI} \tag{3}$$

Next we extend the concept of $\mathrm{EROI_{IO}}$ to derive the energy returned to society from n units of energy. We adjust the energy content price differential to include the energy price and content for all energy sources available. We then weight the energy content and price by its contribution to the society being studied (Eq. (3)) (such that the energy price and energy content per unit of fuel is weighted by their net contribution to the total annual energy consumption for each national economy, E_U is the energy (MJ) contained in a unit of energy (Table 1) and E_P is the price (2009, USD) per unit of energy (Table 2)). This value ($\mathrm{EROI_{SOC}}$) represents the thermodynamic difference for each fuel and its contribution to the production of goods and services in a given year for a nation's economy Table 3.

2.4. Multiple regression analysis

$\mathrm{EROI_{SOC}}$, as a single measure of an energy system, is capable of addressing the quality of energy delivered per unit of energy used to get it, but not the total quantity of energy used by that system. Both $\mathrm{EROI_{SOC}}$ and energy per capita appear to be correlated with quality of life indices, however, there is essentially no correlation between these two independent measures of energy availability (Fig. 2).

Correlation coefficient values are calculated on a partial log scale. We performed a multiple regression analysis of $\mathrm{EROI_{SOC}}$ and energy use per capita vs. the dependent variables listed in Table 4 (e.g. HDI), $y = B_0 + B_1(\mathrm{EROI_{SOC}}) + B_2(\text{energy use per capita})$, to determine if using both $\mathrm{EROI_{SOC}}$ and energy per capita may be a more potent means of explaining the linkages between energy use and social indicators of quality of life than using $\mathrm{EROI_{SOC}}$ and energy per capita in a linear (additive) way in a regression model.

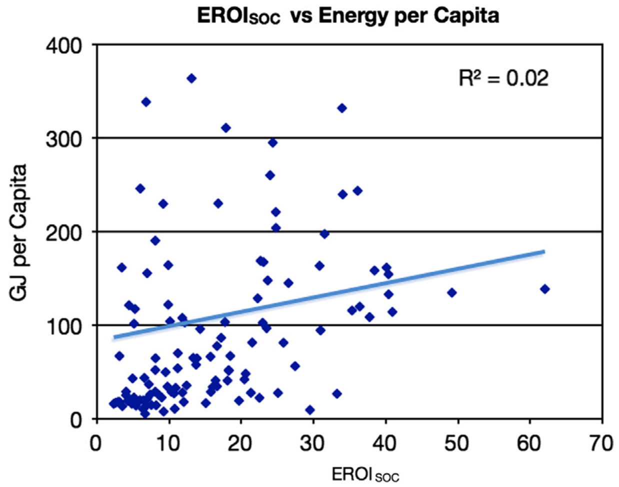

Fig. 2. Comparison of per capita energy consumption with $\mathrm{EROI_{SOC}}$ values showing the independence of these two measures of energy supply (The World Bank, 2012).

Table 4
The coefficient of determination (R^2) for correlation of various measures of energy availability and quality of life indices.

Social indicators	$\mathrm{EROI_{IO}}$	$\mathrm{EROI_{SOC}}$	Energy per capita	Multiple regression[b]	GDP per capita[c]
HDI	0.38	0.55	0.49	0.84	n.a.
% Children underweight	0.07	0.21	0.30	0.44	0.49
GII	0.36	0.52	0.45	0.79	0.73
% Female literacy	0.05	0.22	0.31	0.26	0.51
Health expenditure[a]	0.60	0.57	0.41	0.74	0.79
Improved rural water source	0.24	0.38	0.33	0.52	0.52
GDP per capita[c]	0.52	0.49	0.16	0.78	n.a.

[a] Correlation coefficient values for average health expenditures per capita are calculated using a linear scale.

[b] Adjusted R^2 values reported for multiple regression of the natural log of $\mathrm{EROI_{SOC}}$ and energy per capita (unless otherwise specified).

[c] GDP per capita (in current USD) based on purchasing power parity (PPP).

2.5. Lambert energy index

We developed the Lambert Energy Index (LEI) in an attempt to account for the quality, quantity and distribution of energy delivered to a society more fully. LEI is a composite statistic combining Energy Return on Investment (for society), energy use per capita, and the Gini-Index of income distribution. The explicit purpose of LEI is to shift the focus of the analysis of the factors that determine human well-being from traditional economics to an energy-centered biophysical basis. LEI is not a substitute for existing economic metrics but a new tool for understanding the impact of energy on other social indicators. The LEI combines three factors:

- Energy efficiency of an economic/societal system: $\mathrm{EROI}_{\mathrm{SOC}}$
- Average energy use per capita: GJ per capita
- Income (Energy) Distribution: Gini-Index

We transformed the above variables into a unit-less index between 0 and 1 using the following formula:

$$X_{\mathrm{index}} = \frac{X - X_{\mathrm{min}}}{X_{\mathrm{max}} - X_{\mathrm{min}}}$$

To ensure that all variables have equal weighting we normalized the Gini-index to zero to one, similar to the other two indices (0 being the least energy available to the society and 1 being the most). LEI is generated by taking the geometric mean of the three normalized indices ($\mathrm{EROI}_{\mathrm{SOC}}$ (a measure of the quality of energy delivered per unit of energy use in the production of goods and services), GJ per Cap (the total quantity of energy available per person) and the Gini-index (we assume that the Gini-index of income distribution is a proxy indicator of energy distribution within an economy)):

$$\mathrm{LEI} = \sqrt[3]{\mathrm{EROI}_{\mathrm{SOC(index)}} \bullet \mathrm{GJ\ per\ Capita}_{\mathrm{(index)}} \bullet (1 - \mathrm{Gini}_{\mathrm{(index)}})}$$

3. Results

3.1. Energy availability and quality of life

We find that many indices of human social well-being are well correlated with indices of energy availability ($\mathrm{EROI}_{\mathrm{IO}}$, $\mathrm{EROI}_{\mathrm{SOC}}$, energy per capita and multiple regression adjusted R^2 values) and, as expected, GDP per capita (Table 4). We also find that these quality of life indices are as well correlated with a composite index of energy use and distribution, LEI as they are with GDP. Hence it appears that the quantity, quality and distribution of energy are key issues that influence quality of life.

The higher R^2 generated in the multiple regression analysis suggests that using $\mathrm{EROI}_{\mathrm{SOC}}$ and energy per capita in a linear (additive) way in a regression model may be a more potent means of explaining the relation between energy use and social indicators of quality of life than using $\mathrm{EROI}_{\mathrm{SOC}}$ and energy use per capita individually. LEI values appear to have similar R^2 as those found in the multiple regression analysis of $\mathrm{EROI}_{\mathrm{SOC}}$ and energy use per capita.

3.1.1. Human development index

A plot of the HDI vs. $\mathrm{EROI}_{\mathrm{SOC}}$ gives a saturation curve (Fig. 3a). The coefficient of determination (R^2) of 0.55 is slightly higher with $\mathrm{EROI}_{\mathrm{SOC}}$ than with energy use per capita (Fig. 3b). Nations with $\mathrm{EROI}_{\mathrm{SOC}}$ values below 15:1 have HDI values below 0.7 (excluding thermal heat-rich Iceland). Nations with HDI levels above 0.7 have national $\mathrm{EROI}_{\mathrm{SOC}}$ values above 15:1 (Fig. 3a). Nations using less than 50 GJ of energy per capita remain consistently below the 0.75 HDI achieved by “wealthy” nations (Fig. 3b). The correlation appears to saturate at about 150 GJ per capita. High HDI values (above 0.75) appear possible with as little as 120 GJ per capita energy use. The adjusted R^2 value of 0.84 is considerably higher for a multiple regression than for either $\mathrm{EROI}_{\mathrm{SOC}}$ or energy use per capita (Table 4). The multiple regression results in the prediction equation: HDI=0.113 LN($\mathrm{EROI}_{\mathrm{SOC}}$)+0.112 LN(energy use per capita)−0.176 which indicates that HDI is predicted to increase 0.113 when the natural log of $\mathrm{EROI}_{\mathrm{SOC}}$ increases by one, increase by 0.112 when the natural log of energy use per capita goes up by one, and is predicted to be −0.176 when both $\mathrm{EROI}_{\mathrm{SOC}}$ and energy use per capita are zero. HDI is likewise highly correlated (R^2=0.84) with LEI. Nations with LEI values below 0.15 appear to have a nearly linear improvement in HDI for each incremental increase in LEI. Nations with LEI values below 0.40 consistently have HDI values below 0.75. Nations with LEI values above 0.4 have HDI levels above 0.75 (Fig. 3c).

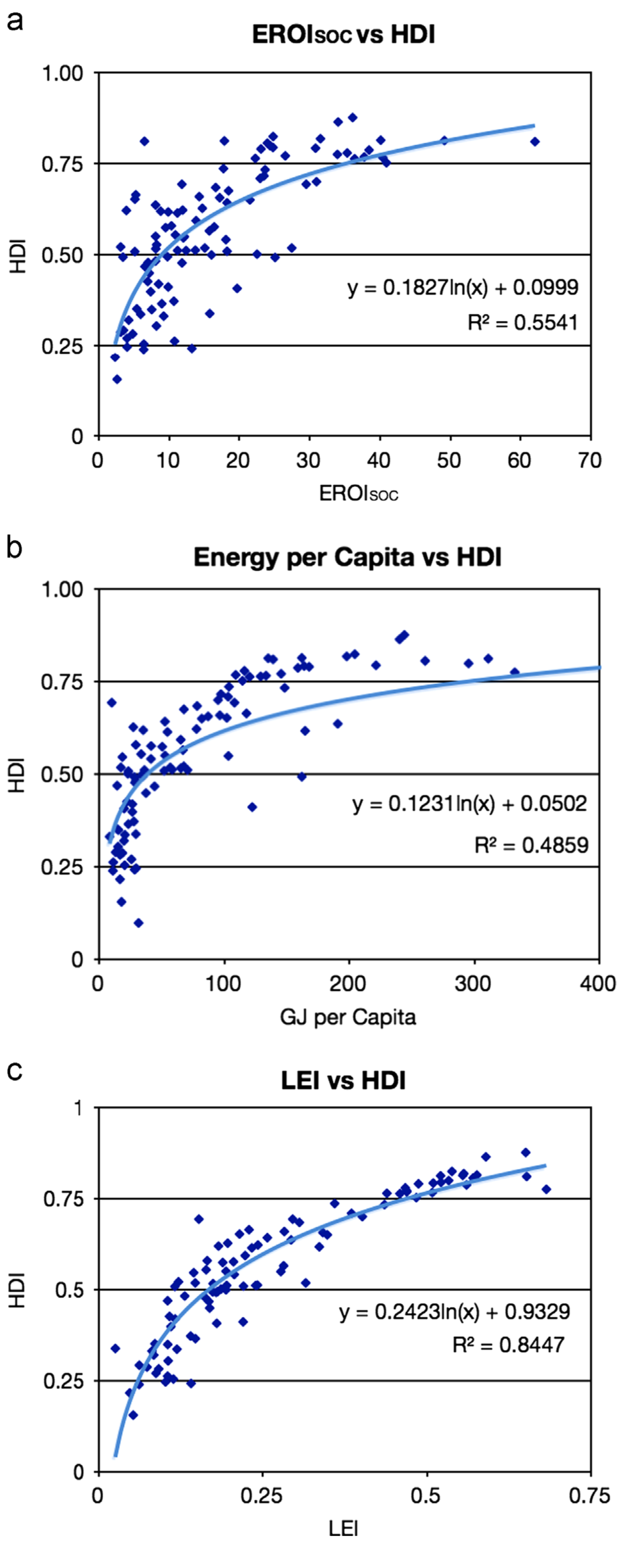

Fig. 3. Comparison of HDI with (a) $\mathrm{EROI}_{\mathrm{SOC}}$, (b) energy use per capita and (c) LEI values (The World Bank, 2012; EIA, 2012a; FAO, 2012).

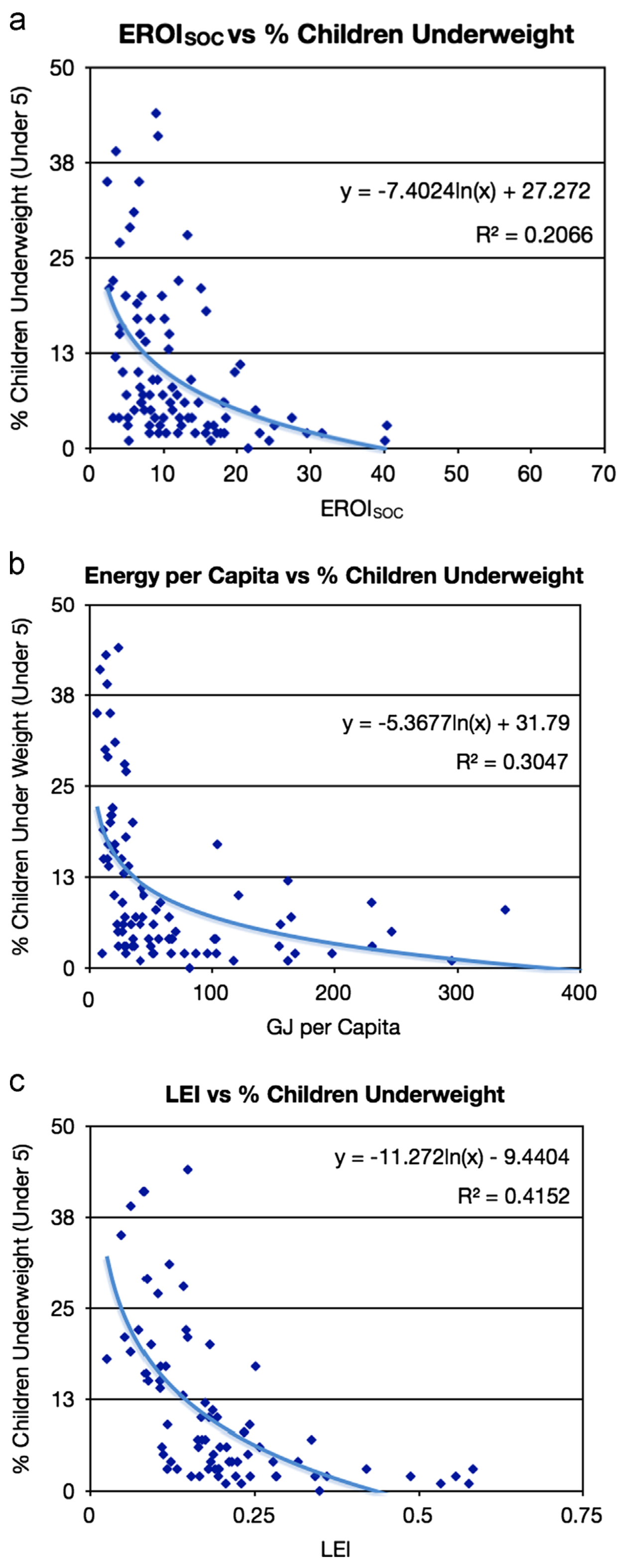

Fig. 4. Comparison of percent of children underweight (under 5) with (a) $\mathrm{EROI}_{\mathrm{SOC}}$, (b) energy use per capita and (c) LEI values (The World Bank, 2012; EIA, 2012a; FAO, 2012).

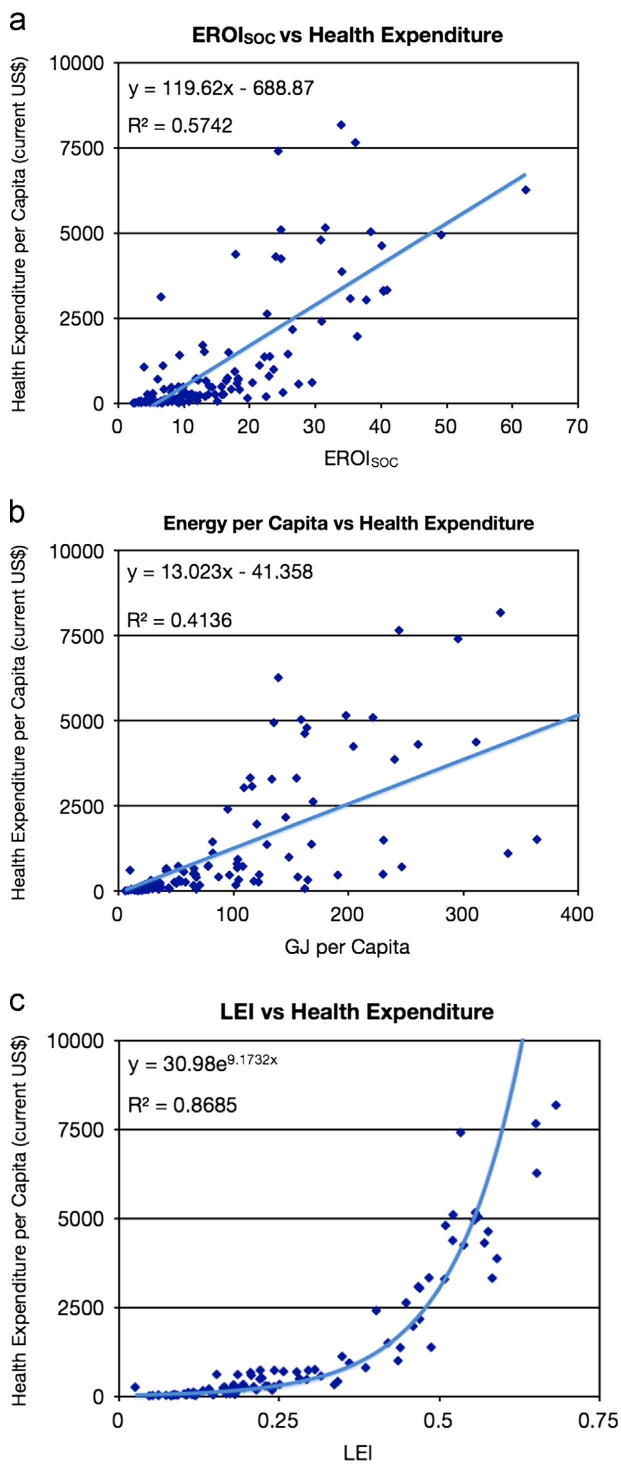

Fig. 5. Comparison of average per capita health expenditure (current USD) with (a) $\mathrm{EROI}_{\mathrm{SOC}}$, (b) energy use per capita and (c) LEI values (The World Bank, 2012; EIA, 2012a; FAO, 2012).

3.1.2. Energy and percent of children underweight (under 5)

Nations with a national $\mathrm{EROI}_{\mathrm{SOC}}$ below 15:1 tend to have greater than 12 percent of their children underweight. Few countries with high national $\mathrm{EROI}_{\mathrm{SOC}}$ values (above 20:1) have underweight children and hence are not plotted in Fig. 4a (this may be partly responsible for a low correlation of 0.20). Countries with $\mathrm{EROI}_{\mathrm{SOC}}$ values above 20:1 are characterized by less than 5 percent of their children underweight (Fig. 4a). Countries that use greater than 100 GJ of energy per capita tend to be more prosperous and have the lowest percent of children underweight (below 12 percent) (Fig. 4b). Countries that use more than 200 GJ of energy per capita, however, do not appear to have a corresponding decrease in percent of children underweight suggesting that increased per capita energy consumption, in excess of 100 GJ, has little or no influence on the percent of children, under the age of 5, who remain underweight (Fig. 4b). A multiple regression analysis shows a higher correlation (adjusted $R^2=0.44$, Table 4). The prediction equation generated is Percent Children Underweight$=-5.78$ LN(EROI_{SOC})-6.11 LN(energy use per capita) $+46.4$. As is the case with other indices, the preceding equation extends beyond the fixed boundaries of the index, in this case spanning from 0 to 100 percent). The correlation between LEI and percent of children underweight is stronger than the relation between EROI_{SOC} or energy use per capita and percent children underweight. There is little difference between the R^2 values for LEI and percent children underweight and the multiple regression above (Fig. 4c). Nations with LEI values greater than 0.25 have less than 13 percent of their children under the age of five underweight.

3.1.3. Energy and health expenditure per capita

There is correlation between national EROI_{SOC} and average per capita health expenditure (Fig. 5a). Countries with a low EROI_{SOC} tend to have low-average health expenditure per capita (e.g. Mozambique: EROI_{SOC} of 2.6 and average health expenditure of 24.70 USD) and similarly, countries with a high EROI_{SOC} have a high health expenditure per capita (e.g. Norway: EROI_{SOC} of 36:1 and average health expenditure of 7660 USD) (Fig. 5a). Average per capita health expenditure is also correlated with energy use per capita (R^2 value of about 0.41) (Fig. 5b). The adjusted R^2 value of 0.74 is much higher for a multiple regression analysis than with either EROI_{SOC} or energy use per capita individually (Table 4). The multiple regression results in the prediction equation: average health expenditure per capita$=106$ (EROI_{SOC})$+7.47$(energy use per capita)-1187. There is a high correlation between LEI and average per capita health expenditure (R^2 value of about 0.87) (Fig. 5c). There is an exponential relation between per capita health expenditures and increased energy availability.

3.2. Energy and female literacy rate (% of females ages 15 and above)

Countries with a high EROI_{SOC} have high female literacy rates and countries with low EROI_{SOC} may have either high (e.g. Kazakhstan, EROI_{SOC} 10:1 and 99.6 percent female literacy) or low (e.g. Senegal, EROI_{SOC} 11:1 and 38.7 percent female literacy) literacy values (Fig. 6a). Unfortunately large gaps in the data exist for high EROI_{SOC} nations and it is possible that our low correlation between national EROI_{SOC} and female literacy rates (0.22) is at least partially due to incomplete data needed to establish trends. The correlation between adult female literacy and energy per capita is low because high levels of female literacy occur in countries at nearly all levels of energy per capita (Fig. 6b). However, low female literacy rates are found only in countries that use less that 75 GJ per capita. Multiple regression analysis results in a low adjusted R^2 value of 0.26; this is below the correlation $R^2=0.31$ found for energy use per capita individually. Percent female literacy is more strongly correlated with LEI and also saturates at high LEI (Fig. 6c). Nations with LEI values above 0.25 have high female literacy.

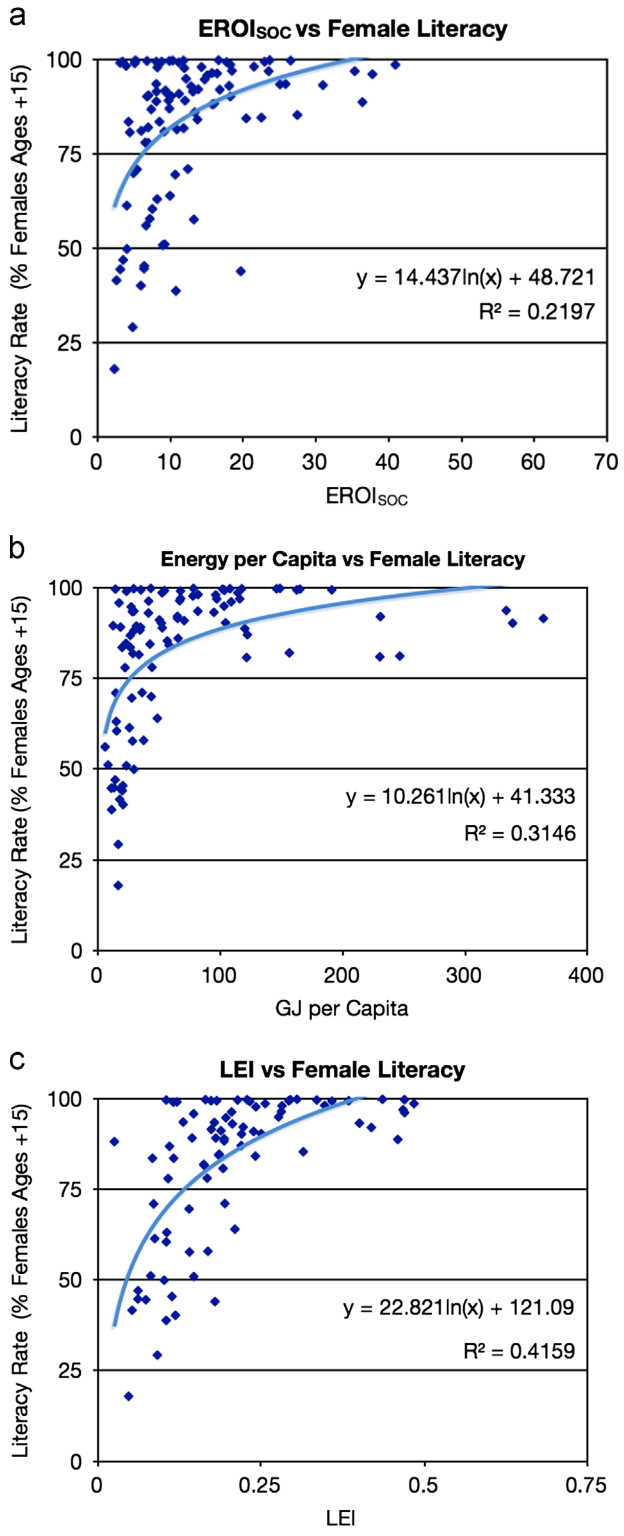

Fig. 6. Comparison of percent of adult female literacy (females ages 15 and above) with (a) EROI_{SOC}, (b) energy use per capita and (c) LEI values (The World Bank, 2012; EIA, 2012a; FAO, 2012).

3.2.1. Energy and gender inequality index

GII is correlated more strongly with EROI_{SOC} than average per capita energy suggesting that EROI_{SOC} is a more robust indicator (or perhaps even a determinant) of a nation's gender equality (Fig. 7a). As with previous indices described in this section, high GII corresponds with low EROI_{SOC} values. GII values vary widely for nations with moderate EROI_{SOC} values (between 20 and 30:1). GII values are low in nations with high EROI_{SOC} values. As with many social indices, GII saturates when EROI_{SOC} values are 30:1 or greater (Fig. 7a). All countries with low per capita energy use have high GII values (Fig. 7b). All countries (except Saudi Arabia) with high per capita energy availability tend to have low GII values. As with most social indicators, no additional increase occurs for countries with greater than 100–150 GJ per capita energy consumption (Fig. 7b). As with HDI, a multiple regression analysis of the relation between EROI_{SOC} and energy use per capita vs. GII shows a high correlation of 0.79. The prediction equation

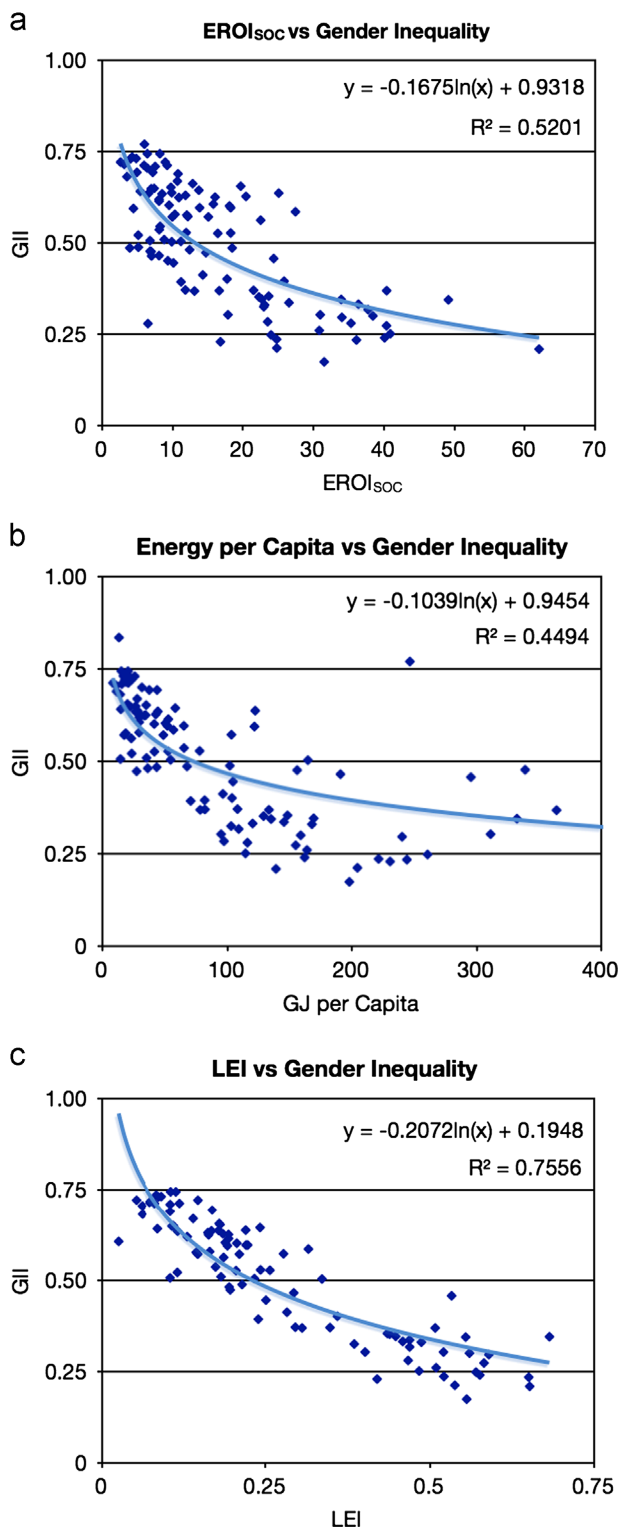

Fig. 7. Comparison of Gender Inequality Index with (a) $EROI_{SOC}$, (b) energy use per capita and (c) LEI values (The World Bank, 2012; EIA, 2012a; FAO, 2012).

is: $GII = -0.098\ LN(EROI_{SOC}) - 0.096\ LN(\text{energy use per capita}) + 1.15$ indicating that GII is predicted to decrease by 0.098 when the natural log of $EROI_{SOC}$ increases by one, decrease by 0.096 when the natural log of energy use per capita increases by one, and is predicted to be 1.15 when both $EROI_{SOC}$ and energy use per capita are zero. The R^2 value generated in the multiple regression analysis discussed above is similar to the R^2 value generated when

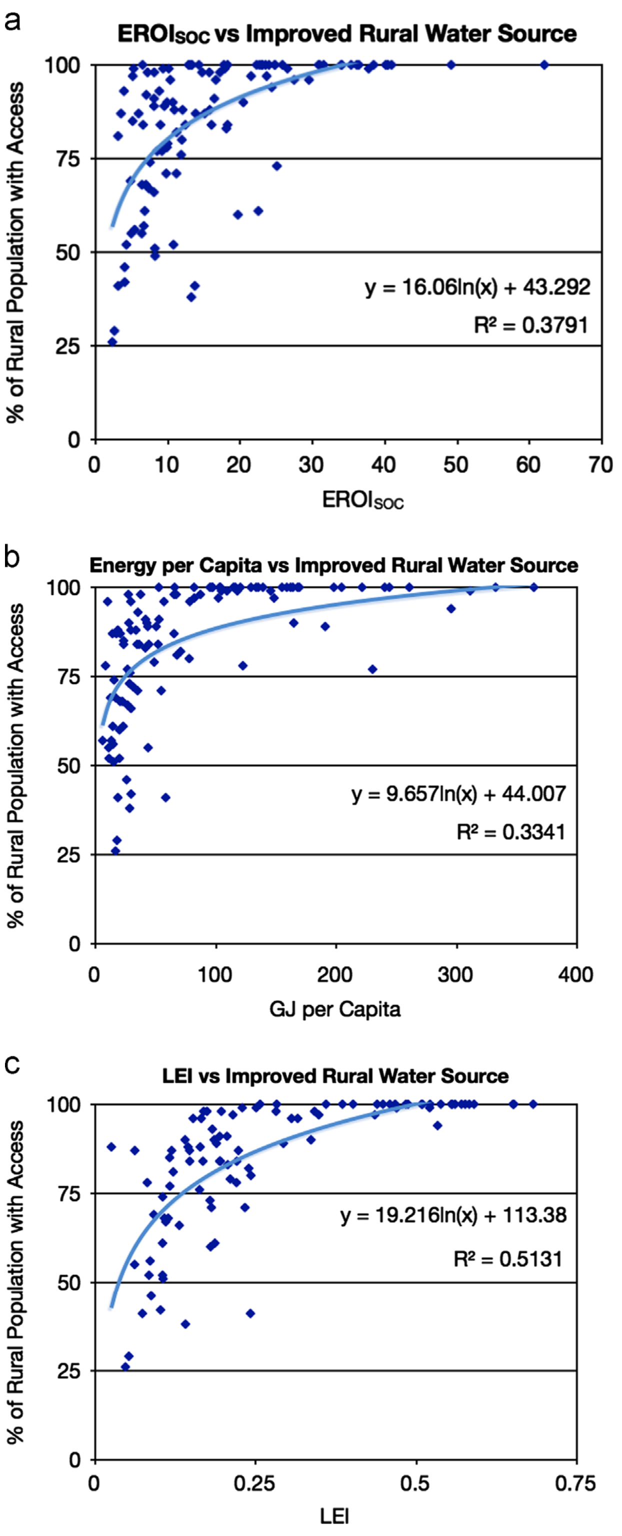

Fig. 8. Comparison of percent of rural population with access to improved water with (a) $EROI_{SOC}$, (b) energy use per capita and (c) LEI values (The World Bank, 2012; EIA, 2012a; FAO, 2012).

correlating LEI and GII. Nations with LEI values above 0.3 consistently have GII values below 0.5 (Fig. 7c).

3.2.2. *Energy and access to clean water*

Nations with an $EROI_{SOC}$ exceeding 20–30:1 have rural populations with access to improved water approaching 100 percent (Fig. 8a).

Similarly nations with greater than 100 GJ per capita consistently have greater than 75 percent of rural populations with access to improved water (Fig. 8b). The adjusted R^2 value of 0.52 is considerably higher for a multiple regression analysis (Table 4). In nations with greater than 0.25 LEI (Fig. 8c) more than 75 percent of the rural population has access to improved water.

3.3. *LEI Results in more detail*

Our results indicate that: energy surplus from fossil fuels and increases in the efficiency of energy use in an economic system ($EROI_{SOC}$) and especially their combination in LEI are correlated with various social indicators. For example, Canada has a moderate $EROI_{SOC}$ (18:1) but an extremely high energy use per capita (311 GJ per capita) and a moderate Gini-index (32.5), resulting in a high LEI value (0.52, Fig. 9) and a high quality of life (e.g. HDI=0.81). Conversely a nation such as Denmark has a very high $EROI_{SOC}$ (62:1) but a moderate energy use per capita (139 GJ per capita) and low Gini-index (24.7) and giving a similar LEI value (0.65, Fig. 9) and a high quality of life (e.g. HDI=0.8). In contrast developing nations such as Mexico or Brazil have moderate $EROI_{SOC}$ values (13:1 and 18:1 respectively) but low energy use per capita (65 and 52 GJ per capita respectively) and higher Gini-index (51.74 and 53.9 respectively). Mexico and Brazil have low LEI values (both 0.22, Fig. 9). These countries also have correspondingly lower quality of life indicators (e.g. HDI=0.59 for Mexico and 0.51 for Brazil). In severely impoverished countries (e.g. Pakistan and Nigeria) with low $EROI_{SOC}$ values (5:1 and 4:1 respectively), low energy use per capita (20 and 29 GJ per capita respectively) and low overall energy availability (LEI=0.12 an 0.10 respectively, Fig. 9) and quality of life (e.g. HDI=0.336 and 0.246 respectively) are closely correlated. In other words, greater energy availability (high LEI values) appears to corresponds with higher "quality of life." Figs. 10–12

3.4. *EROI for imported oil for developing countries*

Developing nations, defined in this paper as those with an $EROI_{SOC}$ of 20:1 or less, are also countries characterized as having high, and sometimes very high, population growth rates. As these populations grow and as the bulk of these people become increasingly located within cities, the task of feeding these urban dwellers becomes impossible without industrialized agriculture (e.g. Pracha and Volk, 2011). Agricultural products, grown with high yield, tend to be especially energy-intensive whether grown for internal consumption or for export, (e.g. Hall, 2000; LeClerc and Hall, 2007). In addition, most of these emergent countries are developing their industries; exportation of agricultural and industrial products is often how they obtain foreign exchange to obtain needed industrial inputs.

In general, as the GDP of a developing nation increases so does its energy use (or perhaps the converse). Consequently, for these and many other reasons fuel use in developing nations tends to increase rapidly. Most developing countries, however, do not have their own energy supplies, especially oil, which is needed to run their economic machine. We examine how the EROI of this imported oil ($EROI_{IO}$) is changing over time. To do this we have selected a diverse list of developing nations that are net energy importers: Bangladesh, Brazil, China, Ethiopia, India, Nepal, Pakistan, Sierra Leone, Thailand, Uruguay, Zambia and Zimbabwe, to investigate the potential linkages between social indices and the $EROI_{IO}$ for these nations.

The $EROI_{IO}$ of these countries during "good times" (i.e. the late 1990s) and "bad times" (i.e. 2006–2008) are given in Fig. 10. The patterns in the data for these countries have broadly similar trends over time.

There were two $EROI_{IO}$ peaks for oil imported into the twelve developing nations selected for examination. The first peak occurred in the years just prior to 1973. But, with the "oil shocks"

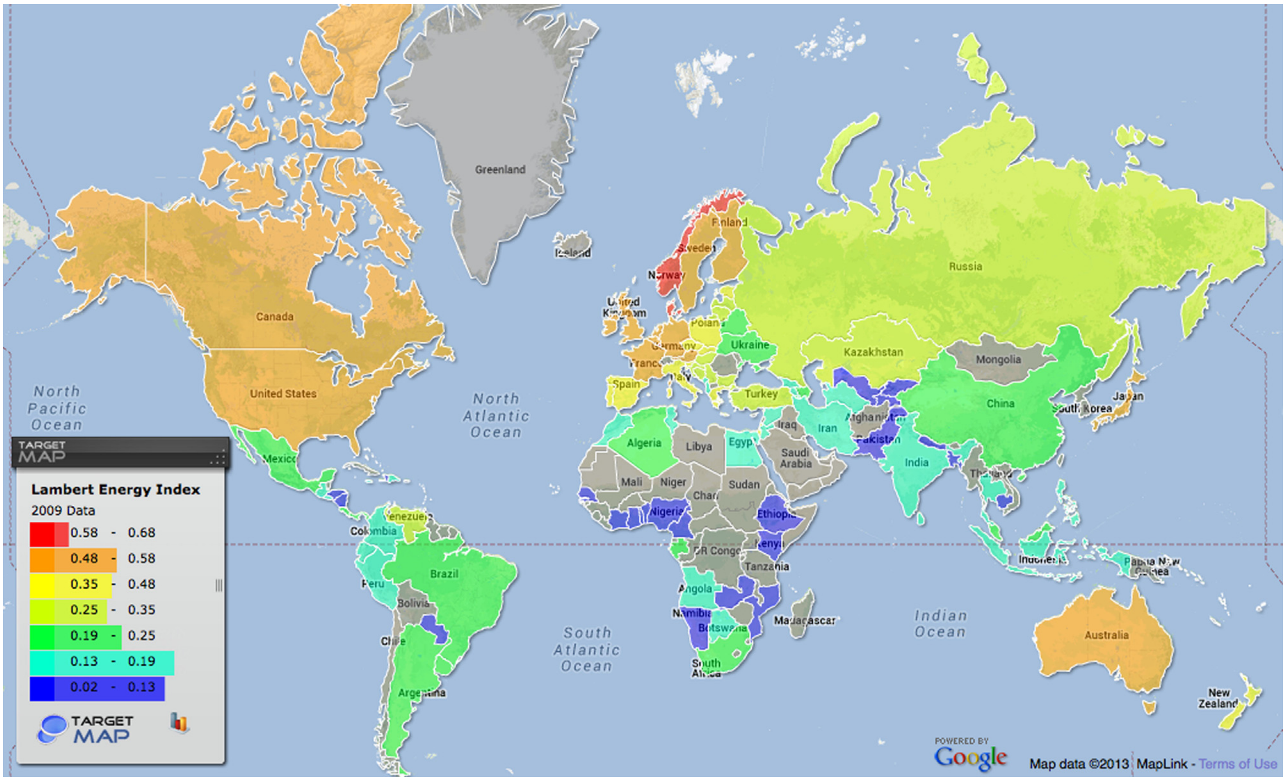

Fig. 9. LEI for nations evaluated in this study.

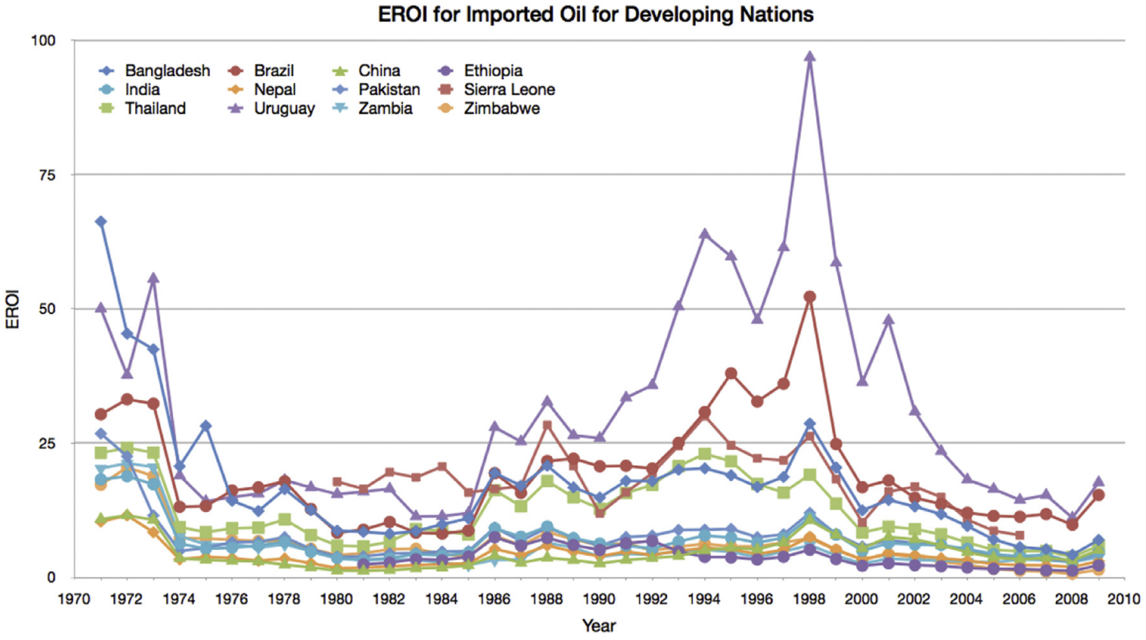

Fig. 10. EROI calculated for imported oil ($EROI_{IO}$) for select developing nations (The World Bank, 2012).

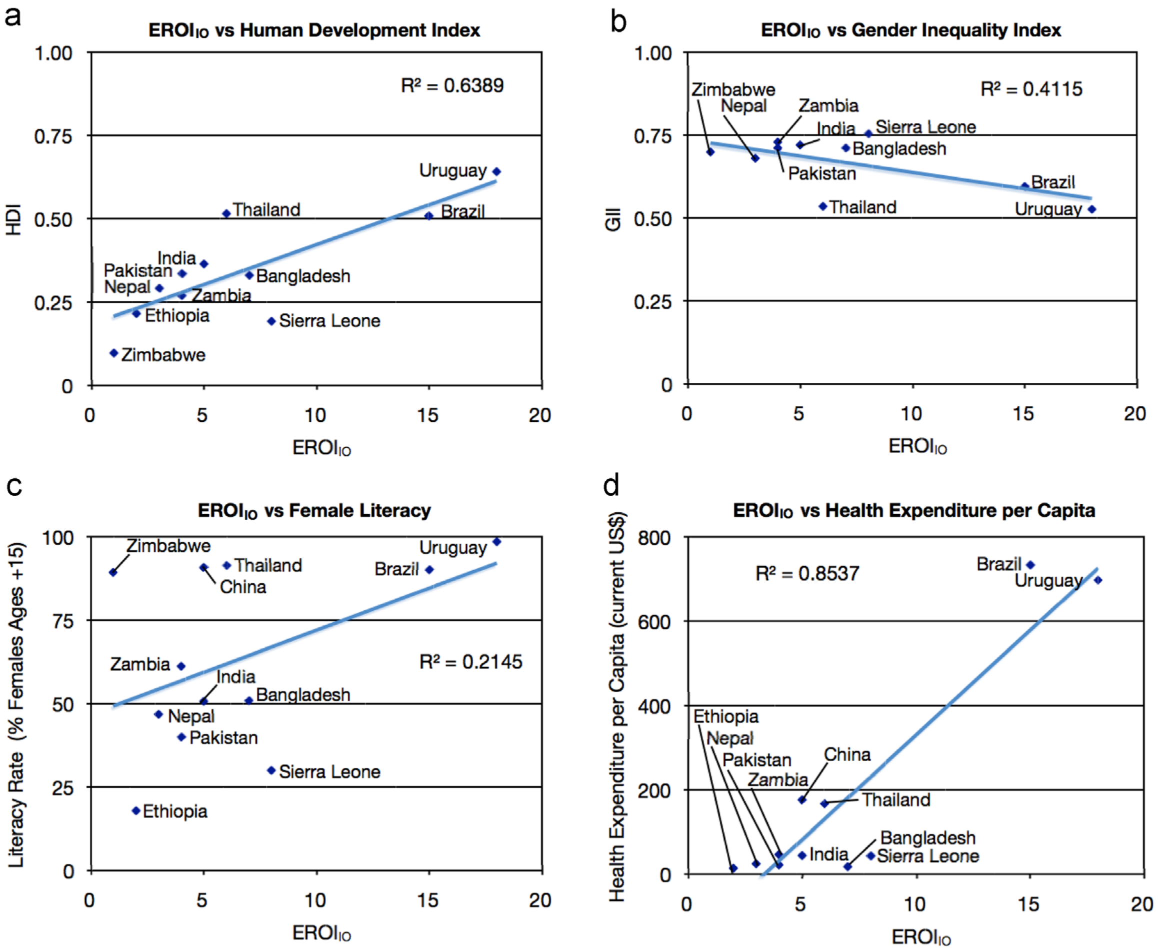

Fig. 11. Comparison of HDI (a), GII (b), literacy (percent of females ages 15 and up) (c) and health expenditures per capita (d) with $EROI_{IO}$ values (The World Bank, 2012; FAO, 2012).

of the 1970s the EROI declined and remained relatively low for each country through 1985–1987, after which it began to increase to a second peak in 1998 followed by a sharp and sustained decline until 2008 as oil prices again increased relative to exported commodities.

3.4.1. *EROI for imported oil and quality of life*

There is a moderately strong correlation between a sub-set of the indicators of a society's performance described above (Human Development Index (HDI), Gender Inequality Index (GII), female

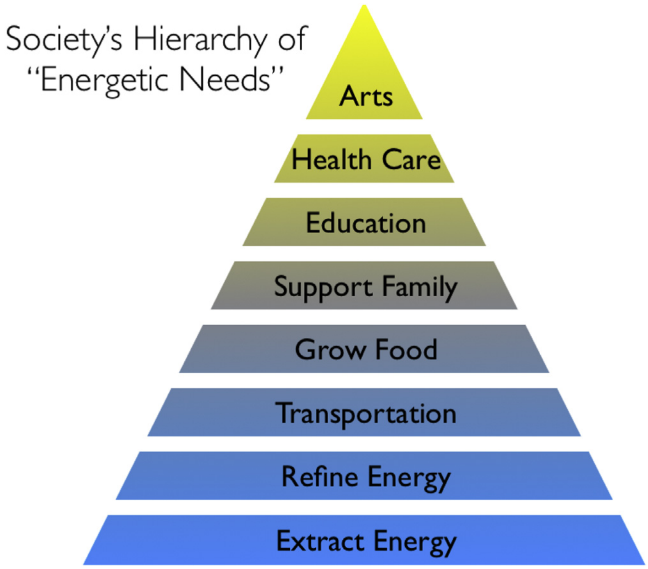

Fig. 12. "Pyramid of Energetic Needs" representing the minimum EROI required for conventional oil, at the well-head, to be able to perform various tasks required for civilization. The blue values are published values: the yellow values are increasingly speculative (figure from Lambert and Lambert (in preparation)). If the EROI of a fuel (say oil) is 1.1:1 then all you can do is pump it out of the ground and look at it. Each increment in EROI allows more and more work to be done (Hall et al., 2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

literacy rate and health expenditures) and the EROI for imported oil for the twelve less affluent net energy importing countries in 2009.

Most developing nations with $EROI_{IO}$ values below 8–10:1, are consistently below 0.50 on the HDI index (Fig. 8a). There is a slightly lower correlation between GII and the $EROI_{IO}$ for our selection of developing nations (Fig. 8b). There is only a small correlation between female literacy and $EROI_{IO}$ (Fig. 8c). There is a relatively strong correlation between per capita health expenditure and $EROI_{IO}$ (Fig. 8d) suggesting a linear relation between $EROI_{IO}$ and a nation′s access to costly medical treatment. Nations with high $EROI_{IO}$ values (Brazil and Uruguay) spent between six and seven hundred USD per person on health care. Nations with low $EROI_{IO}$ values (below 8:1) consistently spent less than two hundred USD per person on medical care.

4. Discussion

4.1. The implications for all nations

Traditionally, economists have viewed quality of life indices as a consequence of economic input and well-being. However we find that $EROI_{SOC}$ and per capita energy use are as strong a statistical predictor as traditional economic indices. Both energy per capita and $EROI_{SOC}$ are independent measures of the influence of energy availability on the ability of an economy to do work, which includes the generation of economic well-being and "quality of life." Most measures are linearly correlated to $EROI_{SOC}$, and also energy used per capita, often up to a saturation point. Three major findings that would appear to impact values for all nations are:

1. For the indices examined countries with an $EROI_{SOC}$ of less than 15–25:1 and/or less than 100 GJ per capita per year tend to have a poor to moderate "quality of life." LEI values below 0.3 also correspond with a poor quality of life.
2. A threshold is passed with an $EROI_{SOC}$ of from 20 to 30:1 and/or access to 100–200 GJ per capita per year which is correlated with a "higher" standard of living (e.g. an HDI index of above 0.7). This trend is reflected in an LEI threshold between 0.3 and 0.4.
3. This improvement in well-being appears to level off at $EROI_{SOC}$ values above 30:1 and/or greater than 200 GJ per capita per year, observed in LEI value greater than 0.4. There is little or no additional improvement in societal well-being above these levels.

Overall, our analysis suggests that having, or having access to, large quantities of high quality energy appears to contribute substantially to social well-being. It is consistently evident that relatively high GDP is associated with higher social welfare, at least to a point. The causative chain may be simply higher $EROI_{SOC} \gg$higher surplus energy$\gg$higher GDP$\gg$higher social well-being or it may be it is more complex.

4.2. Implications for developing nations

Our results suggest that, at least for the twelve developing nations examined, the 1973 oil crisis corresponded to a precipitous drop in the EROI for imported oil ($EROI_{IO}$) and tremendous economic drain. These and other nations have not returned to their pre-1973 high $EROI_{IO}$ values. Nevertheless the price increases of the 1970s made other sources of oil more profitable leading to the development internationally of many previously found but undeveloped fields. This, in turn, led to a decline in the price of oil. Economic recoveries that occurred in the mid-1980s to late-1990s were linked to increases in energy availability and a decrease in energy price. Generally, the EROI for oil imported to these nations continued to increase with declining oil prices, finally peaking in 1998 with a low imported oil price of 12.07 USD/bbl (The World Bank, 2012). Over the next two years this pattern was reversed as the price of oil increased by 120 percent, reaching 27.72 USD/bbl in 2000. The EROI of imported oil declined in response to this price increase and this impacted greatly developing nations that had become dependent on inexpensive fuel for use in the production of goods for export to "developed" nations. Except for a very minor increase in 2009, their $EROI_{IO}$ has continued to decline steadily.

The process of developing fuel-intensive domestic industries to generate exports has worked reasonably well for many developing nations in the past when the price of oil was low compared to the prices of exports. However, the trends suggested by our data imply that the increasing oil prices observed over the past decade, if they continue, will impact developing nations and their ability to produce goods substantially. When oil prices increase, these oil importing nations are “stuck” with the industrial investments that the people of that nation have become dependent upon. For a nation without domestic sources of fossil fuels, an environment of rising imported energy prices relative to price of exports obligates that nation to dedicate more and more of its production (and therefore energy use) to obtain the next unit of energy needed to run the economy. Large and increasing populations, mechanized agriculture and industrialization all are making developing nations increasingly dependent on foreign fuels. When the ratio of the price of oil to exports is low, times are good. When, inevitably, the relative price of oil increases things become much tougher. Once a developing nation steps on to this “fossil fuel treadmill,” it becomes difficult to step off. If the price of oil continues to increase and hence the $EROI_{IO}$ declines, this is likely to correspond to lower quality of life indices for the citizens of these nations. Specifically, health expenditures per capita, HDI and GII are likely to decline.

5. Economic policy implications

5.1. The concept of minimum EROI

What is the minimum EROI required for a typical “developed” society? That depends on what is perceived as the essential requirements for the creation and maintenance of such a society. Certainly history is littered with cities and entire civilizations that could not maintain a sufficient net energy flow (Tainter, 1988), showing us that certain thresholds of surplus energy must be met in order for a society to exist and flourish. As a civilization flourishes and grows it tends to generate more and more infrastructure which requires additional flows of energy for its maintenance metabolism.

The concept of a hierarchy of “energetic needs” required for the maintenance and perhaps growth of a typical “western” society (Fig. 9) is somewhat analogous to Maslow′s “pyramid of (human) needs” (Maslow, 1943). Humans must first meet their physiological and reproductive needs and then progressively less immediate but still important psychological needs. Like Maslow′s vision of a system of human hierarchical needs, a society′s energy needs are hierarchically structured. In this theory, needs perceived as “lower” in the hierarchy, e.g. extraction and refining of fossil fuels, must be satisfied before needs “higher” in the hierarchy become important at a societal level. For example, the need to first extract and then refine fuels must be met in order to meet the need for transport of that energy to its point of use. In Western society, the energy required to e.g. grow and transport sufficient food cannot be met without first fulfilling these first three needs (i.e. extraction, refining and transport of those fuels to their point of use). Energy for the support required for the maintenance of a family, the provision of basic education for the next generation of citizens, and healthcare for all citizens follows the hierarchical structure; each progressive level of energy needs requires a higher EROI and must be fulfilled before the next can be met. Discretionary use of energy e.g. the performing arts and other social amenities can be perceived as a societal energetic necessity only once all levels beneath this are fulfilled. The rating of importance of “the arts” probably is related to the socio-economic position that individuals or societal groups hold and may be operative only for those at the top of that society. A society′s pyramidal hierarchy of energetic needs represents the relative importance of various components of a society, ranked by importance to human survival and well-being, and the quality of energy devoted to the production and maintenance of infrastructure required to support those components of society. The specific and concrete nature of the lower levels may appear increasingly obscure and ambiguous to those at “higher” levels but is absolutely essential for their support. What represents the upper tier of the hierarchy of energetic needs is by no means definitive and levels are likely to change based on socio-economic, demographic and cultural differences. But this concept acknowledges the reality that not all human wants and needs can be met simultaneously and that there are tradeoffs and opportunity costs such that meeting one want or need uses energy that is then not available for another, especially in a society with little or no growth.

5.2. Economic policy as it stands for developing countries

In order to meet our international humanitarian responsibilities for the peace, well-being and improved quality of life, national and international agencies have provided support and aid to attempt to ensure the betterment of the human condition. National development agencies such as the UK-Department for International Development (UK-DFID) and the United Nations have provided large quantities of aid in an attempt to attain a greater degree of prosperity and improved quality of life for developing nations (e.g. UK-DFID spent roughly 200 million pounds in 2012 on humanitarian projects in Bangladesh DFID, 2012). While billions of dollars in aid continue to flow into developing nations, little, if any, of that aid is allocated to increasing net-energy availability. However, as population growth continues to rise and energy demand skyrockets (and affects EROI), there has been chronic underinvestment in net energy assessment, development and distribution. Humanitarian efforts continue to focus on poverty reduction programs (e.g. healthcare and education). Our results suggests that the metrics of societal well being and per capita net-energy available to society appear to be linked; policies developed with the purpose of improving the human condition within a society may have little impact on a society′s well-being without accompanying increases in per capita net energy delivered to that society. Oftentimes that society will be simply too far down the energy pyramid to derive the desired ends. So, for example, countries such as Bangladesh receive approximately 200 million USD investment in energy (with private participation) while receiving between 1 and 2 billion USD in annual net official development assistance (The World Bank, 2012). Even with this assistance, they continue to have a low HDI value (below 0.40). Brazil, on the other hand, receives considerably less, between 300 and 900 million USD per year, in development assistance but also receives between 8 and 25 billion USD investment in energy (including private sources) (The World Bank, 2012). With this additional investment into energy, Brazil is able to achieve moderate to high HDI values. These examples suggest that for international aid to be “successful” in ameliorating poor HDI values in disadvantaged economies within impoverished societies, energy issues must be effectively addressed. We propose that funding needs to provide the necessary energy infrastructure that facilitates stable economic development that can support long-term social progress.

5.3. Economic policy as it stands for developed countries

As we use up our best fossil fuels and the EROI of traditional fossil fuels continues to decline countries with currently high $EROI_{SOC}$ and energy use per capita values may find themselves in a deteriorating position, one with lower $EROI_{SOC}$ and energy use per capita. Policy decisions that focus on improving energy infrastructure, energy efficiency and provide additional non-fossil fuel energy sources (e.g. nuclear) within these nations may stem the tide of declining energy quality.

6. Conclusion

The price of oil is likely to continue to remain high or increase as, apparently inevitably, EROI for extracted oil declines, a situation that is expected to exacerbate problems currently facing developing countries. The question that must be asked is, “What opportunities do these countries have to mitigate the effects of these rising energy prices, and declining EROI of imported fuels?” Most alternatives to oil have a very low EROI and are not likely to generate as much net economic or social benefit. Improving the efficiency at which their economies convert energy (and materials) into marketable goods and services is one means of improving energy security. What might be the response of development agencies to this state of affairs? We suggest that the process of conventional development might be rethought, that current economic remedies such as the introduction of more “modern” (and hence fuel intensive) agricultural development procedures or the construction of more factories requiring more energy to run them may be less effective solutions to social problems than once was the case. The promotion and support of moderate EROI renewable energy production might serve to improve the net energy balance of a developing nation with a poor EROI for imported oil through trade, however, some of the economic implications of doing so are less clear. Further economic and energetic analysis is warranted on a case-by-case basis.

These conditions may be conducive to the construction of renewable energy projects that provide higher net energy returns than imported fuels. Indeed, many developing nations (see e.g. the Caribbean nations Haiti or Guatemala (The World Bank, 2012)) have been pursuing development of renewable energy generation to replace oil-fired electric plants. Unfortunately as noted above, rising energy prices require nations to dedicate a larger amount of domestic fuel consumption to produce goods and services to generate international trade, leaving less energy, and importantly foreign exchange, available to invest in these capital-intensive renewable technologies. There is evidence too that once payments for energy rise above a certain threshold at the national level (e.g. approximately 10 percent in the United States) that economic recessions follow (Hamilton, 2009; Hall et al., 2009; Murphy et al., 2011). Despite the best intentions of improving net energy balances for a developing nation, the large-scale introduction of renewable energy generation may have too low an EROI and may prove too expensive to facilitate continued growth in developing economies.

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