

# EROI of Global Energy Resources

*Status, Trends and Social Implications*



October 2013



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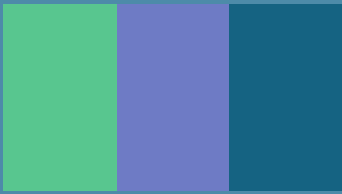
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## NOTE FROM THE AUTHORS

*All forms of economic production and exchange involve the transformation of materials, which in turn requires energy. Until recently cheap and seemingly limitless fossil energy has allowed many to ignore the important contributions from the biophysical world to the economic process and potential limits to growth.*

*The report that follows, commissioned by the United Kingdom's Department for International Development (DFID) and developed by the State University of New York College of Environmental Science and Forestry (SUNY-ESF) and Next Generation Energy Initiative (NGEI), examines the energy used by modern economies over time. This work centers on assessing the relation of energy costs of modern day society and its connection to the quality of human life. A focus of this report is energy return on investment (EROI) and some important characteristics of our major energy sources over time.*

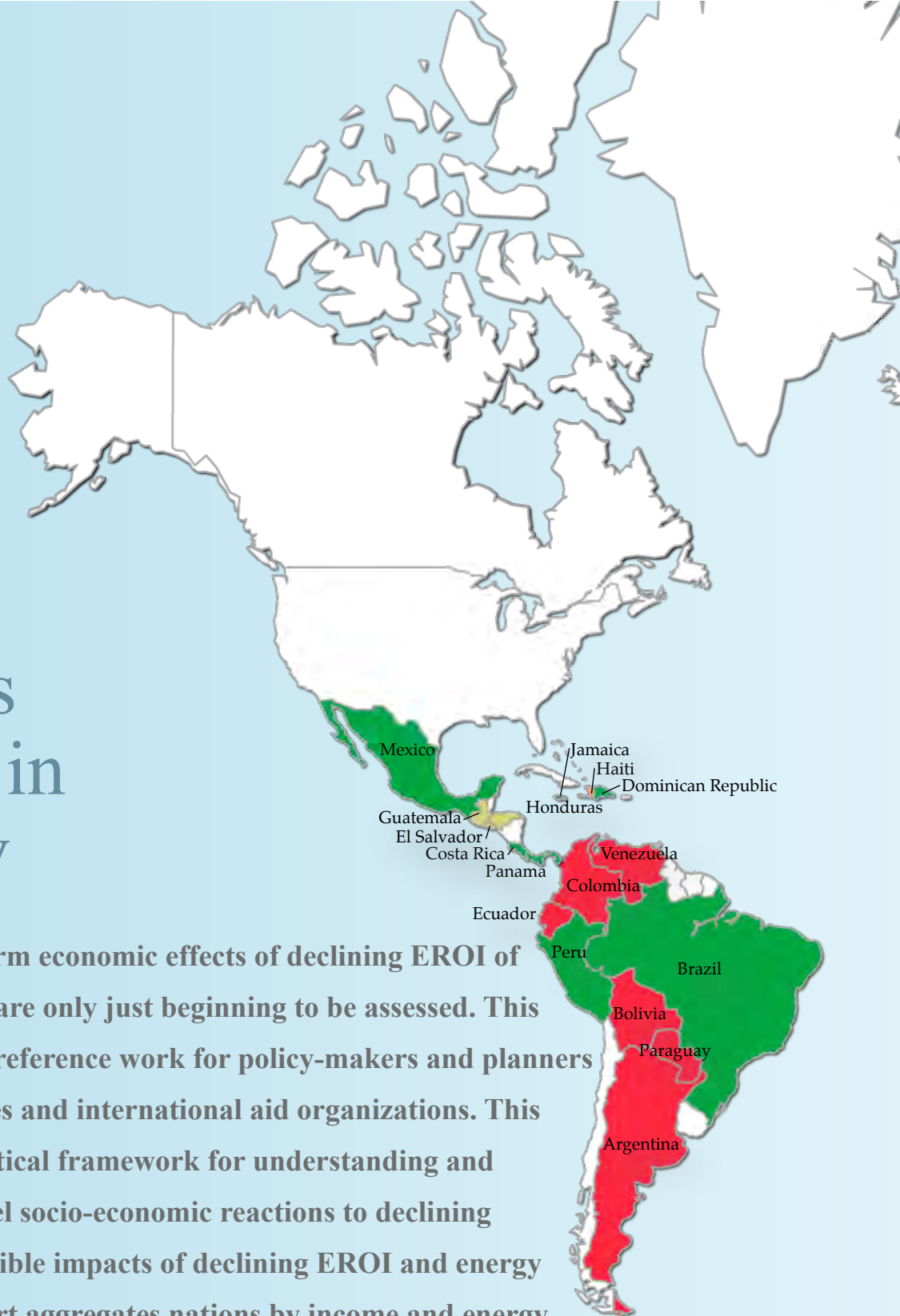
*We find the EROI for each major fossil fuel resource (except coal) has declined substantially over the last century. Most renewable and non-conventional energy alternatives have substantially lower EROI values than conventional fossil fuels. Declining EROI, at the societal level, means that an increasing proportion of energy output is diverted to getting the energy needed to run an economy with few discretionary funds available for "non-essential" projects. The declining EROI of traditional fossil fuel energy sources and its eventual effect on the world economy are likely to result in a myriad of unforeseen consequences.*

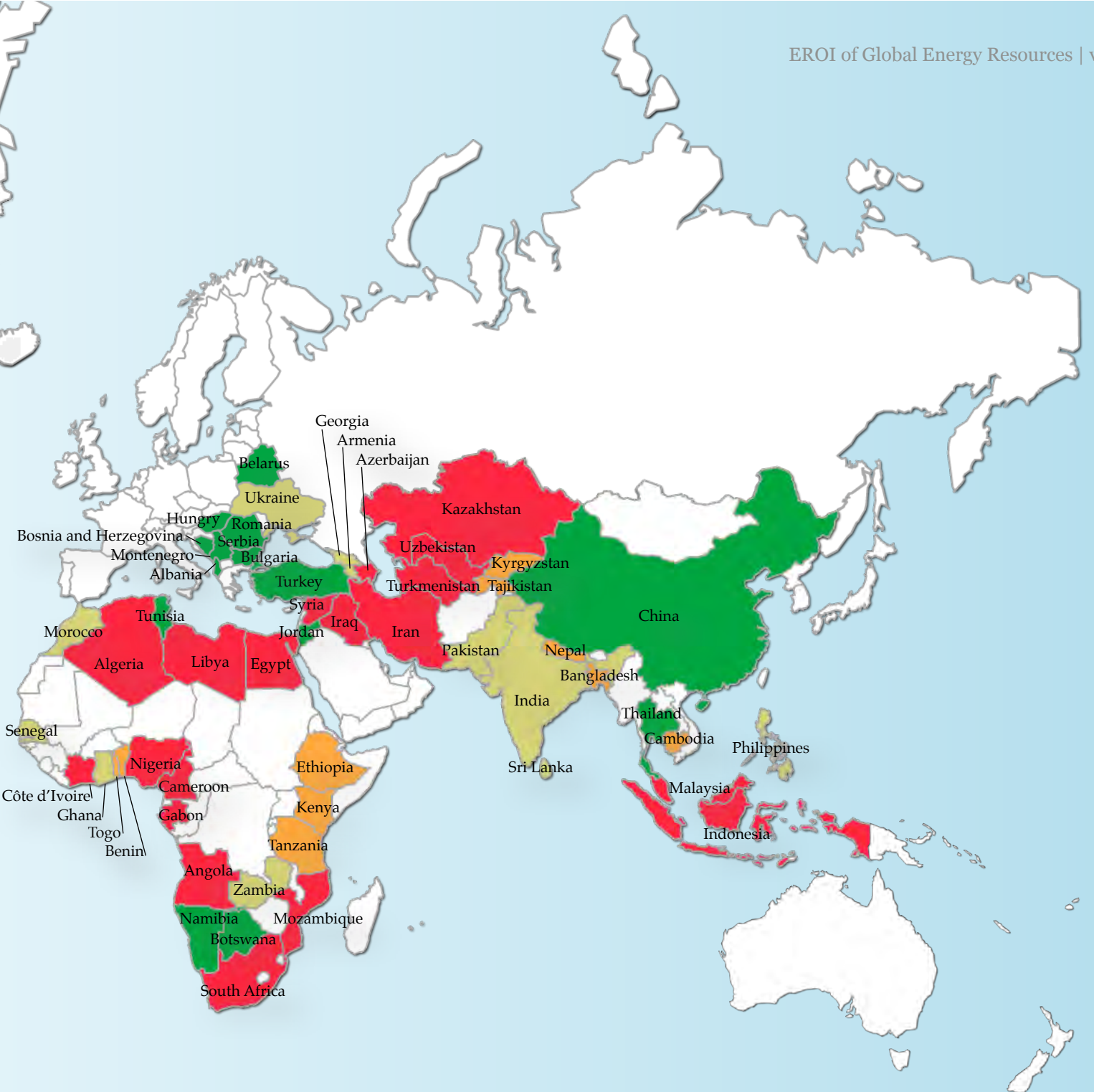
*We offer this report as a window into the EROI of global energy sources, the effect of policy and world events on past, present, and future EROI values, the EROI of renewable, non-conventional and imported energy sources, and provide a brief discussion on how declining EROI values may influence the economies of select developed and developing nations.*



# Countries Included in the Study

The near- and long-term economic effects of declining EROI of our global fossil fuels are only just beginning to be assessed. This document serves as a reference work for policy-makers and planners in developing countries and international aid organizations. This report offers an analytical framework for understanding and assessing national-level socio-economic reactions to declining EROI values and possible impacts of declining EROI and energy availability. This report aggregates nations by income and energy trade. We examine three categories: low income energy importing countries, lower middle income energy importing countries and upper middle income energy importing countries. Countries that are net energy exporters are discussed within their income category. By design, there is a certain amount of overlap among the sections dealing with the three income / oil importing categories.





### Countries Included in the Study

Data: World Bank, 2013

- Net Energy Exporting Countries
- Low Income Energy Importing Countries
- Lower Middle Income Energy Importing Countries
- Upper Middle Income Energy Importing Countries





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Next Generation Energy Initiative is a non-governmental organization (NGO) composed of education and energy professionals devoted to improving our world by combining research, education and practical energy solutions in a way that integrates energy, ecology and economics in support of a sustainable planet.



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## Abbreviations

BP	British Petroleum
BoP	Balance of payments
CCS	Carbon capture and sequestration
CIA	US Central intelligence agency
EIA	US Energy information administration
EROI	Energy return on investment
$EROI_{st}$	Standard EROI
$EROI_{pou}$	Point of use EROI
$EROI_{el}$	Electric generation EROI
$EROI_{ext}$	Extended EROI
$EROI_{IO}$	Imported Oil EROI
$EROI_{SOC}$	Societal EROI
FAO	Food and agriculture organization
FEMA	Forum of energy ministers of Africa
GDP	Gross domestic product
GII	Gender inequality index
GNI	Gross national income
HDI	Human development index
LEI	Lambert energy index
LMIC	Lower middle income countries
MDG	Millennium development goals
MENA	Middle East and North Africa
NER	Net energy ratio
PPP	Purchasing power parity
PRSP	Poverty reduction strategy papers
PV	Photovoltaic
OECD	Organization for economic co-operation and development
OPEC	Organization of the petroleum exporting countries
UMIC	Upper middle income countries
UNDP	United nations development programme
USDA	US Department of agriculture

## Units of Measurement

bbbl	Barrel of Oil
BTU	British Thermal Unit
GJ	Giga Joules
kWatt	Kilo Watts
MJ	Mega Joules
tcf	Trillion Cubic Feet
ton	Metric Ton
USD	United States Dollar

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# Executive Summary

**All forms of economic production and exchange involve the use of energy directly, and also the transformation of materials, which in turn requires energy.**

For most of the past century, cheap and seemingly limitless fossil energy has allowed most of society to ignore the importance of contributions from the biophysical world to the economic process as well as the potential limits to growth. This work centers on assessing the cost of energy to modern day society and its relation to GDP. The most important focus is the important characteristics of our major energy sources including each fuel's energy return on investment (EROI) (Note: we use the word "fuel" here to include all energy sources to society, including all combustible fuels (e.g. fossil fuels), nuclear, geothermal and other primary energy (e.g. electricity from wind turbines), although electricity is not technically a fuel or source but a carrier). The EROI of our most important fuels is declining and most renewable and non-conventional energy alternatives have substantially lower EROI values than traditional conventional fossil fuels even as the EROI of the most important traditional fuels decline. At the societal level, declining EROI means that an increasing proportion of energy output must be diverted to attaining the energy needed to run an economy, leaving fewer discretionary funds available for "non-es-

sential" purchases which often drive growth and provide for social well-being. This concept generates new challenges to society in general and development in particular.

## Summary of EROI Research

Humans have tended to develop, and often deplete, the highest quality fuels first. This tends to lead to a decline in EROI of fuels (even while technological advances might otherwise decrease the energy cost of production and hence increase EROI). EROI for oil and, somewhat less clearly, for natural gas and coal, have tended to decline over time as less energy is provided to society for each unit of energy invested in attaining it. One result of this, obvious to many consumers, is that both the nominal and the inflation-corrected price of fuels has been increasing as more resources are used in the extraction of lower quality, less accessible fuels. We review published and some non-published time series data to establish how the EROI of traditional fossil fuels are changing over time, and also examine the socio-political ramifications associated with these trends.

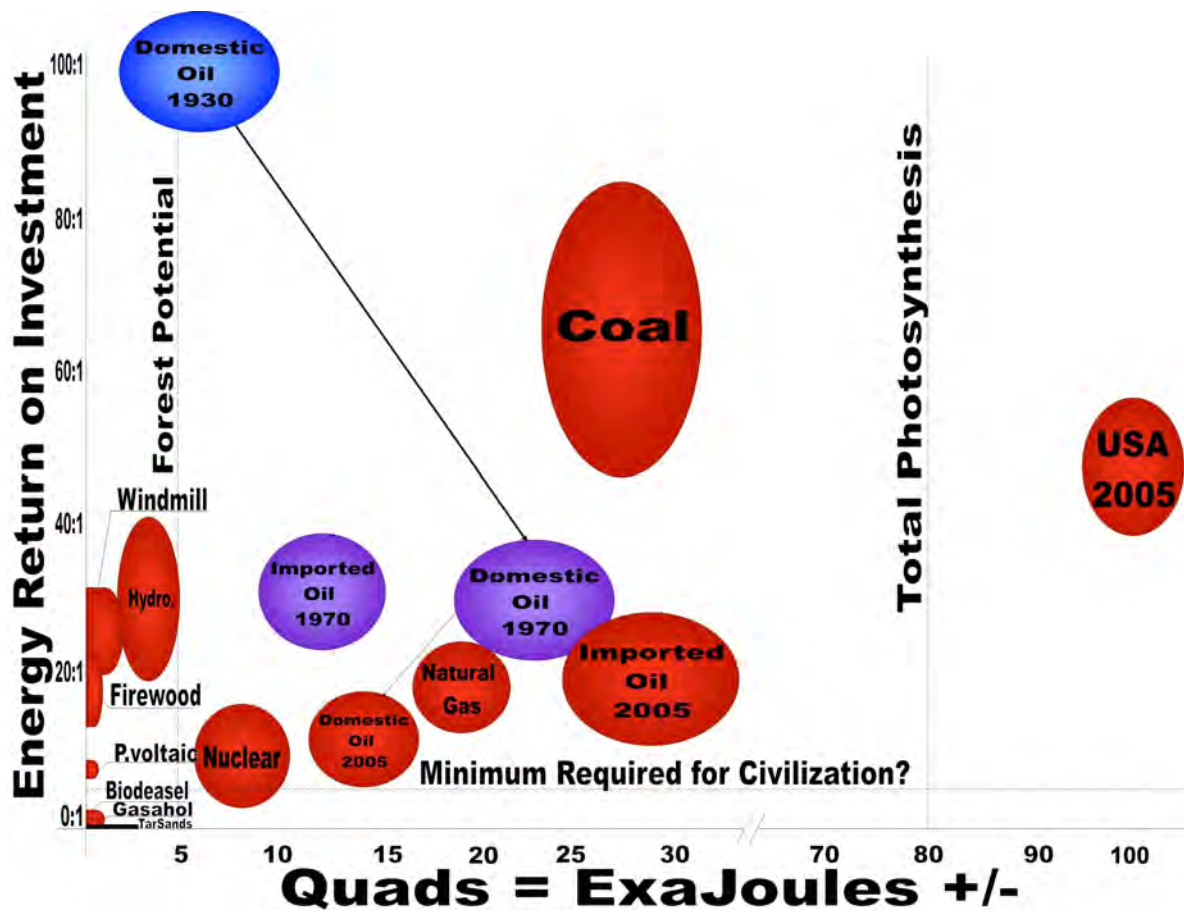


Figure 0.1: "Balloon graph" representing approximate net-energy (vertical axis) and quantity (horizontal axis) of various fuels used by the United States' economy at various times (blue represents the 1930s, purple represents the 1970s and red represents 2005). Arrows connect fuels from various times (i.e., finding domestic oil (and gas) in 1930, and producing it in 1970 and 2005), and the size (volume) of the "balloon" represents part of the uncertainty associated with EROI estimates (Data for 2005 Source: C. Hall 2006)

Figure 0.2: Summary of EROI for four energy categories

**Oil and Gas**



Image: "Two Oils Of Alberta" by Rosemary Ratcliff

**Coal**



Image: "Coals" by dan

**Nuclear**



Image: "Power Station Cooling Towers" by xedos4

**Renewables**



Image: "Solar And Wind Energy" by dan

The EROI for discovering oil in the US has decreased from more than 1000:1 in 1919 to 5:1 in the 2010s, and for production from about 30:1 in the 1970s to less than 10:1 today (Guilford et al. 2011). The global EROI for the production of oil and gas has declined from 30:1 in the mid 1990s to about 18:1 in 2006 (Gagnon et al. 2009). It is difficult to establish EROI values for natural gas alone as these values are usually aggregated in oil and gas statistics (Murphy and Hall, 2010, Gupta and Hall, 2011).

The EROI for production declined from 80:1 to 30:1 by the 1980s, but returned to 80:1 by about 1990. This pattern may reflect an increase in less costly surface mining. The energy content of coal has been decreasing even though the total tonnage has continued to increase at least until recently (Hall and Klitgaard, 2012). This is true for the US where the energy content (quality) of coal has decreased while the quantity of coal mined has continued to increase. The maximum energy yield from US coal seems to have occurred in 1998 (Hall et al. 2009, Murphy and Hall 2010).

Nuclear has a debatable moderate EROI value (5-15:1, some unpublished studies say more). Newer analyses need to be made as these values may not adequately reflect current technology, ore grades or environmental issues e.g. the energy costs associated with the impacts of Chernobyl or Fukushima (Hall and Klitgaard, 2012).

Nearly all renewable energies have low EROI values when compared to conventional fossil fuels. Corn-based ethanol has an EROI value of less than 2:1 (e.g. Patzek, 2004, Pimentel and Patzek, 2005, Farrell et al. 2006, Hammerschlag, 2006). Wind power has a high EROI value (perhaps 18:1) (Kubiszewski, 2010) while photovoltaic (solar electric) power remains relatively low, perhaps only 7:1 or less (Prieto and Hall, 2012). Correcting for the issue of intermittency is likely to decrease the EROI more; weighting for the quality of electricity would lead to higher EROIs.

Language adapted from: Hall, C. and Klitgaard, K. Energy and the Wealth of Nations: Understanding the Biophysical Economy. Springer, 2012.

Language taken/adapted from: Murphy, D. and Hall, C. Year in review—EROI or energy return on (energy) invested. Ann. N.Y. Acad. Sci. 1185 (2010) 102–118

Language adapted from: Hall, C. and Klitgaard, K. Energy and the Wealth of Nations: Understanding the Biophysical Economy. Springer, 2012.

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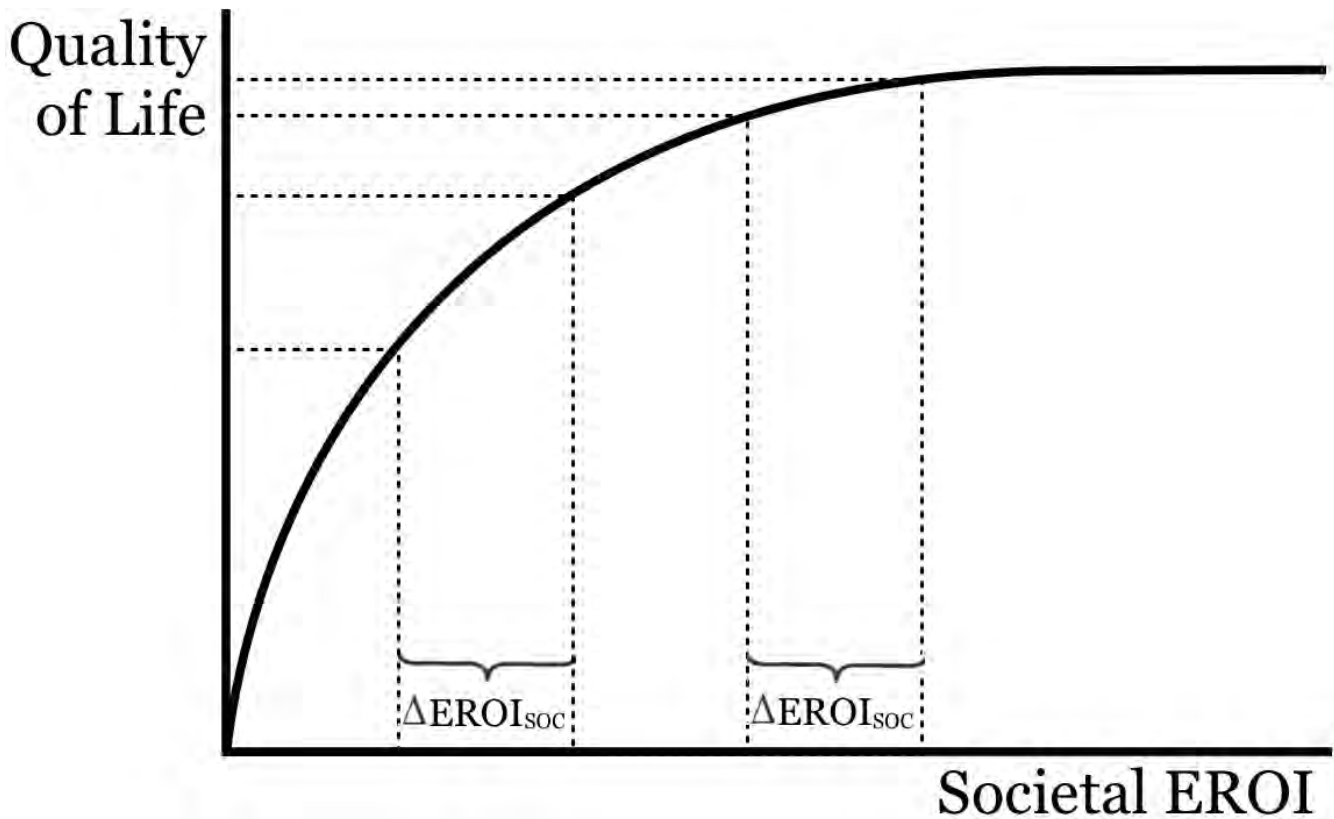


Figure 0.3: Relation of quality of life to EROI for society ( $\text{EROI}_{\text{soc}}$ ).

### Energy Availability and Quality of Life

The near- and long-term societal effects of declining EROI are uncertain, but probably most people would consider them 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 have developed a preliminary assessment of energy availability and its impact on society. The indices of energy available are: (1) EROI at a societal level, (2) energy use per capita, and (3) a new composite energy index (Lambert Energy Index). We compared each to select indicators of quality of life

(Human Development Index, 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 social well-being and that social well-being is linked to increasing per capita access to energy, at least to a point (Figure C). We also find a saturation point at which increases in per capita energy availability (greater than 150 GJ per year) or EROI (above 20:1) are not associated with further improvement to society.

### Policy Implications

Past policies for both developed and developing countries were based on economic expansion. Economic growth used

But, the imminence of peak oil, the decline of EROI for our most important fuels, and the relationship of oil, and energy more generally, to economic activity and growth generate new challenges to world economies and the maintenance of what we call civilization. If human development indices are as closely related to, and presumably dependent upon, energy, development will have to shift increasingly from many past patterns, where direct and indirect industrialization has been very effective, to something else. A particularly important issue is that where development of e.g. new factories or more intensive agriculture often worked in the past, this may be less easy in the future because of the high price of fuels, which in many developing countries means oil. On the other hand, many less developed countries are good candidates for renewable energies

such as photo-electric or wind electricity because there is less existing traditional infrastructure, i.e. that would require reliable electricity, and rigid work patterns.

## Conclusion

The declining EROI of traditional fossil fuel energy sources and the effect of that on the world economy are likely to result in a myriad of consequences, most of which will not be perceived as good. Declining EROI for the world's largest energy sources (oil, natural gas and perhaps coal) appears to be influencing economies now and is likely to have an increasing impact on the world economy on social well-being and strategies of development in the coming decades.







# 1. Introduction



*“The prosperity and stability of modern society is inextricably linked to the production and consumption of energy, especially oil.”*



# Introduction

## 1.1 Energy and the Economy

*Energy has played a critical role throughout human society's demographic, economic and social development. The availability of various energy and material resources to a society is linked to the general trend of the settlement, growth, and eventual decline experienced by each civilization (Tainter, 1988). A society must have an energy surplus for there to be division of labor, creation of specialists, and the growth of cities, and substantially greater surplus for there to be widespread wealth, art, culture and other social amenities. But this process also has led to depletion of the resource that led to that growth. Economic fluctuations tend to result, directly or indirectly, from variations in a society's access to cheap and abundant energy (Tainter, 1988, Cleveland et al. 1984, Lambert and Lambert, in preparation). The question for our time is whether the economic level and growth that we have taken for granted will be available in the future (Hamilton, 2009).*

Today, fossil fuel resources are among the most important global commodities and by their large energy surplus are essential for the production, distribution and consumption of the rest. Globally fossil fuels supply greater than 75 percent of the total energy consumed by society (Hall et al. 2009, Hamilton, 2009). The prosperity and stability of modern society is inextricably linked to the production and consumption of energy, especially oil (Hall and Klitgaard, 2012). While many less developed nations still depend largely on biomass even there oil is critically important for transportation and often agriculture.

Economic production and growth, the usual indices of material well-being, requires physical work and consequently a steady and consistent flow of energy (Figure 1.1). Historically intervals of economic growth have been punctuated by numerous periods of recession. In general, the

growth of real GDP is highly correlated with rates of oil consumption (Appendix A). According to Hamilton and others four out of the five recessions experienced in the US since 1970 can be explained by increased oil prices (Hamilton, 2009, Jones et al. 2004). During periods of recession, oil prices decline, eventually encouraging renewed consumption. Alternatively, during periods of expansion oil prices increase and higher energy consumption, and hence economic expansion, are eventually constrained by these higher prices (Jones et al. 2004).

Economic growth and stability is dependent on not only the total quantity of energy accessible to society but also the cost of this energy to different sectors of that society. A number of papers develop this concept. For example Jones et al.'s 2003 article, *Oil Price Shocks and the Macroeconomy*, reveals a clear relation between oil

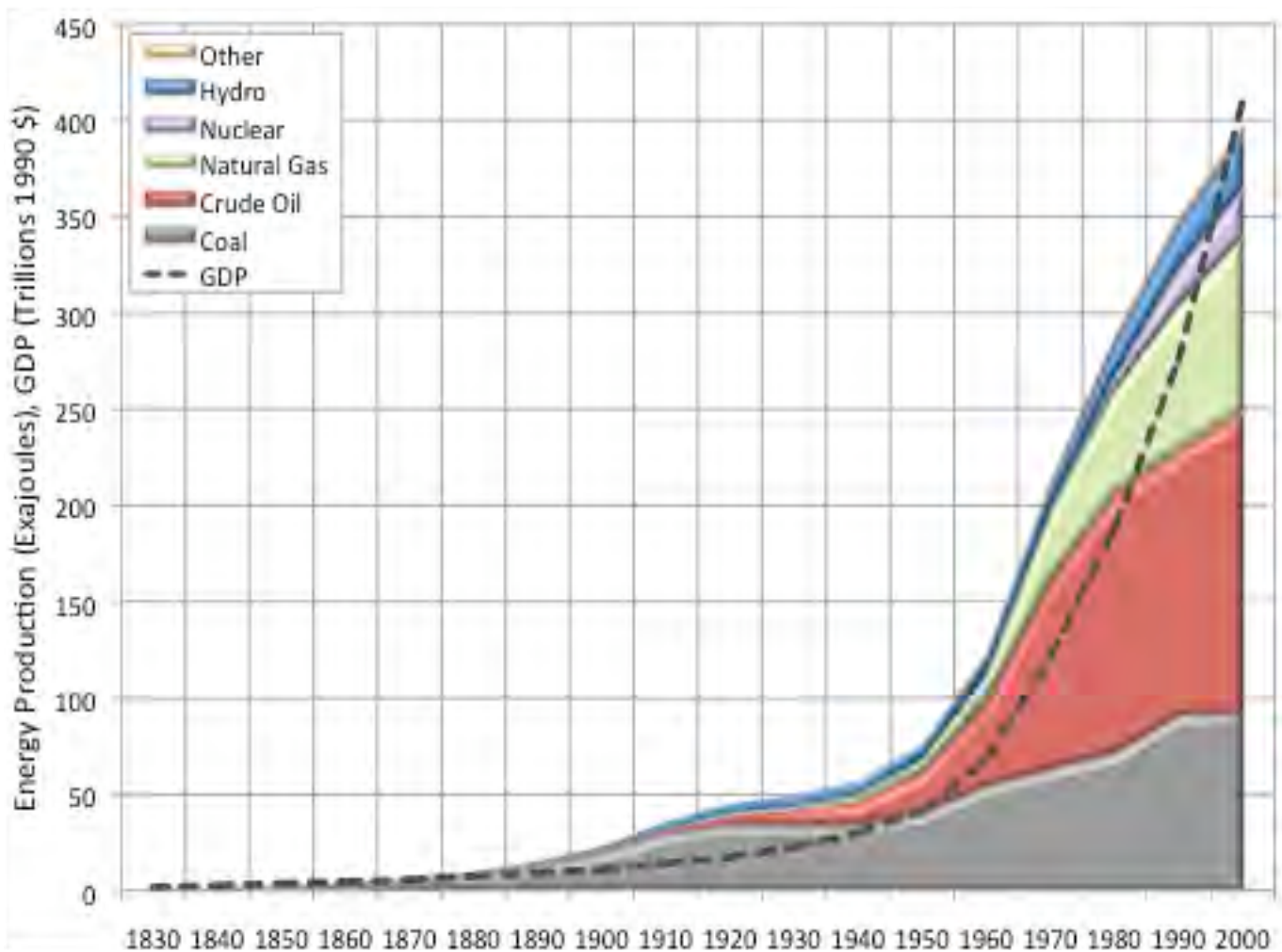


Figure 1.1: The global use of hydrocarbons for fuel by humans has increased nearly 800-fold since 1750 and about 12-fold in the twentieth century. The most general result has been an enormous increase in the ability of humans to do all kinds of economic work, as represented by the increase in GDP (Murphy and Hall, 2011).

price and GDP (Jones et al. 2004). The main conclusions drawn from Jones et al. are:

“First, the most thorough research to date has found that post-shock recessionary movements of GDP are largely attributable to the oil price shocks, and are not events that alternative monetary policy largely could have avoided.

Second, two nonlinear and asymmetric specifications of oil price shocks have been found that yield stable oil price-GDP relationships over the entire post-World War II period. ...

Third, detailed empirical research has shown that considerable reallocation of labor occurs after oil price shocks, amounting to as much as 11 percent of the labor force in manufacturing, and similar reallocations outside manufacturing. Much of this movement is within industry classifications that are sufficiently closely related that they would be missed in studies even at the 3-digit level. These allocative channels by which price affects output turn out to be surprisingly large and influential compared to the more traditionally

anticipated, aggregate output channels ...

Fourth, the best current, empirical estimates (as opposed to simulation constructions) of the oil price-GDP elasticity are around -0.055. This is the cumulative effect on GDP over a 2-year period of a shock in one period only, regardless whether the price increase is sustained.

Finally, findings from studies of the effects of oil prices on the stock market parallel the findings from more direct examination of current activity in the form of GDP.”

## 1.2 Economic Cost of Energy

It is possible to examine in several ways the ratio of the cost of energy to a society compared to the benefits of using it to generate wealth. Most explicitly this is accomplished by dividing the money required to buy energy by the total gross domestic product:

$$\text{Economic Cost of Energy} = \frac{\text{Dollars to Buy Energy}}{\text{GDP}}$$

Equation 1: Hall and Klitgaard, 2012

When this ratio is low, typically around five percent, economies grow strongly (Hall and Klitgaard, 2012). When this ratio is high, about ten percent (and, historically, up to fourteen percent), recessions tend to occur (Hamilton, 2009). For example, in 2007 over eight percent of US GDP was spent on the acquisition of energy necessary to produce the goods and services that comprised the GDP. A sudden

climb (followed by a subsequent decline) in the proportion of the GDP spent for energy occurred in the 1970s and also the mid-2008 “oil price shocks” (Hall and Klitgaard, 2012). Energy needs are relatively inelastic (i.e. use does not decrease in proportion to increases in price because of its critical importance to all we do). Thus, rapid increases in the economic cost of energy (e.g. from five to ten percent) result in the diversion of funds from what is typically devoted to discretionary spending to energy acquisition (Hall and Klitgaard, 2012). Consequently, large changes in energy price influence the global economy, and increases in energy cost can have large and adverse impacts on developing economies.

The energy and economic communities currently host strongly polarized discussions about whether the quantity and quality of fossil fuel resources available to society are declining and, if so, are they best considered from the perspective of the potential repercussions that they would have for societal well-being and economic growth. Some of these arguments are best considered using the concepts of “net energy” and “energy return on investment” (EROI). Net energy analysis is sometimes called the assessment of energy surplus, energy balance, or, as we prefer, EROI.

## 1.3 Aims and Research Questions

The objectives of this research are to review the current and historical EROI for fossil fuels and their alternatives, and then to examine the relationship between sev-

eral energy indices, including EROI at the societal level, and human well-being. We hypothesize that access to cheap, abundant and high EROI energy sources is related to an individual's and society's ability to attain a higher "quality of life."

Then we use the results to provide insight to those governmental and non-governmental organizations involved in formulating development strategies in an uncertain energy future.

## 1.4 Methodology

Net energy analysis is a means of measuring the energy surplus of various fuels by calculating the difference between the energy delivered to society and the energy invested in the capture and delivery of that energy. This technique enables the relations between energy flows and economic growth and human well-being in a society to be explored (Murphy et al. 2011). Traditionally, economic growth is measured by changes in the production of goods and services. These goods and services are physical manifestations of the net energy once delivered to society (Hall, 2011).

### 1.4.1 Defining EROI

Energy return on investment (EROI, or sometimes energy return on energy invested, EROEI) is the ratio of energy returned from energy exploration and exploitation activities compared to the energy invested in those energy-gathering processes. EROI is calculated using the following generalized equation:

$$\text{EROI} = \frac{\text{Energy returned to society}}{\text{Energy required to get that energy}}$$

Equation 2: Hall, Balogh and Murphy, 2009

The numerator and denominator in Equation 2 are usually defined using the same units. Sometimes corrections are used to adjust for the quality of the energy obtained or used. Different investigators may use different boundaries for their analysis generating different results and leading to controversy.

## 1.5 History of EROI Concept

The theory of EROI was based on Howard Odum's teachings on net energy (Odum, 1972, Odum, 1973). The concept was first formally applied to fuels (as net energy) in Hall and Cleveland's 1981 paper "Petroleum Drilling and Production in the US: Yield per Effort and Net Energy Analysis." Studies by Herendeen and Plant, 1981 and Herendeen, 1988 centered on the "Energy Cost of Energy," which is, for all intents and purposes, the same idea as EROI although not expressed quite the same. Other early conceptions of net energy analysis can be found in publications by sociologist Leslie White (1959) and economist Kenneth Boulding (1966).

Hall et al. (1979) published the first article to use the term EROI. This work was developed further and more broadly received in a paper published in *Science* several years later (Cleveland et al. 1984). A more detailed and comprehensive summary of the literature on EROI was compiled and published in 1986 in *Energy*

and Resource Quality: *The Ecology of the Economic Process* by Hall, Cleveland and Kaufmann (1986).

Interest in this theory lagged throughout the “energy glut” of the late 1980s to about 2005 but has become popular again within the “energy community” with the increase

in oil prices during the last decade (Hall and Klitgaard, 2012). This has resulted in a flurry of new EROI-related papers (see MDPI Sustainability 2011 (Hall, 2011); these papers have just been published as a separate book with Hall as editor and MDPI as publisher).

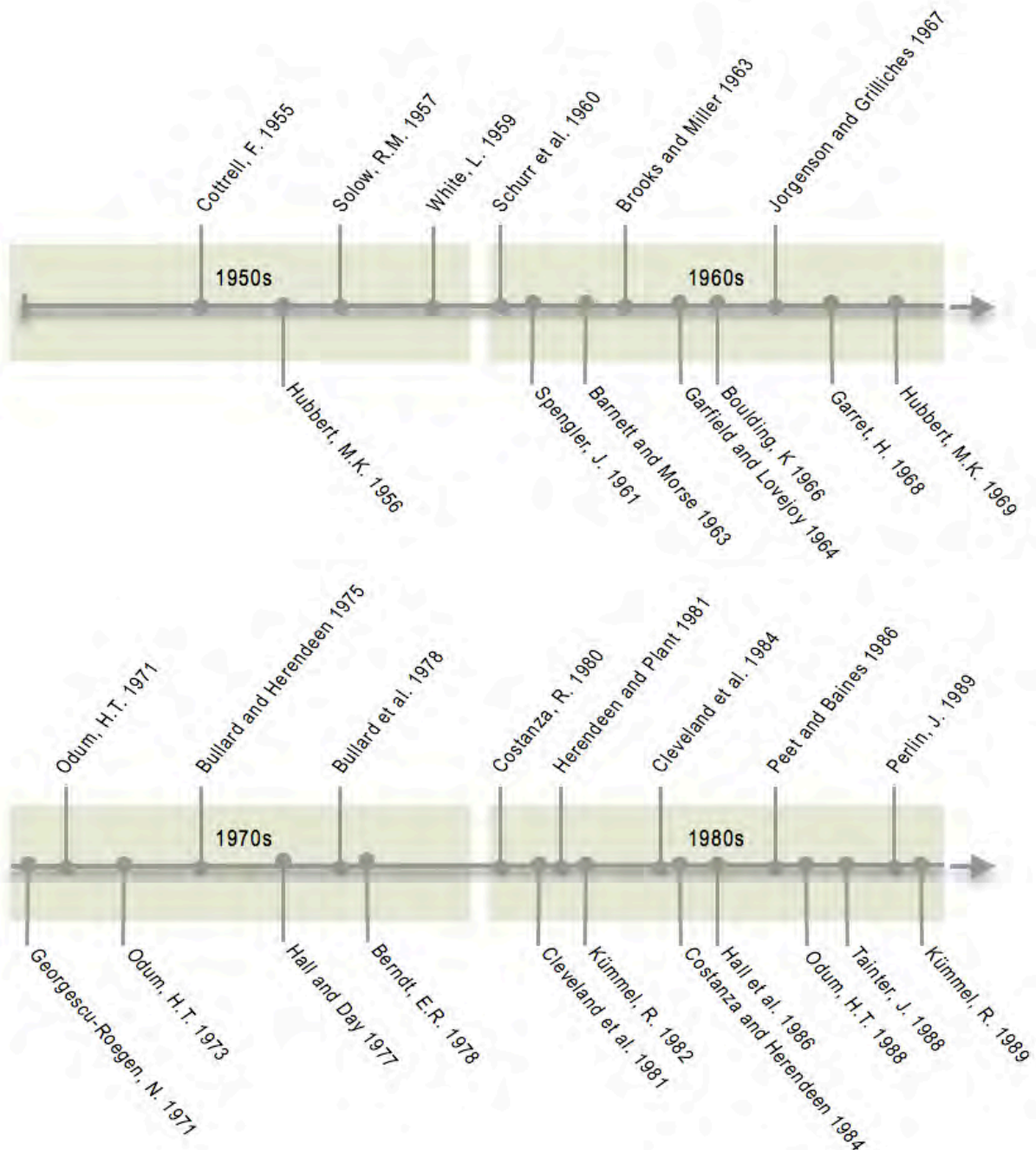


Figure 1.2: a (top) and b (bottom): A timeline (not drawn to scale) of influential works in the fields of energy science, EROI, biophysical economics and net energy.

Note: Solow (1957) is included because his influential paper neglects energy.

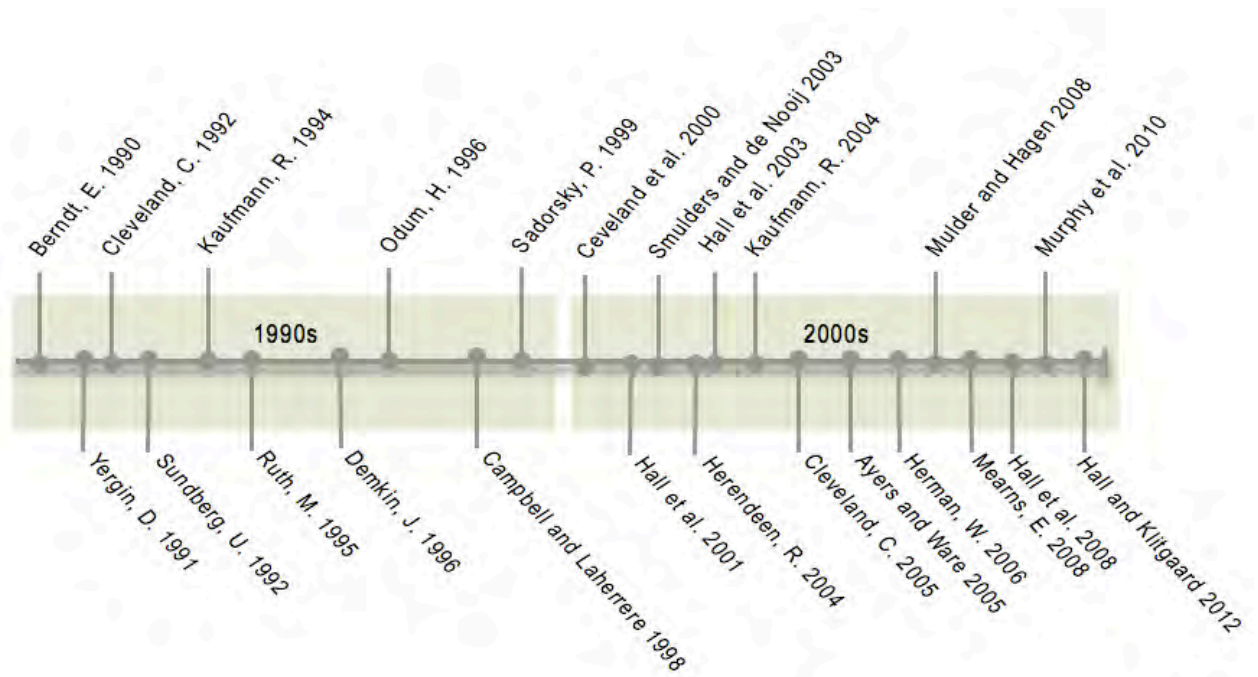


Figure 1.3: A timeline (not drawn to scale) of influential works in the fields of energy science, EROI, biophysical economics and net energy published in the 1990s and 2000s.

As of this writing, there have been few quantitative studies of the EROIs of energy producing systems that existed in the medium or distant past. This is not surprising as the very concept of energy was little understood until about 1850 and little or no data on these systems was collected. One exception is the detailed assessment of the energy cost of energy in early Sweden by Sundberg (1992). Very productive metal mines and an aggressive foreign policy backed by high quality metal weapons made Sweden the most powerful country in Northern Europe from 1560 until 1720. Enormous amounts of energy were required for this mining and smelting activity. The source of this energy was charcoal made from wood cut from Swedish forests. This was needed to produce the high temperatures required for metal production. Hall and Klitgaard (2012) examine Sundberg's calculations:

“a typical forester and his family, self-sufficient on 2 hectares of farmland, 8 hectares of pastures and 40 hectares of forest (collectively intercepting 1500 TJ of sunlight) generated approximately 760 GJ of charcoal per year for the metal industry. This required about half a GJ of human energy or 3.5 GJ if we include the draft animal labor. This yields a rough EROI of the human investment as high as 1500:1, or some 250:1 if we include the animals. But that is just the direct energy, as it took 105 GJ to feed, warm and support the farmer and his family (which includes his replacement) and probably at least that to support the animals.” (Hall and Klitgaard, 2012)

They conclude that if both direct and indirect energy are included, the EROI is reduced to approximately 4:1 (Hall and Klit-



gaard, 2012). As long as the Swedish forests were not over harvested, this system was sustainable. Unfortunately this was not the case. Severe over harvesting resulted in insufficient resources to maintain the metallurgy industry. By the middle of the 19th century many Swedes emigrated from Sweden in search of more prosperous opportunities (Sundberg, 1992).

## 1.6 Approaches to deriving EROI

Deriving energy gains for an energy-producing facility (or a series of such facilities, such as the collective oil and gas wells for a country) is usually straightforward since energy production statistics, in physical, or less commonly, monetary units are normally maintained. Deriving energy costs is usually much more difficult. There are three main methods that have been used by investigators in the past to generate energy costs: 1) a "process based" approach where all inputs are measured in physical units and where energy costs per physical unit are reasonably well known: 2) data collected on energy use by main sectors of the national economy by governments. These data are collected by professionals through questionnaires and follow ups to major industry members. In the past in e.g. the US they were supplied with error estimates which were normally in the vicinity of 5 percent. 3) the use of financial data which is then converted to energy use through the use of an energy intensity value representing the energy used per monetary flow in that society. This can be done most easily but least accurately by deriving a mean energy intensity for the national

economy as a whole, which is done easily and straightforwardly by dividing the national annual energy use by the GDP for that same year or series of years. For example in 2008 about 8.3 MJ were used per dollar of GDP for the US economy. Of course different aspects of the economy are more and less energy intensive than this mean, with "engineered" projects being more energy intensive than national mean values, and financial activities are less so. In the 1970's Hannon, Herendeen and Bullard at the University of Illinois undertook detailed energy "Input-Output" analyses of the entire US economy where both direct and indirect energy used to generate goods and services were assessed by examining the energy intensity of each sector (including the energy costs of the goods and services it purchased from). These analyses provided for the first and only time a quite detailed estimate of the energy used to generate a unit of essentially every good and service of the entire economy. Unfortunately these assessments are very out of date. Much more recently, but rather more opaquely, the Carnegie Mellon "Green building" program has assessed a number of the components of the economy. These studies appear to be in rough agreement when energy intensities are corrected for inflation, and we can conclude that "engineered" projects used about twice the energy per dollar spent as the national mean and financial services about one third (See Murphy and Hall (2011) and Prieto and Hall (2012)). While it is true that different engineered and different financial services use more and less energy

per dollar according to these I-O analyses, a large industry such as a petroleum corporation uses a mix of inputs from a wide range of engineered and also financial sectors of the economy so to some degree the final energy intensities are likely to “come out in the wash”.

These three methods tend to have a trade-off between accuracy and comprehensiveness. In principal process-based analyses where explicit energy costs are applied to explicit physical units of required inputs should be the most accurate, and financially-based analyses less so. On the other hand there is far more comprehensive data on financial costs, and one can assume that wherever money is spent energy is used. In fact most analyses use some of each procedure. Usually more than half of the energy expenditures are derived from government statistics collected from e.g. the US Bureau of Census on the total energy use of a particular industry (i.e. oil and gas, including diesel for drilling, gas for pumping and pressurizing fields etc.) and a (usually smaller) half from monetary expenditures on “indirect” inputs, including e.g. drill bits, steel forms, cement, pipes, engineering studies, financial services, etc. An interesting comparison was done by Prieto and Hall (2012) where they derived the energy cost of solar PV installations in Spain. They found, perhaps fortuitously, that in 2008 the energy cost per MW derived by multiplying the cost in Euros times the energy intensity of the Spanish economy was almost exactly the same as the energy cost derived from estimating the energy cost of each of thirty some inputs. It would be

good to undertake more such comparative studies so that we have a better idea of what the energy costs of energy really are. However the analyses are done it is usually best to include some sensitivity analysis of the associated uncertainty, and it is probably best to at least start with the protocols set forth in Murphy et al. (2011) unless there is a good reason to do otherwise.

## **1.7 Timing of costs and gains for EROI**

For traditional energy sources, such as conventional oil and gas, investment of energy during the extraction and production process is required. The majority of energy used in the production process is for pressurizing and pumping the field. Initially, however, additional energy is required to prepare the site, drill and prepare the hole and connect to distribution sites. For the oil and gas industry this misalignment of investment and return is unimportant as it is generally an ongoing process, with investments made routinely. An interesting aspect, however, is that when the price of oil goes up there tends to be increased investment in drilling. This results in increases in indirect energy used (i.e. for steel, cement, drilling bits etc.) relative to the direct energy used for production. These increases, during intensive drilling episodes, which tend to occur when oil prices spike, cause an increase in energy costs related to the energy gained from production, resulting in a decrease in EROI. In contrast, renewable energy source development such as photovoltaic and wind turbines require large amounts

of up front energy investment and little continued routine investment. This results in relatively low EROI with less net energy transformed to society, at least initially. Once turbines and panels are operational there is little routine investment and EROI may become more favorable. A discussion of this issue is found in Kessides and Wade (2011).

## 1.8 EROI and Energy Quality

Essentially all energy units measure the ability of a unit of energy to heat water, for that is essentially the only unambiguous way to measure the potency of that energy. Hence most EROI studies begin with an analysis of energy costs and gains in heat or thermal units (e.g. Joules, Calories, BTUs and the like). But the per unit heat or energy content of a given fuel, i.e. the energy density, while the most important, is only one of several important characteristics of the energy quality of a fuel. Quality refers to the ability of one heat unit of energy to do useful work (Hall and Klitgaard, 2012). (A more explicit measure of this kind of quality is called exergy, which is the useful portion of the energy in a fuel, as opposed to that part that will be turned into non useful heat. But this is difficult to implement as the particulars of the use of the fuel is required. Thus it is probably more useful to use thermal values).

Other important characteristics of quality include form (electricity is more useful per heat unit than coal), transportability and ease of use (oil is transported and used today more easily than coal) and many other features, which are often reflected in price

per heat unit. Thus if EROI analyses are to assess the complex combination of physical, technical, environmental, economic, and social attributes that determine a fuel's usefulness to society (Stern, 1993) some correction for energy quality must be undertaken, most commonly by adjusting electricity inputs by a factor of about three (Hall and Klitgaard, 2012). There is no single measure of an energy system which is able to evaluate this multitude of variables. Kaufmann's work suggests that over time, market signals (prices) tend to reflect the perceived economic usefulness of a fuel (Kaufmann, 1994, 2004). Thus it is possible to make a correction for energy quality through the use of prices, e.g. by the use of the Divisia index (Berndt, 1978). King and Hall (2011) found that unsubsidized price of fuels are inverse to EROI (the price of fuels increased as the EROI declined). Many energy analyses use both heat units and some kind of quality correction to give a quality adjusted EROI.

## 1.9 Historical Occurrences of Changing EROI

### 1.9.1 1900-1939

The industrial revolution was in full swing by the early 1900s. Abundant high quality coal (with high EROI), capable of generating an enormous amount of net-energy was harnessed by humans to do all kinds of economic work including: heating, manufacturing, the generation of electricity and transportation. Biomass energy, in the form of wood burning for domestic use (heating and cooking), remained an important contributor to the world's

energy portfolio. During this period the oil industry was in its infancy and was primarily used for transportation and lighting (in the form of kerosene in non-urban/non-industrial regions). High quality oil remained a small energy contributor until the end of the 1930s although rapidly becoming available on a global scale (Hall and Klitgaard, 2012).

### **1.9.2 1940-1979**

The massive WWII war effort during the 1940s saw increased use of coal and oil for the manufacture and transport of war machinery. During the post war era, the great oil discoveries of the early twentieth century found a use in global reconstruction and industrialization. Throughout the 1950s and 1960s the repair of war-torn Europe and the proliferation of western culture resulted in massive increases in the manufacturing and transport of goods and the oil necessary for their use. By the late 1960s the EROI of coal (mostly from deep mines) began to decline while the EROI of oil remained high. The quantity and quality of coal being produced had decreased while world oil production was increasing. The peak of US oil production in 1970 meant an increased reliance on OPEC (Organization of Petroleum Exporting Countries) oil, mostly from the Middle East. The oil price increased, in part, to reflect the increased energy required to purchase this fuel. The price of other economic activities increased at similar rates (Hall and Klitgaard, 2012). Most natural gas was flared during this period. The oil shocks of the 1970s ended this long period of increased oil use.

### **1.9.3 1980-Present**

In the 1980s post “energy price shock” era, oil that had been found but not developed suddenly became worthy of developing, as well as pipelines for gas. World oil resources were developed and overdeveloped. Heating and transportation, historically fueled by coal, had been transformed to use oil and gas. Energy from coal production shifted to and remains essential to manufacturing and the production of electricity. The 1990s was a period of abundant oil and plummeting oil prices bringing the real cost of oil back to that of the early 1970s (Hall and Klitgaard, 2012). Discretionary spending, often on housing, increased. Discretionary spending decreased with the energy price increases from 2007 to the summer of 2008. This extra 5 to 10% “tax” from increased energy prices was added to the US (and other) economy as it had been in the 1970s, and much of the discretionary spending disappeared (Hall et al. 2008). Speculation in real estate was no longer desirable or possible as consumers tightened their belts because of higher energy costs (Hall and Klitgaard, 2012).

## **1.10 Conclusion**

Thus the 20th century was a remarkable time, characterized not only by terrible wars but also unprecedented increases in population and per capita affluence, fueled by a ten fold increase in our use of energy. Much of the increase in economic activity has been attributed to innovation, technology, the capitalist system, national virtues and other human attributes. Certainly some of these are true, but it seems

to us that it is overwhelmingly the availability of low energy- (and hence financial-) cost energy that has allowed and facilitated the incredible and unprecedented growth of economies. Development success stories such as Japan, Korea, Mexico and now China are countries where economic growth is matched approximately one for one with an increase in energy use, and energy use increases more rapidly than populations. Per capita wealth tends to remain flat where populations grow at the same rate as energy use, such as Costa Rica for much of the last decades of the twenty-first century (Hall, 2000). As we enter the twentieth century it is not so clear that this rapid increase in energy can continue. The production of conventional oil has been flat globally and many developed nations are having to import more and more energy from the less developed world. Economic growth in the OECD countries of Japan, Europe and the United States is much lower than previously and in many cases has ceased. There are many

who argue that while oil and gas can continue to be produced, its increasingly high cost, driven mostly by a declining EROI, as is also the case when substituting alternatives (when relatively complete boundaries are used), makes economic growth difficult or impossible. If this trend continues, which we think very likely, then it is only by increasing efficiency that economies can achieve growth. This is an issue that is quite unresolved now, partly because the necessary inflation corrections are quite uncertain and possibly tainted. All of this makes planning for development increasingly difficult, for many effective development strategies in the past were based on increasing the energy intensity of agriculture or industrial production. We consider this in more detail later.



# 2. Methods



*“In reality, economics is about “stuff,” and the supply of services, all a part of the biophysical world and all requiring energy for their production and use.”*





# Methods

## 2.1 Energy Return on Investment

*Published EROI values for similar fuels sometimes have large variations leading to large differences within the published data for each fuel. Some of this variability represents true geographical, temporal or technical variability, but some is methodological. One important difference is between assessments of a given project vs. that for a nation or region. To reduce these differences Murphy et al. (2011), in "Order from Chaos: A Preliminary Protocol for Determining the EROI of Fuels" derived a standard EROI calculation method. While recognizing the uncertainties involved in and inherent to all EROI calculations, Murphy et al. (2011) proposed that these differences can be largely reduced when assessed by using similar system boundaries. Murphy et al. 2011 recommended both a standard and different subcategories of EROI to try to standardize the approach while leaving room for creativity. Hall et al. 2009 further clarify some past uses of EROI by defining these uses more explicitly.*

## 2.2 Standard EROI (EROI<sub>st</sub>)

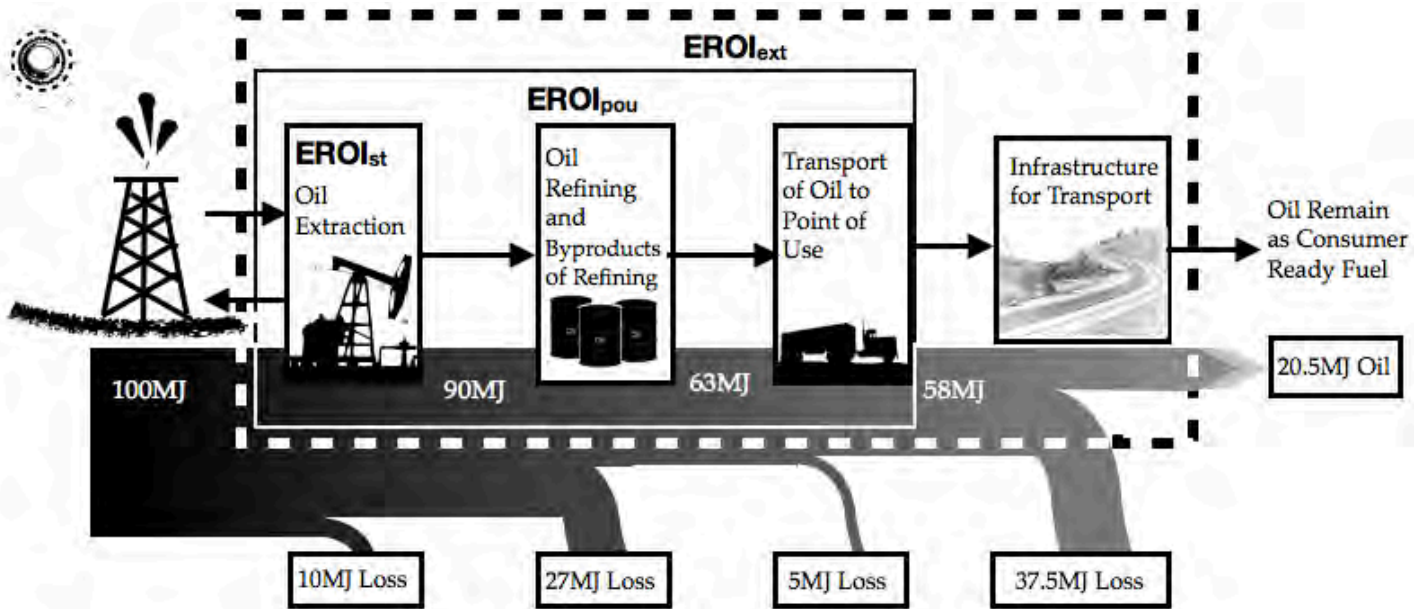
Our first more explicit definition for EROI is the "standard approach" which is in fact that most commonly used, and is what is meant in this publication unless specified more explicitly (as below). The standard EROI approach uses simple energy output (in thermal units such as Joules) divided by both the direct energy (i.e. energy used on the site of production, such as diesel for drilling and natural gas for pumping and pressurizing the field and including site preparation and dismantling) and indirect energy (i.e. offsite energy needed to make the products used on site (but produced off site) such as steel forms, cement, pipes and business services—anything paid for with money and used to generate that output except (usually) wages). This EROI calculation is applied to fuel at the point where it leaves the extraction or production facility (well-head, mine mouth, farm

gate, etc.) unless explicitly stated otherwise. This approach allows the comparison of different fuels even when the analysts do not agree on the methodology that should be used (Murphy et al. 2011).

For example, the finding and extraction of oil and gas in the US requires about a tenth of a barrel of energy for every barrel's worth of energy delivered at the well head. If all of the energy produced is consumed in the production of yet more energy (for example a very poor oil deposit) then the EROI = 1:1 and no net energy is produced to power society.

## 2.3 Point of Use EROI (EROI<sub>pou</sub>)

Point of use EROI is a more comprehensive EROI that includes the energy costs associated with refining and transporting the fuel. As the boundaries of the analysis are expanded, the energy cost of getting the energy to that point increases, result-



$$EROI_{st} = \frac{\text{Energy returned to society}}{\text{Direct and indirect energy required to get that energy}}$$

Equation 3: Lambert et al. 2013

$$EROI_{pou} = \frac{\text{Energy returned to society}}{\text{Energy required to get and deliver that energy}}$$

Equation 4: Lambert et al. 2013

$$EROI_{ext} = \frac{\text{Energy returned to society}}{\text{Energy required to get, deliver and use that energy}}$$

Equation 5: Lambert et al. 2013

$$EROI_{soc} = \frac{\text{Energy returned to society from all economic activity}}{\text{Energy required to perform all economic activity}}$$

Equation 6: Lambert et al. 2013

Figure 2.1: Boundaries of various types of EROI analyses. Standard EROI ( $EROI_{st}$ ) refers to direct and indirect energy used to generate the product at the wellhead. EROI at the point of use ( $EROI_{pou}$ ) and extended EROI ( $EROI_{ext}$ ) include energy loss associated with the processing of oil as it is transformed from “oil at the well-head” to consumer ready fuels (figure adapted from Lambert and Lambert, in preparation, calculations by Hall et al. 2009).

ing in a reduced EROI (Hall et al. 2009).

## 2.4 Extended EROI (EROI<sub>ext</sub>)

This expanded analysis considers the energy required not only to get but also to use a unit of energy, for example to drive a truck, including the energy to counter the depreciation of the truck and roads and bridges, e.g. the energy used to build the required infrastructure as shown in Figure 2.1. In other words, extended EROI is the required EROI at the mine mouth for that energy to be minimally useful to society, although it does not include the energy required to put something into the truck (e.g. grow some grain) (Hall et al. 2009).

Each progressive EROI methodology extends the boundaries of an analysis to become ever more inclusive. Hence, the minimum standard EROI for crude oil production (the minimum energy surplus needed to perform an economic activity such as driving a truck), is not 1.1 to 1, but about three times that, or 3.3 to 1 (Hall et al. 2009, Hall, 2011, Hall and Klitgaard, 2012).

Table 2.1: Minimum EROI values to break-even for conventional sweet crude at various points along the path of using oil using the EROI methodologies explained above

Type of EROI	Minimum EROI Required
EROI <sub>st</sub>	1.1 : 1
EROI <sub>pou</sub>	1.5 : 1
EROI <sub>ext</sub>	3.3 : 1

We employ methodology discussed by Murphy et al. (2011) throughout our fuel-

specific EROI study to achieve the greatest possible degree of scientific rigor and replicability. While that paper embraces “methodological pluralism” and recognizes that several more familiar methods (i.e. energy return from dollars invested) could be employed to perform similar economic analyses, the authors conclude that EROI calculations have proven a robust economic tool and a useful approach for assessing the advantages and disadvantages of a given fuel or energy source when standard methods are used.

## 2.5 EROI for Domestic Oil

For oil-producing countries such as the US or Norway (Hall et al. 2013), or, in principle, Nigeria and Yemen, the EROI for an oil field or for the entire economy 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, business services and so on. The procedures for evaluating the energy costs of the indirect inputs, and some options for sensitivity analysis, are given in Murphy et al. (2011). Unfortunately that kind of information is almost never available for developing countries (China is an exception (Hu et al. 2013)).

## 2.6 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 ( $EROI_{IO}$ ) can be derived with a moderate degree of accuracy, especially for countries whose industrial economy runs principally on oil. The EROI for imported oil is the ratio between the energy value of the amount of fuel purchased with one 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. 7). 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. To put it another way, what proportion of one barrel's worth of oil must be used to generate the money to buy that barrel of oil.

Pakistan, for example, imported an estimated 122.1 million barrels of oil in 2009 (EIA, 2012), which cost the country (i.e. its various buyers) some 7.2 billion USD (EIA, 2012). Thus they received some (122.1 million times 6.1 GJ/Bbl), or 745 million GJ, divided by 7.2 billion USD, or 107 MJ for each US dollar. To get these dollars, Paki-

stan exported 21.1 billion dollars' worth of various commodities (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 7.2 billion dollars to buy its oil, Pakistan had to use some 172 million GJ of energy (7.2 billion dollars times 24 MJ/dollar) to run its farms, factories and so on, an amount equal to some 28 million barrels of oil. Thus it took the energy contained in 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 (i.e. 107MJ/USD divided by 24 MJ/USD). Hence the EROI for imported oil for Pakistan in 2009 was about 4.4:1 (Lambert et al. 2013).

## 2.7 Societal EROI ( $EROI_{soc}$ )

Societal EROI, the most inclusive EROI assessment, is the total energy surplus generation by a society or nation. This is achieved by expanding the boundaries of analysis to include all energies and materials used by a society and the total energy used in the production and acquisition of that energy or material. We employ methodology discussed by Lambert et al., 2013 to get an approximate value from readily obtainable data.

In a world with perfect data collection and unfettered access to it, the calculation for  $EROI_{soc}$  would be quite simple: One would just need to sum all the energy con-

Table 2.2.: Energy (MJ) per unit of fuel ( $E_U$ ).

Fuel	Energy per Unit of Fuel	Source
Coal	4,882 to 29,107 MJ per ton	EIA, 2012a
Oil	5,455 to 6,521 MJ per Bbl	EIA, 2012a
Natural Gas	945 to 1,372 MJ per tcf	EIA, 2012a
Combustible Renewables	5,702 MJ per ton (green wood)	USDA, 2004
Primary Energy	3.6 MJ per kWatt	BP, 2012

Table 2.3.: Price per unit of fuel ( $E_P$ ) in 2009.

Fuel	Price per Unit of Fuel	Source
Coal	10 to 150 USD per ton	EIA, 2012b
Oil	59 USD per Bbl	World Bank, 2012
Natural Gas	4.19 USD per tcf	EIA, 2012c
Combustible Renewables	52 USD per ton (Green wood)	USDA, 2004
Primary Energy	1.1 USD per kWatt	BP, 2012

sumed in a year for a national economy (or at other scales of interest e.g. at the regional level, common political bloc, or at smaller scales such as metropolitan areas, etc.), and then divide that by the energy invested by the energy procuring sector of the economy (e.g. the oil and gas producers, coal mines, nuclear miners and plant operators, and so on). Since a complete set of this biophysical data is not available even for industrialized nations with more extensive energy data collection, we must turn to primary consumption estimates and financial data, both of which are readily available for most countries, to use as a proxy. To do so, we use Kaufmann's (1986) formula (Eq. 7) for the EROI for imported oil as a template for determining the  $EROI_{SOC}$  for national economies that utilize diverse energy flows to power economic production. In a sense we concep-

tualize all fuels as "imported" into the economic system, as firms must pay for the next units of these fuels with revenues generated through economic activity. The  $EROI_{SOC}$  for a country is calculated as the ratio of the amount of energy obtained per the average dollar spent on fuels (a function of the average energy content and price for those fuels) to the average energy "cost" of producing a dollar's worth of production (i.e. the energy intensity of the nation's economy).

This method relies in part on King and Hall's (2011) finding that there is a correlation between EROI and fuel prices: the lower the EROI the higher the fuel price. We expand Kaufmann's (1986) methods for imported fuels (discussed above) to include the energy delivered to the rest of the economy from the energy portion. This includes the use of domestic and im-

$$EROI_{IO} = \frac{\text{Energy in a barrel of oil}}{\text{price of a barrel of oil}} \div \text{Energy intensity of the economy}$$

Equation 7: Lambert et al. 2013

$$EROI_{SOC} = \frac{\eta_1 E_{U1} + \eta_2 E_{U2} + \eta_n E_{Un}}{\eta_1 E_{P1} + \eta_2 E_{P2} + \eta_n E_{Pn}} \div \text{Energy intensity of the economy}$$

Equation 8: Lambert et al. 2013

ported 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; pretax US dollars per Bbl for oil) is assumed to be about the same for each country examined (Table 2.3). For energy-producing nations, energy invested in the extraction of today's and some 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. For energy producing nations, energy invested in the extraction of future energy is assumed to be included within the price of the fuel.

$EROI_{SOC}$ , an estimate of the EROI for an entire economy or nation and one measure of the energy efficiency of that society, is the ratio between all energy supplied to the economy and the energy used in that economy to get it. The numerator is all fuels consumed in a nation's economy in a

Table 2.4: Variables identified in Eq. 7 and 8.

Variables	Meaning	Unit
$E_T$	Total Energy Consumed by Society	MJ
GDP	Gross Domestic Product	USD
$E_U$	Energy per Unit of Fuel	MJ
$E_P$	Price per Unit of Fuel	USD
$\eta$	Ratio of net Energy Contribution	n.a.

year. The denominator is the energy cost to that economy of generating the money to purchase it, either domestically or from imports. It is calculated as the annual monetary cost of each fuel used multiplied by the mean energy intensity of the economy (Eq. 8). The denominator is sensitive to changes in the intensity of the economy, the average price paid for a unit of energy and the country's energy mix. Countries that have access to higher EROI fuels (such as coal or domestic natural gas) would get their fuel at a lower cost (in dollars and MJ). We estimate  $EROI_{SOC}$  starting with an equation from Kaufmann (1986) for imported oil (Eq. 7).

We rearrange the components of the Kaufmann equation so that the numerator consists of the average energy content of a barrel of oil (6119 MJ) divided by its price, and the denominator is the energy intensity of the economy. Next we extend the concept of  $EROI_{IO}$  to derive the energy returned to society from n units of various energy sources to include the energy content and price for all energy sources used, and weight the energy content and price by its contribution to the society being studied (Eq. 8).

Using this method, we can calculate EROI<sub>SOC</sub> with the following readily-available data (Table 2.4): GDP and total primary energy consumption (to derive the energy intensity); the energy (MJ) contained in a unit of energy, EU (Table 2.2) and its price, EP (2009, USD) per unit of energy (Table 2.3); and the country's energy mix (proportion of each fuel). Once we have EROI<sub>SOC</sub>, we have an index of the ability of different societies to generate goods and

services. We can then compare this with different quality of life indices.

## 2.8 Lambert Energy Index (LEI)

In the standard economic model energy and matter are subsumed (if considered at all) under the terms "land," and more recently "capital." Unfortunately, the term "capital" does not fully encompass the breadth and significance that energy and materials play in our economy and world.

# South Africa



We illustrate the concept of EROI<sub>SOC</sub> with data from South Africa for the year 2009. To calculate the numerator, the 'energy obtained by society,' we calculate the average amount of energy able to be purchased per dollar in that nation's economy. We determine this by multiplying the proportion of each fuel's use in the economy by the average energy content of that fuel, and then dividing that product by the price. We do so for all fuels in the economy and sum them to get average (weighted) energy purchased per dollar spent on energy. For example in South Africa, coal is 68% of total energy use for 2009, has an average energy content of 21 GJ/ton and average cost of \$65/ton ( $(68\% * 23\text{GJ/ton}) / \$65/\text{ton} = 240 \text{ MJ}/\$$ ) (World Bank, 2012). Likewise petroleum is 17% of total energy use, has an average energy content of 6.1 GJ/barrel and cost \$60/barrel on average ( $(17\% * 5.9 \text{ GJ/Bbl}) / \$59/\text{Bbl} = 17 \text{ MJ}/\$$ ). And so on for each fuel. The sum of each of these components gives us the average energy obtained per dollar of spending,  $240\text{MJ}/\$ + 17\text{MJ}/\$ + 5\text{MJ}/\$ + 1\text{MJ}/\$ + 11\text{MJ}/\$ = 274\text{MJ}/\$$ . For the denominator, 'energy required to perform economic activity' we calculate the primary energy needed to produce one dollar's worth of economic production (the energy intensity of the economy). For South Africa this is  $21\text{MJ}/\$$  ( $6\text{EJ}$  of primary energy/ 283 billion USD GDP). Thus the EROI<sub>SOC</sub> for South Africa is  $274\text{MJ}/\$$  (energy returned per dollar spent on fuel) /  $21\text{MJ}/\$$  (energy invested per dollar of economic production) = 13:1. Or said another way, South Africans are able to gain (purchase) 13 units of energy per unit of energy invested in the economy.

In reality, economics is about "stuff," and the supply of services, all a part of the biophysical world and all requiring energy for their production and use. Within the discipline of economics, economic activity is treated as unrelated to energy and matter. In fact all forms of economic production and exchange involve the transformation of matter, which in turn requires energy. In the real world economic activity is as much about the transformation and movement of all manner of biophysical "stuff" in a world governed by universal physical laws as it is of demand satisfaction. Ironically, the recent era of abundance has been unrestrained by significant energy or other resource limitations, allowing traditional economic models to avoid focussing on necessary biophysical economic inputs and instead focus on consumer choice and the desire to receive maximum value from voluntary exchange. Operating within an energy abundant world, economic markets seemed to have been able to satiate these needs and wants by applying traditional economic principles. However, as we enter a new era of resource scarcity, energy has become a game changer for anyone attempting to function within or balance a budget. There is no more important issue as we attempt to move beyond the recent financial trauma of the "great recession."

This way of looking at economic growth is not really new. The idea that measuring the economic strength and vitality of a nation must be judged by quantity of resources dates back to the 1700s. Francois Quesnay, the father of Physiocracy and precursor to Adam Smith, professed the

role that natural resources play in the generations of financial security and well-being. " Without that sense of security which property gives, the land would still be uncultivated." The need for material and energy resources as means of generating wealth was a recurring theme in the writings of most early economists. Adam Smith observed: "As soon as the land of any country has all become private property, the landlords, like all other men, love to reap where they never sowed, and demand a rent even for its natural produce."

But GDP and price have become the economic hobbyhorse for those wishing to discuss economic production and development. Our collective focus on money and its investment has divorced us from discussion of the very resources that are necessary to sustain us. Recent economic difficulties have emphasized the necessity for refocussing our attention on the link between access to energy and resources and the quality of human life.

We believe that generating societal well-being and quality of life is determined not just by the amount of energy made available but also by its cost to society and its distribution amongst citizens. In other words it is clear that neither the total Joules delivered, nor their quality (in terms of physical cost), nor the distribution of this energy amongst all citizens alone measures how that energy is to generate human welfare and social well-being. We developed the composite "Lambert Energy Index", (LEI), perhaps analogous to HDI, in an attempt to account in one number for the quantity, quality and



distribution amongst citizens of all energy delivered to a given society. LEI is a composite statistic combining Energy Return on Investment (for society), energy use per capita, and the Gini-Index of income distribution (Lambert et al. 2013). The explicit purpose of LEI is to shift the focus of the analysis of the determinants of 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 relation of energy to other social indicators. The LEI combines three factors:

- *Quantity*: Average energy use per capita: GJ per capita
- *Efficiency*: Energy efficiency of the economic process as measured by  $EROI_{SOC}$
- *Distribution*: Gini-Index (on a zero to one scale; (we assume that the Gini-index of income distribution is a proxy

indicator of energy distribution within an economy))

Since each of these parameters is given in very different units we converted the first two to a zero to one scale (X index) representing where that value (X) was on a scale going from the minimum ( $X_{min}$ ) to the maximum ( $X_{max}$ ) values found for that parameter in that particular analysis.

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

Equation 9: Lambert et al. 2013

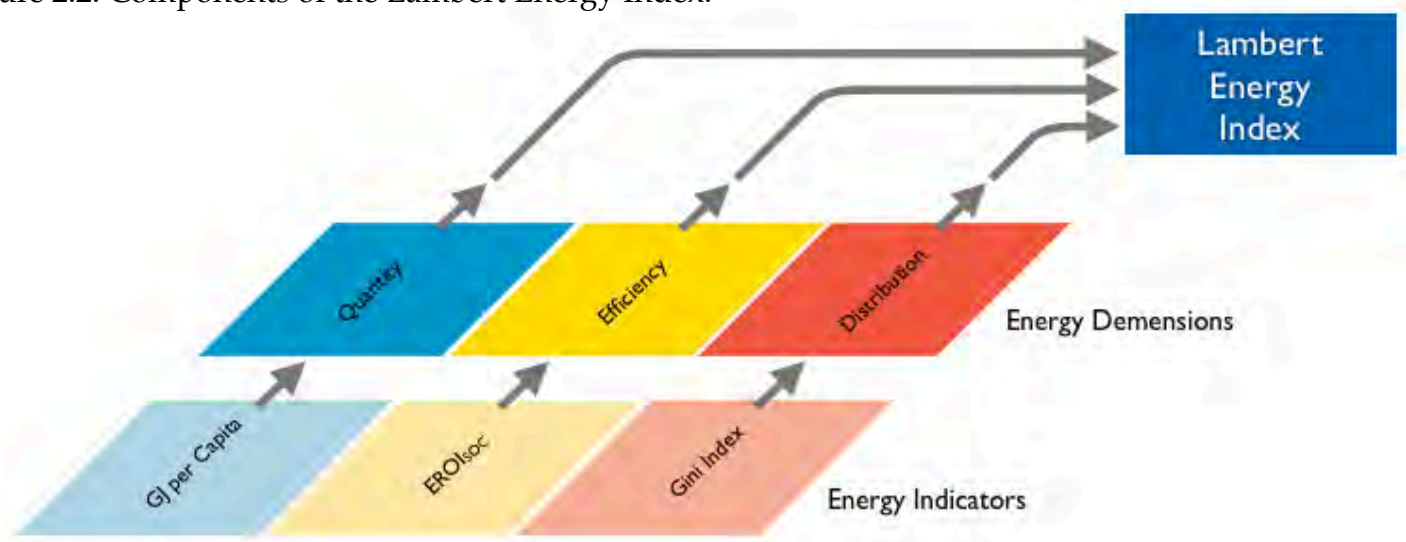
To ensure that all variables have equal weighting we normalized the Gini-index to zero to one, similar to the other two indices (0 being the least energy available to the society and 1 being the most).

The Lambert Energy index, LEI, is generated by taking the geometric mean of the three normalized indices (see Eq 10).

$$LEI = \sqrt[3]{EROI_{SOC(index)} \cdot GJ \text{ per Capita}_{(index)} \cdot (1-Gini_{(index)})}$$

Equation 10: Lambert et al. 2013

Figure 2.2: Components of the Lambert Energy Index.





# 3. EROI of Fuels



*“High EROI fuels allow a greater proportion of that fuel’s energy to be delivered to society ... Conversely, lower EROI fuels delivers substantially less useful energy to society.”*



# EROI of Various Fuels

## 3.1 Introduction

*Our research and that of Dale (2010) summarizes EROI estimates for the thermal energy delivered from various fossil fuels and also the electric power generated using fossil fuel and various renewable energy technologies. These initial estimates of general values for contemporary EROI provide us with a beginning on which we and others can build as additional and better data become available. We have fairly good confidence in the numbers represented here, in part because various studies tend to give broadly similar results when the boundaries are similar. Values from different regions and different times for the same fuels, however, can give quite different results. Given this, we present these values with considerable humility because there are no government-sponsored programs or much financial support to derive such numbers. Nevertheless we see a broad if not precise consistency in the analysis collectively that give us confidence in the general results.*

The generation of EROI values is best developed using either professionally-collected governmental statistics for energy use by the production industries of the countries themselves or by “process analysis;” that is summing the energy used in each process to drill, produce steel and cement etc. in physical units. But this rarely can account for the total energy used for e.g. business services, tax services etc. Such real energy costs usually can be derived only via financial industry- or government-derived data on energy outputs and energy costs (in physical units). But, sometimes, EROI values can be derived only via financial costs that can be translated into energy costs using energy intensities (i.e. energy used “per monetary unit”). In fact, most companies consider their costs proprietary knowledge. Only a few countries, including the US, Canada, the UK, Norway, and China, keep the necessary industry-specific estimates of

energy costs required to perform an EROI analysis. Fortunately, this data, taken as a whole, within a given country, seems to be relatively consistent with various available non-governmental information e.g. values in Gagnon et al. (2009) for all publicly traded companies are in the middle of available values for various countries. However, boundaries and variables differ among nations and may result in conflicting or inconsistent data.

Existing published and unpublished EROI values have been summarized in Hall et al. (1986), Heinberg (2010), Gupta and Hall (2011), and within a special issue of Sustainability. New EROI values have been derived for oil and coal in China and Canada (Feng et al. 2012, Poisson and Hall, in press). Typically estimates of EROI values are calculated by country and by energy source. Here, we organized existing EROI values by year, fuel type, and individual

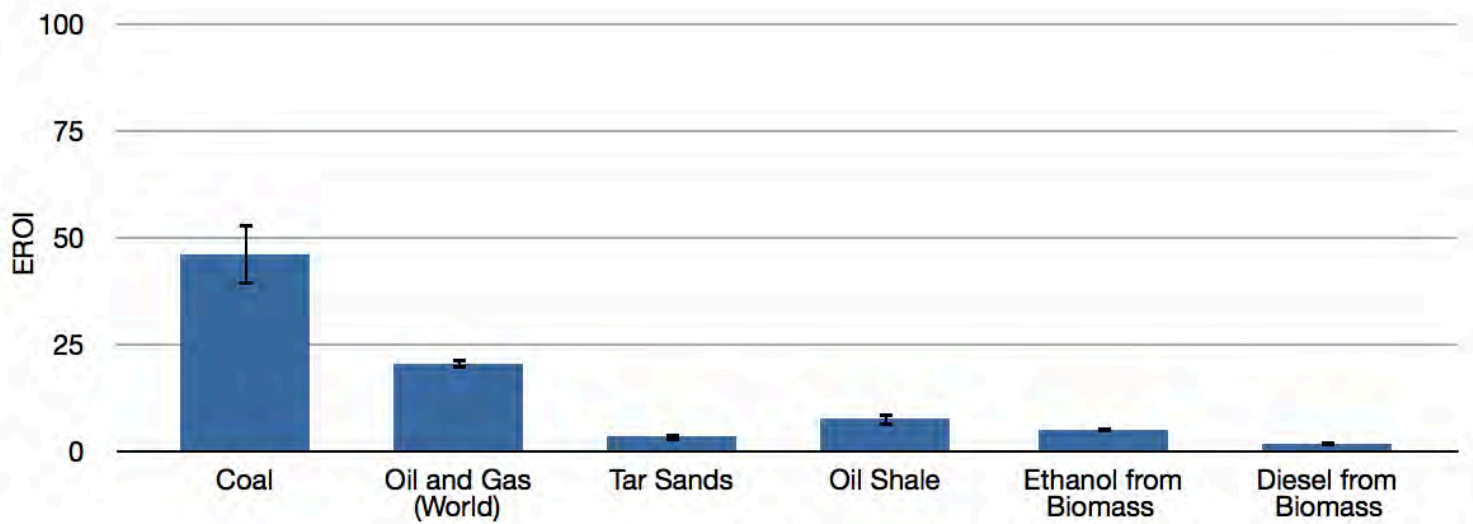


Figure 3.1: Mean EROI (and standard error bars) values for thermal fuels based on known published values (Note: the ranges of the values are much greater than the standard error). Values were derived using known modern and historical published EROI and energy analysis assessments and values published by Michael Dale (2010). See Lambert et al. 2013 for a detailed list of references. Note: please see text for discussion as these values should not necessarily be taken at face value because of boundaries and quality-correction issues.

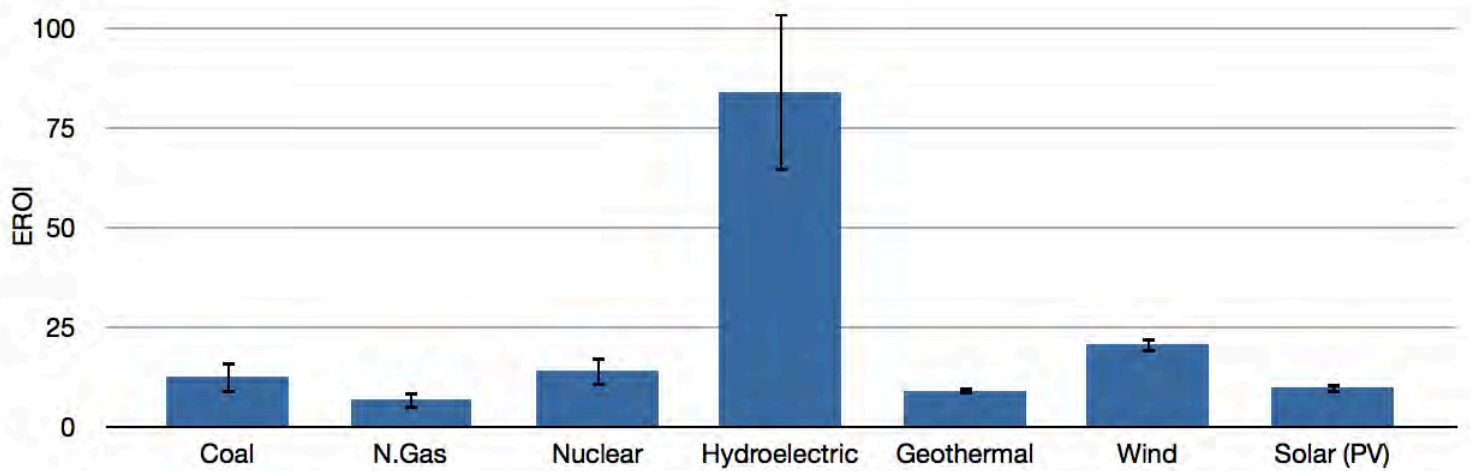


Figure 3.2: Mean EROI (and standard error) values for known published assessments of electric power generation systems (Note: the ranges of the values are much greater than the standard error). Values derived using known modern and historical published EROI and energy analysis assessments and values published by Michael Dale (2010). See Lambert et al. 2013 for detailed list of references. Note: please see text for discussion as these values should not necessarily be taken at face value because of boundaries and quality-correction issues.

study. This information presented in Table 3.1, summarizes existing estimates of EROI values from various energy sources by geographic region and time.

EROI for our most important fuels, liquid and gaseous petroleum, tends to be rela-

tively high (from 10:1 to 30:1 depending on location), but is consistently declining. The EROI for coal is high for the US (60 to 80:1) but much lower in China, and shows no clear trend over time. The EROI of nuclear is moderate (5 to 15:1, including decommissioning costs) but with little recent

Table 3.1.: Published EROI values for various fuel sources and regions, adapted from Murphy et al. 2010.

Resource	Year	Country	EROI (X:1) <sup>1</sup>	Reference
<b>Fossil fuels (Oil and Gas)</b>				
Oil and gas production	1999	Global	35	Gagnon, 2009
Oil and gas production	2006	Global	18	Gagnon, 2009
Oil and gas (Domestic)	1970	US	30	Cleveland et al. 1984, Hall et al. 1986
Discoveries	1970	US	8	Cleveland et al. 1984, Hall et al. 1986
Production	1970	US	20	Cleveland et al. 1984, Hall et al. 1986
Oil and gas (Domestic)	2007	US	11	Guilford et al. 2011
Oil and gas (Imported)	2007	US	12	Guilford et al. 2011
Oil and gas production	1970	Canada	65	Freise, 2011
Oil and gas production	2010	Canada	15	Freise, 2011
Oil, gas & tar sand production	2010	Canada	11	Poisson and Hall, in preparation
Oil and gas production	2008	Norway	40	Grandell, 2011
Oil production	2008	Norway	21	Grandell, 2011
Oil and gas production	2009	Mexico	45	Ramirez, in preparation
Oil and gas production	2010	China	10	Hu et al. 2013
<b>Fossil fuels (Other)</b>				
Natural Gas	2000	US	80	Sell et al. 2011
Natural Gas	1993	Canada	38	Freise, 2011
Natural Gas	2000	Canada	26	Freise, 2011
Natural Gas	2009	Canada	20	Freise, 2011
Coal (mine-mouth)	1950	US	80	Cleveland et al. 1984
Coal (mine-mouth)	2000	US	80	Hall and Day, 2009
Coal (mine-mouth)	2007	US	60	Balogh et al. unpublished
Coal (mine-mouth)	1995	China	35	Hu et al. 2013
Coal (mine-mouth)	2010	China	27	Hu et al. 2013
<b>Other non-renewables</b>				
Nuclear	n/a	US	5 to 15	Hall and Day, 2009, Lenzen, 2008
<b>Renewables<sup>2</sup></b>				
Hydropower	n/a	n/a	>100	Cleveland et al. 1984
Wind turbine	n/a	n/a	18	Kubiszewski et al. 2010
Geothermal	n/a	n/a	n/a	Gupta and Hall, 2011
Wave energy	n/a	n/a	n/a	Gupta and Hall, 2011
<b>Solar collectors<sup>2</sup></b>				
Flat plate	n/a	n/a	1.9	Cleveland et al. 1984
Concentrating collector	n/a	n/a	1.6	Cleveland et al. 1984
Photovoltaic	n/a	n/a	6 to 12	Kubiszewski et al. 2009
Passive solar	n/a	n/a	n/a	Cleveland et al. 1984
<b>Biomass</b>				
Ethanol (sugarcane)	n/a	n/a	0.8 to 10	Goldemberg, 2007
Corn-based ethanol	n/a	US	0.8 to 1.6	Patzek, 2004, Farrell et al. 2006
Biodiesel	n/a	US	1.3	Pimentel and Patzek, 2005

(1) EROI values in excess of 5:1 are rounded to the nearest whole number.

(2) EROI values are assumed to vary based on geography and climate and are not attributed to a specific region/country.

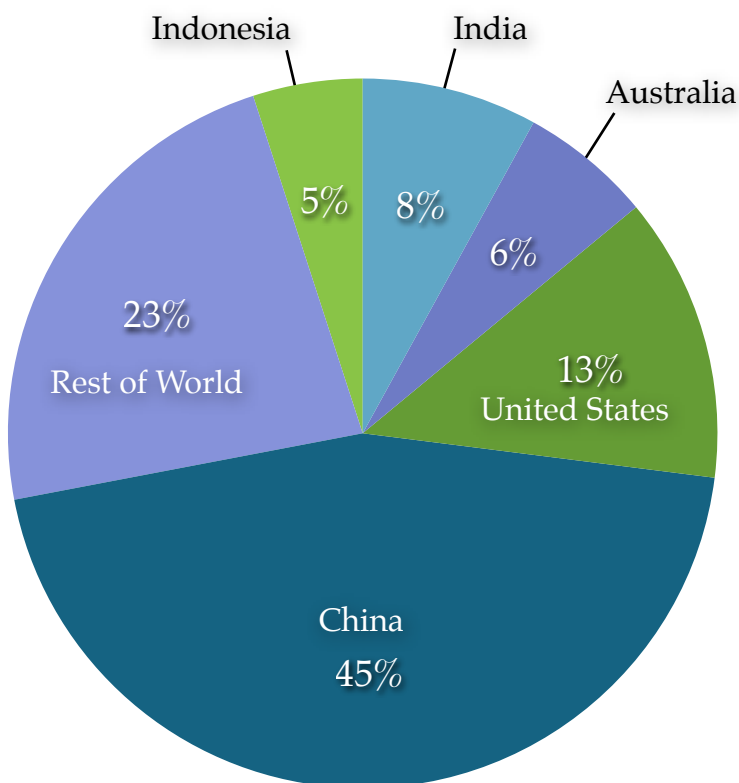
information. The EROI of hydropower is extremely variable, with the best sites in the developed world constructed long ago (Cleveland et al. 1984). Other renewable fuels tend to have low EROIs (below 3 or 4:1; except wind turbines that appear to be at least 18:1) and probably would be lower if the required backups were included (all fuels are summarized in Table 2.1). The most critically important area for EROI research appears to be liquid and gaseous petroleum. Higher exploitation rate tends to decrease EROI relative to secular trends, and may be as important as resource depletion to decreasing EROI. The many trends of declining EROIs for traditional fuels suggest that depletion and increased exploitation rates are trumping new technological developments. Renewable sources of energy tend to have lower EROIs and certainly have problems with intermittency, but EROIs and reliability are probably increasing with technology.

Our research summarizes EROI estimates of the three major fossil fuels, coal, oil and natural gas as well as the most important renewable energies and derives generalized national, regional and/or global EROI values for each fuel respectively. These initial estimates of general trends in EROI provide us with a beginning on which we and others can build as additional and better data become available.

### 3.2 Coal

Much of the discussion about regional and global “peak coal” (e.g., Patzek and Croft, 2010) involves the impact of changing mining technology and capacity on what

Figure 3.3: Global coal production shares (2010)

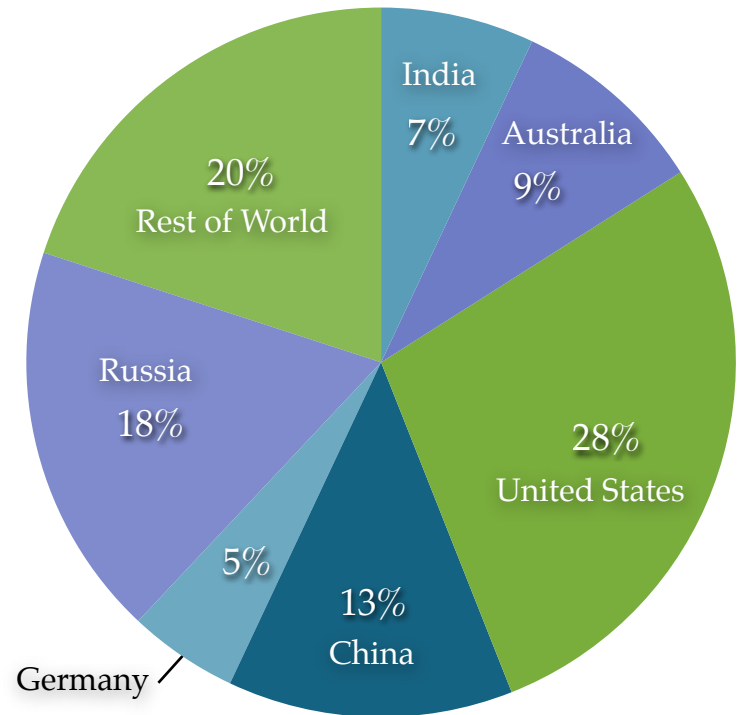


SOURCE: EIA, 2011



can be produced (e.g. the availability of equipment that can mine thin coal seams), rather than the quantity and quality of coal that remains available for extraction. Peak coal will likely have the greatest impact on the world's largest coal user, China, and is thought probable there within a decade or two. Nations with abundant untapped coal resources (e.g. the US and Russia) are likely to be affected only after many decades. Our data on  $EROI_{st}$  of coal represents coal production from the US and China (Figure 3.6). While data on the quantity of coal produced in other areas of the world is available, information on the energy expended to produce this coal remains unclear; this data is therefore not included within this analysis. The total estimated recoverable coal in the US alone is approximately 500 billion tons compared to production in 2009 of about one billion tons. Although it is difficult to predict future production technology, environmental issues, consumption patterns and changes in EROI, it appears that coal may be abundantly available through the next century. The EROI for coal production in the US declined from 80:1 to 30:1 by the 1980s, but returned to 80:1 by about 1990 (Cleveland, 1992). This pattern reflects a shift in the quality and location of coal extracted, the technology employed in the extraction process and especially the shift from underground to surface mining. Initially, coal was mined almost exclusively in the Appalachian mountain region areas of the US using a combination of room and pillar mines with continuous and conventional mining methods. The coal initially extracted from these locations was a com-

Figure 3.4: Global share of recoverable coal reserves



SOURCE: EIA, 2011

### World coal consumption by region, 1980-2010

billion short tons

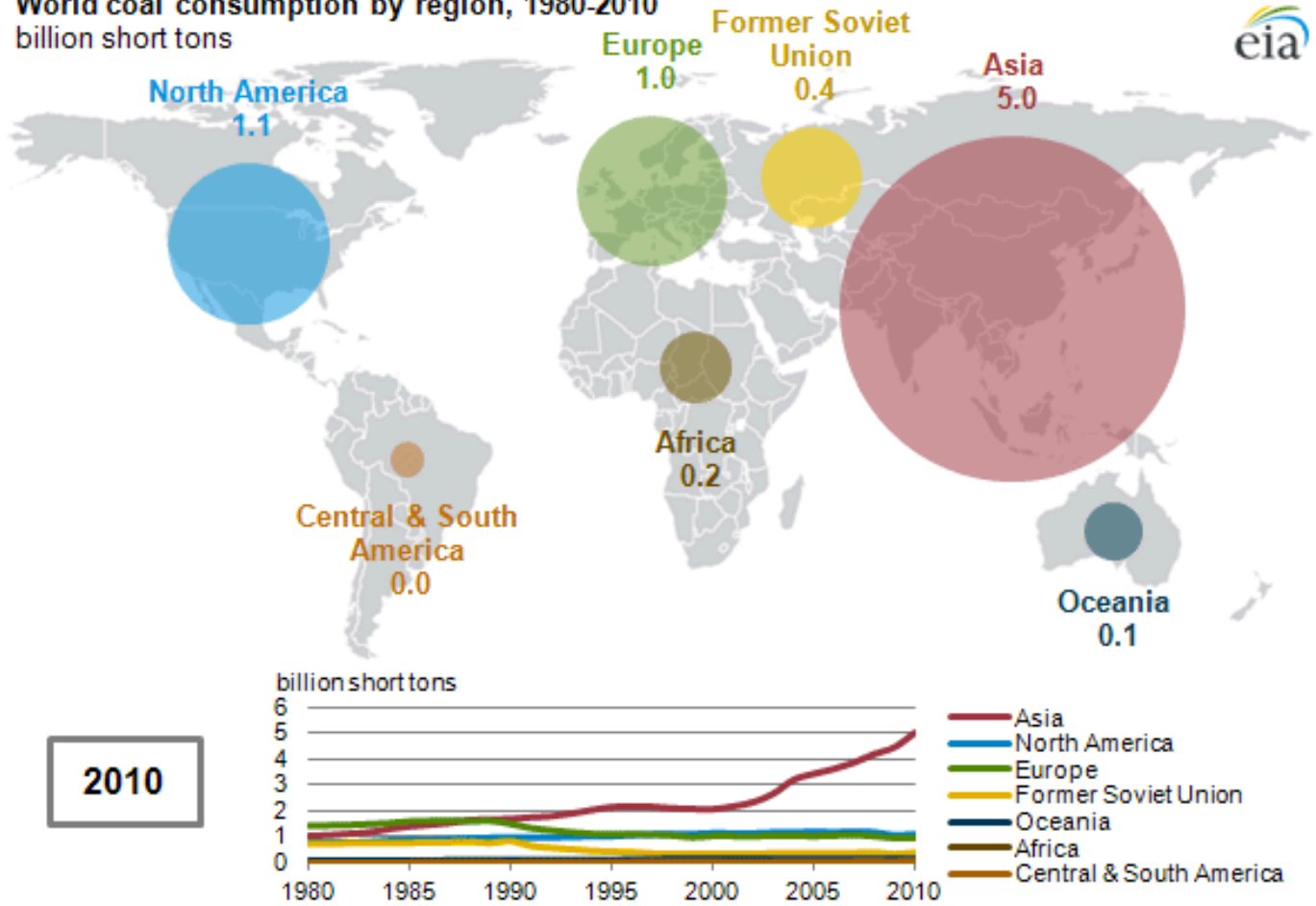


Figure 3.5: World coal consumption by regions (SOURCE: EIA, 2011)

### EROI Values for Coal

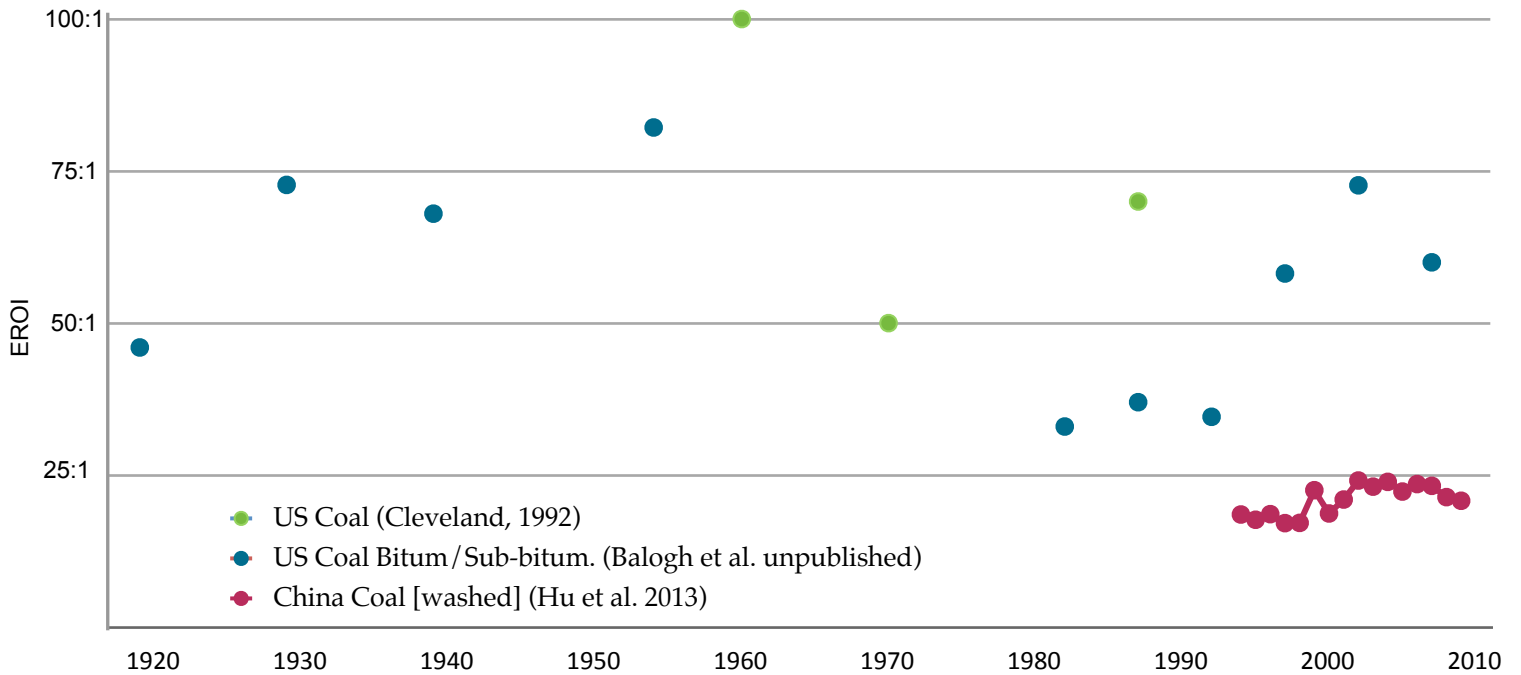


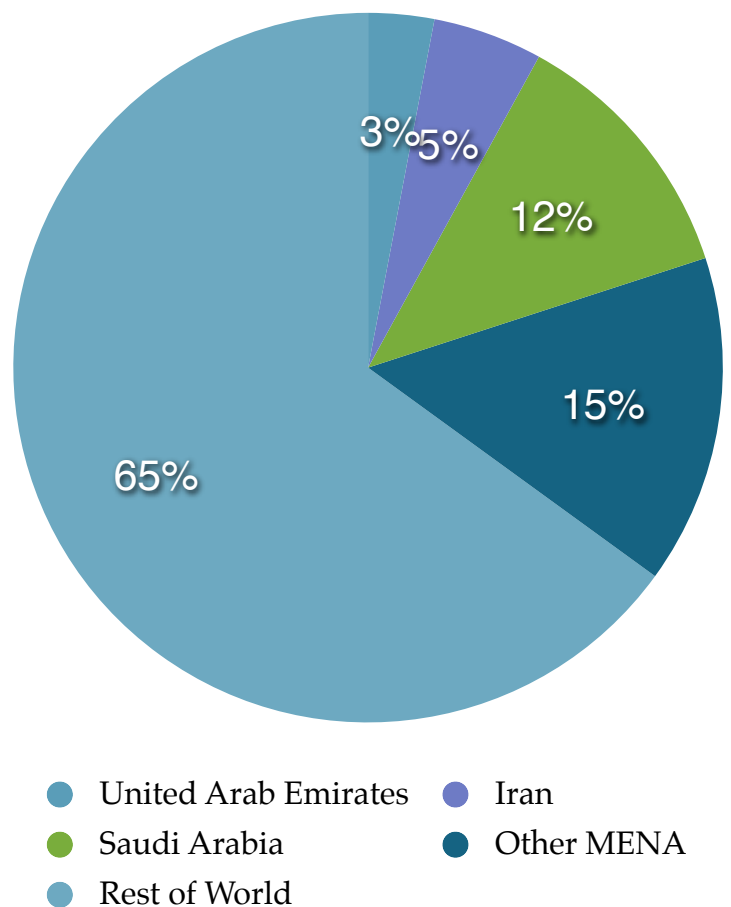
Figure 3.6: EROI of US and Chinese coal production (Hu et al. 2013) derived from various sources (e.g. Hall, Cleveland and Kaufmann, 1986; and as indicated Cleveland, 1992).

combination of anthracite and high quality bituminous coal, coal with high BTUs/ton. As the best coal was used first, the EROI for coal decreased over time. A shift in mining location, to the central and northern interior states, and in extraction method, from underground to surface mining (area, contour, auger, and mountain top mining techniques) resulted in less energy required to mine and clean the coal. The energy content of the coal extracted, however, has decreased. The coal currently mined is principally lower quality bituminous and sub-bituminous coal, coal with much lower BTUs/ton (Hall and Klitgaard, 2012). It is possible that the EROI values for US coal are high because official estimates of the cost of production appear to be incomplete. The EROI of coal for China is much lower reflecting the poorer quality and advanced depletion of coal there.

### 3.3 Oil and Gas

Oil and gas EROI values are typically aggregated together. The reason is that since both are often extracted from the same wells, their production costs (capital and operations) are typically combined, and therefore the energy inputs for EROI calculations are very difficult to separate. Probably the EROI for gas alone would be much higher because typically gas is used to push and pull more valuable oil through formations. Gagnon and Hall (2009) estimated global oil and gas EROI from 1992 to 2006. We also used time series data for oil and gas production in the US going back to 1919 from several sources (Cleveland et al. 1984, Hall et al. 1986,

Figure 3.7: Middle East and North Africa (MENA) share of global liquid fuels production (2010)



SOURCE: EIA, 2011

Global Oil and Gas EROI Values and Trends

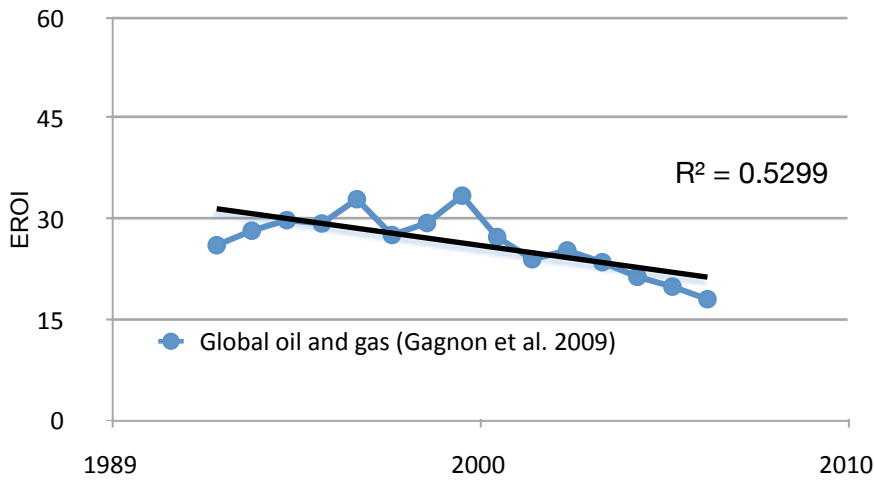


Figure 3.8: Gagnon et al. (2009) estimated the EROI for global publicly traded oil and gas.

Guilford et al. 2011) as well as time series EROI data for Norway (Grandell et al. 2011), Mexico (Ramirez, in preparation), Canada (Freise, 2011, Poisson, in press) and China (Hu et al. 2011).

### 3.3.1 Global Oil and Gas

The EROI for global petroleum production appears to be declining over time, but obtaining reliable data on global petroleum production can be very difficult since most production is from national oil companies, whose records tend not to be public. However, Gagnon et al. (2009) was able to generate an approximate global EROI for publicly traded oil and gas companies using the “upstream” financial database maintained and provided by John H. Herold Company. These results indicate an EROI for publicly-traded global oil and gas of approximately 23:1 in 1992, 33:1 in 1999 and 18:1 in 2005 (Hall and Klitgaard, 2012). This “dome shaped” pattern seems to occur wherever there is a long enough data set, perhaps as a result of initial technical improvements being trumped in time by depletion.

The late 1990s was a time of reduced oil exploration efforts resulting in, apparently, an increase in EROI. The 2000s marked an increase in global oil and gas exploration efforts (Smil, 2011). According to the New York Times, during the beginning of the 21st century oil companies reported deficit spending on oil exploration between 2001-2004; more money had been spent for exploration than had been gained from the dollar value of oil found. Even though the global EROI for producing oil and gas con-

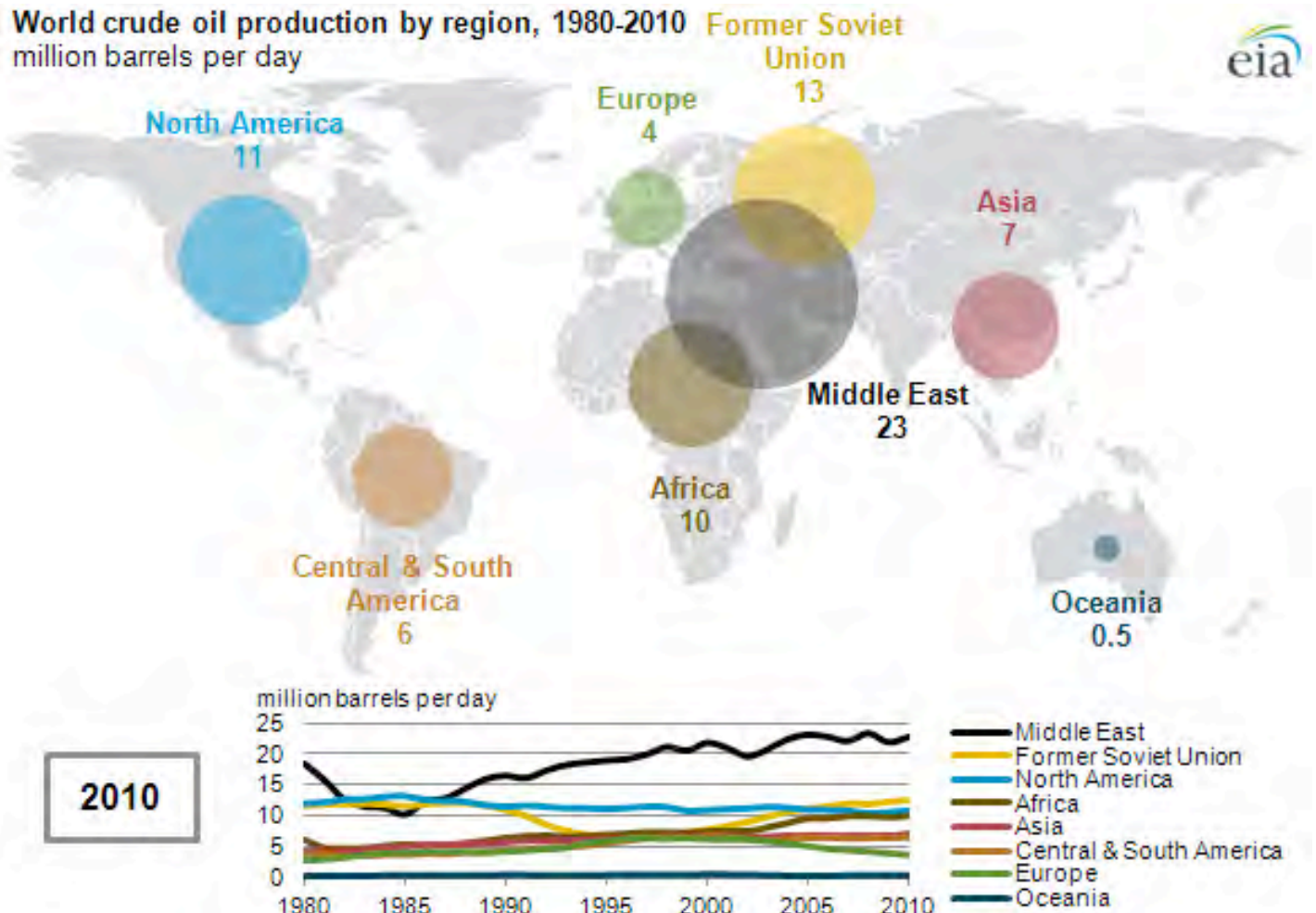


Figure 3.9: World crude oil production by regions (SOURCE: EIA, 2011)

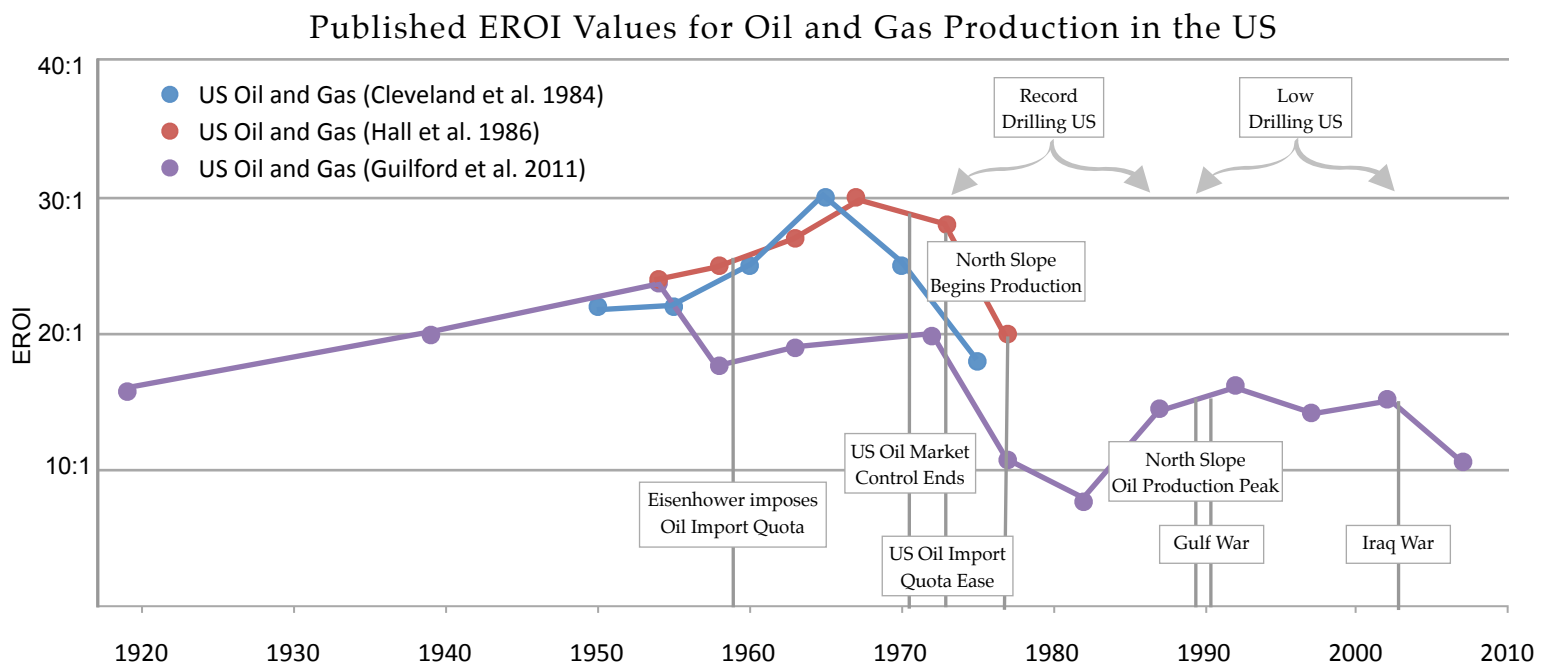


Figure 3.10: Three independent estimates of EROI time series for oil and gas production for the United States plotted along with some important oil-related historical events (Cleveland et al. 1984, Hall et al. 1986, Guilford et al. 2011).

tinues to be reasonably high, it is possible that the EROI of oil and gas will continue to decline over the coming decades (Gagnon et al. 2009). The continued pattern of declining EROI diminishes the importance of arguments and reports that the world has substantially more oil remaining to be explored, drilled and pumped. It does, but oil that requires more energy in the extraction process than is within the extracted oil is clearly not cost effective.

### 3.3.2 United States Oil and Gas

There is a general pattern of decline in EROI over time except as impacted by changes in exploration (drilling) intensity. When the price of oil is increasing (mid 1970s-1980s and late 2000s) exploration intensity, as measured by increased feet drilled and energy used, increases but little or no additional oil is found; hence EROI declines.

Thus overall the EROI for oil and gas production in the US and probably elsewhere appears to be determined mostly by a general increase initially as large new fields are found and developed, and then a decrease over time as depletion of the best prospects occurs. This general trend is affected by the rate of exploitation intensity so that increased oil prices tend to cause favorable conditions for investment, which is reflected in increased drilling rates. But (apparently) there has been historically little additional return from these additional investments, since normally good drilling prospects are derived from a careful consideration of past seismic and drilling results. An additional interesting as-

US Oil and Gas EROI Values and Trends (1990-2010)

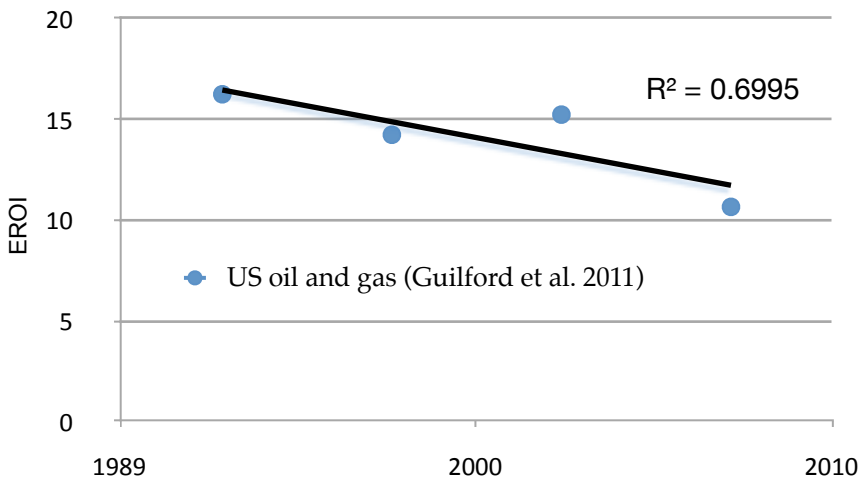


Figure 3.11: US oil and gas values published by Guilford et al. (2011) from 1992 to 2007.

## EROI Values for Oil and Gas Production in Canada

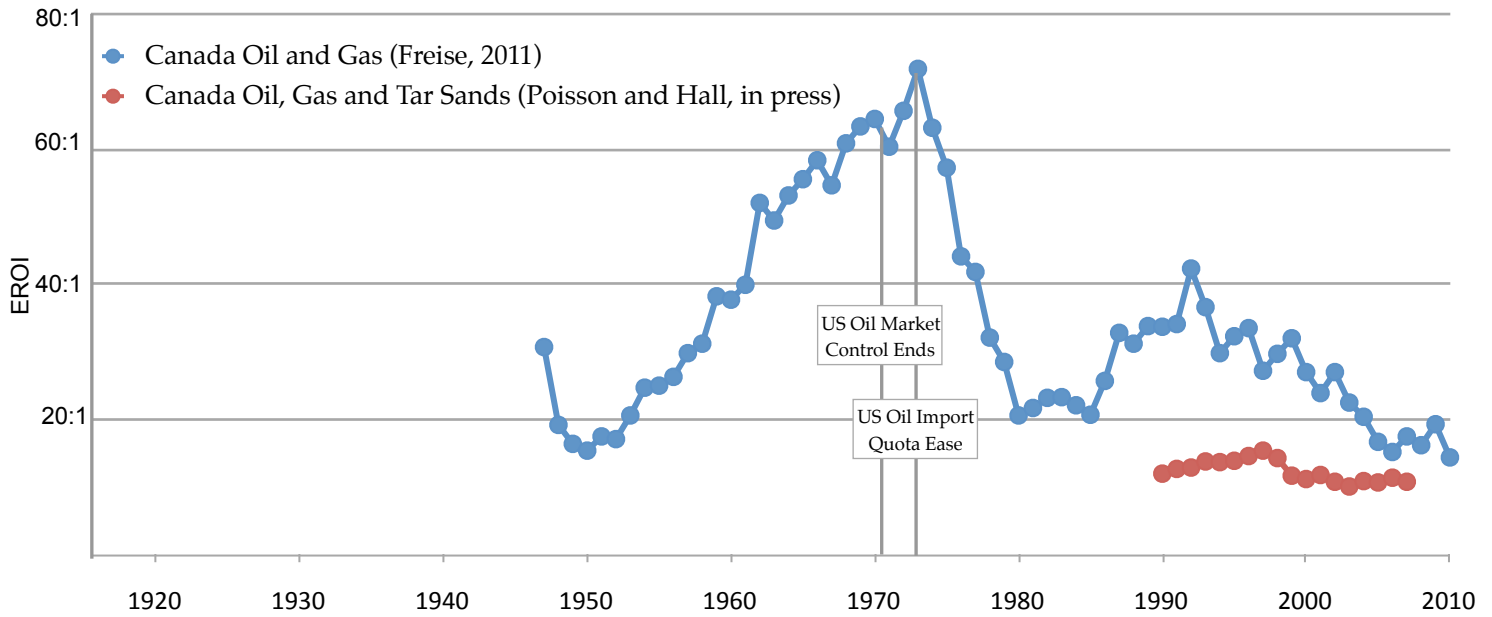


Figure 3.12: Two independent EROI estimates for Canadian petroleum production: oil and gas (blue line, from Freise, 2011) and oil, gas and tar sands combined (red line, from Poisson and Hall, in press).

pect is that the amount of indirect energy compared to direct energy used, as judged by e.g. the results of Guilford et al. (2011), increases during periods of high oil prices and consequent increase in exploration effort.

### 3.3.3 Canadian Oil and Gas

Freise, 2011, estimates the EROI of western Canadian conventional oil and gas over time from 1947 to 2010 as well as western Canadian natural gas from 1993-2009. The oil shocks of the 1970s led to an increase in oil prices and this resulted in an increase in drilling activity and the exploitation of more marginal resources. Poisson and Hall (in press) found that the EROI of both conventional oil and gas and that of combined oil-gas-tar sands have been decreasing since the mid-1990s from roughly 20:1 to 12:1 and 14:1 to 7.5:1, or a decline of 25% and 22% respectively. Poisson and Hall estimated EROI values for Canadian

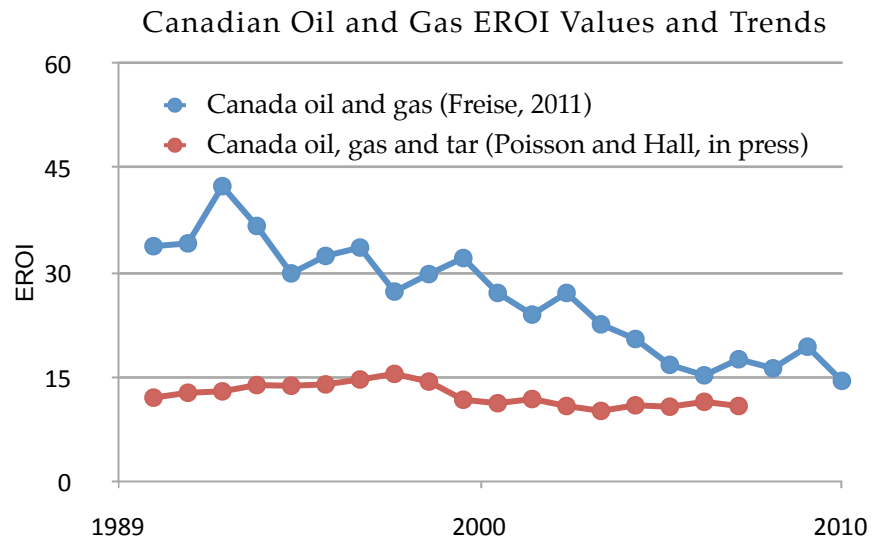


Figure 3.13: Canada oil and gas and oil, gas and tar sand values by Freise (2011) and Poisson and Hall (in press).

oil and gas were about half those calculated by Freise, and their rate of decline is somewhat less rapid. Poisson and Hall (in press) estimate of the EROI of tar sands is relatively low, around 4.5 (conservative estimate, front end of the life-cycle), which decreases the EROI of the oil and gas extraction industry as a whole. Their estimates would be even lower if more elements of the full life cycle were included in the calculation.

### 3.3.4 Norwegian Oil and Gas

Norwegian oil and gas fields are relatively new and remain profitable both financially and with regard to energy production. Grandell et al. (2011) estimate that the EROI of oil and gas range from 44:1 (early 1990s) to 59:1 (1996), to approximately 40:1 (latter half of the last decade). The recent declining trend, is described by Grandell et al. (2011) as probably due to “aging of the fields.” It is likely that varying drilling intensity has had minimal impact on the net energy gain of these fields. Grandell et al. (2011) expects the EROI of Norwegian oil and gas production “to deteriorate further as the fields become older”.

### 3.3.5 Mexican Oil and Gas

Ramirez’s oil and gas trends for Mexico are in preparation and require further analysis (Ramirez, 2012). Mexican production has declined substantially in the past decade because of the aging of the super giant Canterell oil field, which was the world’s second largest producer of oil roughly a decade ago. It is not clear whether newly developed fields in this re-

Norwegian Oil and Gas EROI Values and Trends

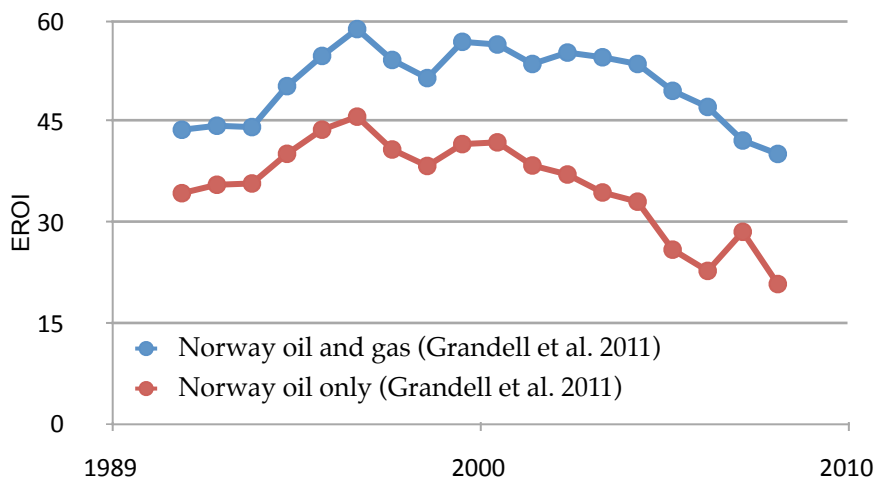


Figure 3.14: Grandell (2011) estimated the EROI for Norway publicly traded oil and gas.

Mexican Oil and Gas EROI Values and Trends

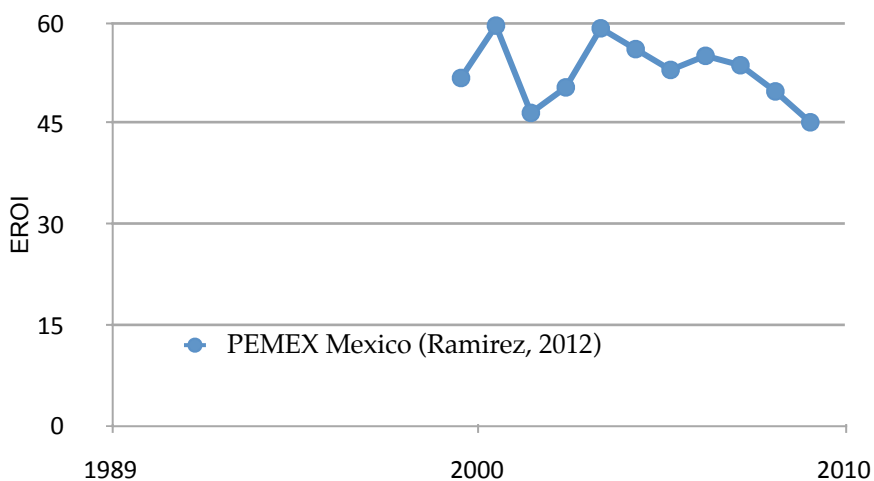


Figure 3.15: Ramirez (2012) estimated the EROI for PEMEX Mexico publicly traded oil and gas.



gion can make up for the loss in production of Canterell.

### 3.3.6 Chinese Oil and Gas

The EROI for the Daqing oil field, China's largest, declined continuously from 10:1 in 2001 to 6:1 in 2009. Meanwhile, China's use of oil has expanded enormously so that China has been importing a larger and larger proportion of its oil from the rest of the world. Recently, China has increased its oil exploration efforts tremendously, both inside and outside of China. Even so, Hu et al. (2013) suggests that China appears to be approaching its own peak in oil production.

China Daqing Oil and Gas EROI Values and Trends (1990-2010)

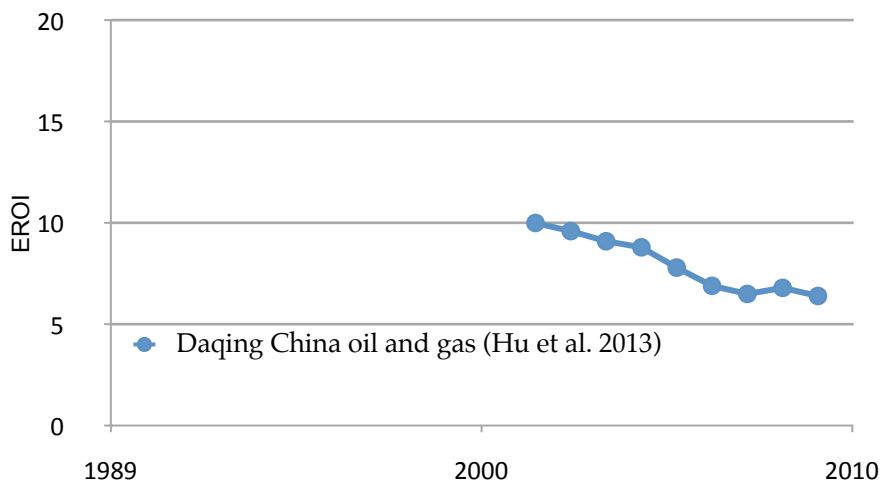


Figure 3.16: Hu et al. (2013) estimated the EROI for Daqing Chinese oil and gas.

### 3.3.7 US Shale Oil

At this time there is considerable interest in conventional oil derived from "shales", e.g. the Bakken formation in North Dakota. Waggoner et al., in preparation, finds relatively high EROI values for more recent shale (e.g. "tight") oil extracted from a few sweet spots which are already becoming depleted. Aucott (2013) found an EROI of tight gas at the wellhead in "sweet spots" in Pennsylvania of 80:1, and preliminary data on US Shale oil suggest that it will not be nearly as high. It is too early to understand the total impact of these new production systems and it is still unclear how these deposits will affect the national or global picture, although the first such resources to be developed (e.g. Barnett, Hainesville, probably Bakken) appear to have already peaked in production (Waggoner, personal communication).

### 3.3.8 Oil Shale

According to Cleveland and O'Connor, Brandt's 2008 and 2009 studies indicate that the EROI value for oil shale (a low grade oil precursor not to be confused with shale oil or "tight" oil) is between 1:1 and 2:1 (self-use energy is included in these assessments). This suggests that, given current technology, the EROI value for shale oil is considerably less than the EROI value for conventional crude oil (Figure 3.17).

Comparison of Published EROI Values at Wellhead

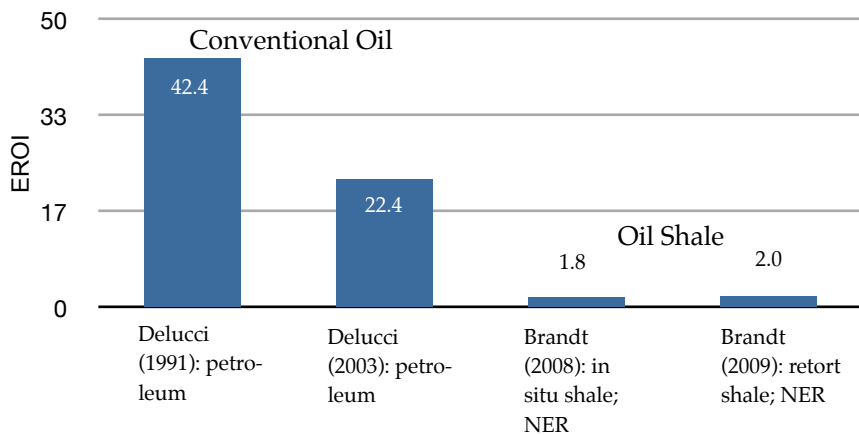


Figure 3.17: A comparison of estimates of the energy return on investment (EROI) for conventional oil and oil shale published by Cleveland and O'Connor (2011).

### 3.4 Dry Natural Gas

Most studies combine data on natural gas with that of oil, making it difficult or impossible to assess the production energy costs of these fossil fuel resources independently. US Natural gas appears to have had two "peaks" in production. The first peak occurred in 1973 as the largest conventional fields peaked and declined. Subsequently, US "unconventional" fields developed to a second peak in recent years (Sell et al. 2011). New technologies such as horizontal drilling and hydrofracturing, are currently keeping the total production levels of non-conventional plus conventional natural gas production at the same or similar rates achieved previously by conventional natural gas alone. The only EROI analysis published on shale gas suggests that at least for favorable locations the EROI may be quite high, as high as 80:1 (Aucott, 2013). This value is considerably greater than the value for combined oil and gas although the EROI value might be much less by the time the gas is delivered to the consumer. Given the numerous

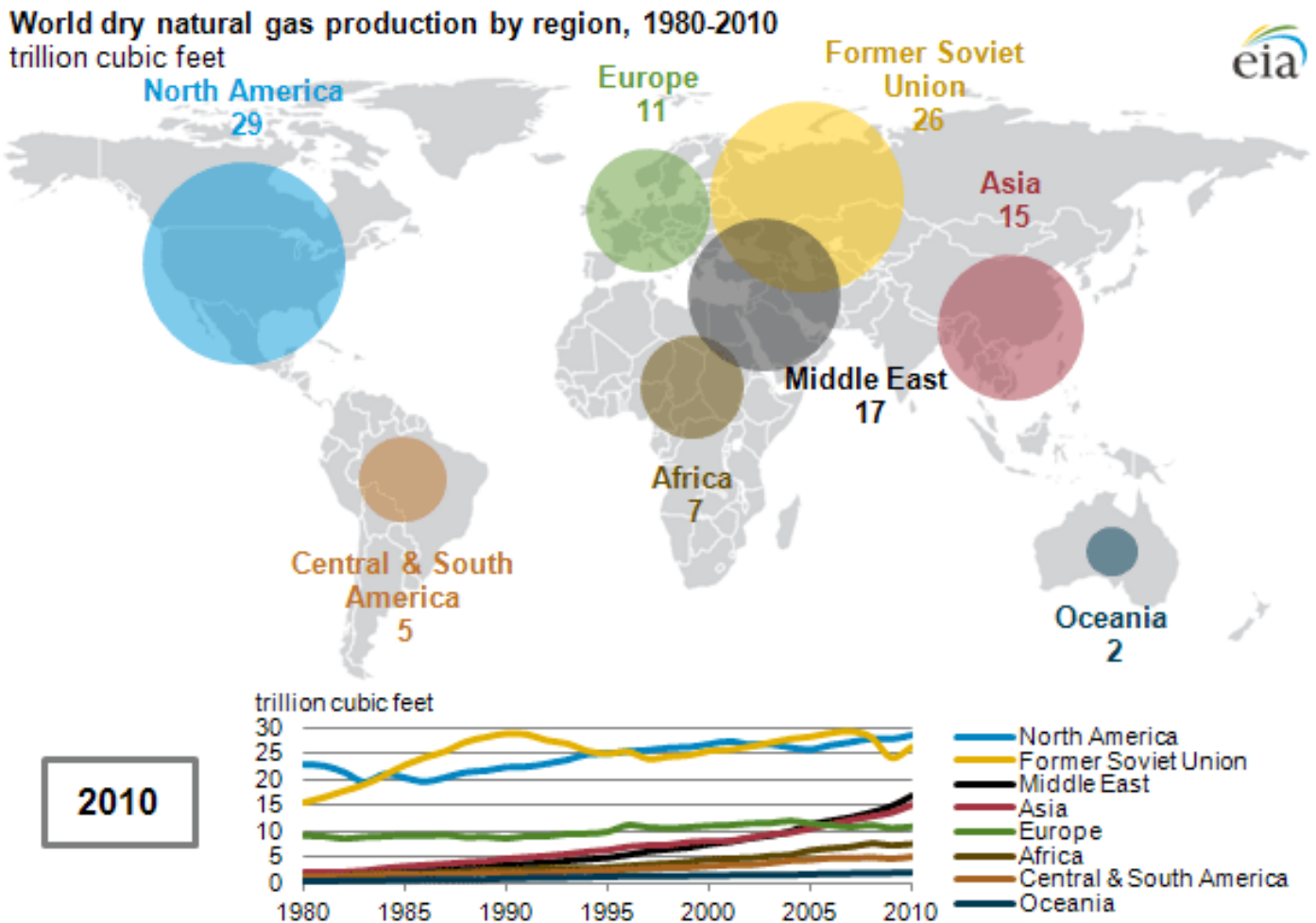


Figure 3.18: World dry natural gas production by regions (SOURCE: EIA, 2011)

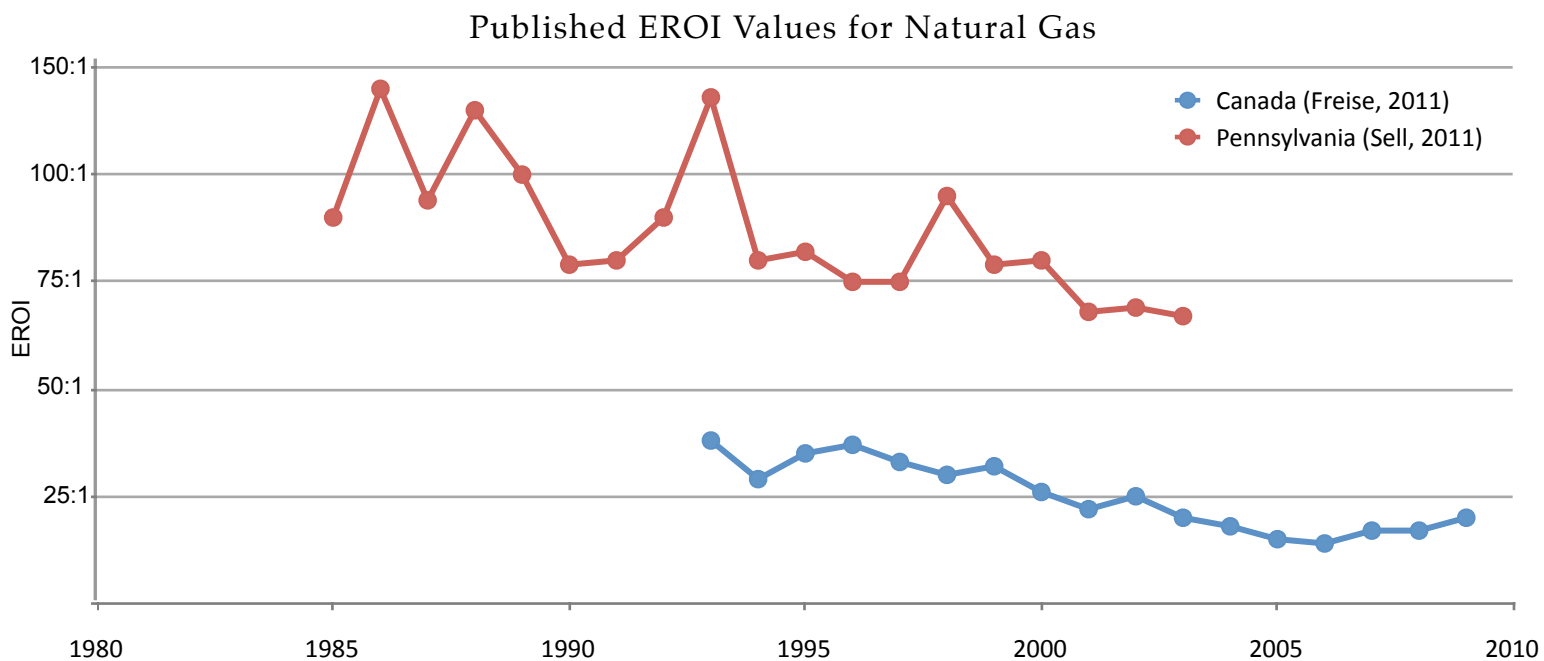


Figure 3.19: There are two published studies on the EROI of dry natural gas (not associated with oil): Sell et al. (2011) examined tight natural gas deposits in the Appalachian Mountains in the US, and Freise (2011) performed an analysis of all conventional natural gas wells in western Canada. Sell's study focused on direct energy costs and might be considered a high estimate.

shifting environmental variables and social issues surrounding horizontal drilling and “fracking”, it is difficult to predict the future of natural gas (Hall and Klitgaard, 2012).

### 3.5 Wind

Alternative renewable energy obviously lacks many of the undesirable features, but also many of the desirable traits, of non-renewable fossil fuels. Specifically renewable energy sources:

1. Are not “energy dense” in the sense that oil is,
2. Tend to be intermittent,
3. Lack transportability,
4. Have relatively low EROI values, and
5. Currently lack the infrastructure that is required to meet current societal demands.

On the other hand renewable energies tend to be cleaner, non-depletable and high quality electricity. Although wind energy is currently one of the world’s most rapidly growing renewable energy sources, it continues to account for less than one percent in both the US and the larger global energy portfolio. When attempting to calculate the energy costs for inclusion within a wind EROI analysis, should one include the backup systems required for the time when there is insufficient wind blowing as well as the initial energy capital costs per unit output? The input for an EROI analysis is the mostly “upfront” capital costs in contrast to the less well known “return” over the lifespan of the system. Therefore, a variable re-

ferred to as “energy pay back time” is often employed when calculating the EROI values of wind and other renewable energy sources. This is the time required for the renewable energy system to generate the same amount of energy that went into the creation, maintenance, and disposal of the system. In both approaches an important issue is the spatial and temporal boundaries utilized to define the energy costs. Thus it would appear that a shift from nonrenewable to renewable energy sources would result in declines in both the quantity and EROI values of the principle energies required for economic activity.

In a meta-analysis of earlier studies on the EROI of wind turbines, Kubiszewski and Cleveland (2010) examined a total of 112 turbines from 41 conceptual and operational analyses. They found an average EROI value of 24.6:1 for all systems studied and an average EROI value of 18.1: 1 for all operational systems. Higher EROI values found in the conceptual studies result from assumptions of more favorable conditions (within simulations) than those actually experienced in real life. For example, English wind turbines were found to operate considerably fewer hours per month than anticipated (Jefferson, 2012). Studies employing input–output analysis were found to have an estimated average EROI value of 12:1 while those utilizing less comprehensive process analysis had an average EROI value of 24:1. According to Kubiszewski and Cleveland (2010) this variation in EROI values (between process and input output analyses) stems from a

greater degree of subjective system boundary decision-making by the process analyst, resulting in the exclusion of certain indirect costs. Examination of concrete input and output data from operational wind turbines appears to offer the best opportunity to calculate wind EROI values accurately.

Kubiszewski and Cleveland (2010) also found that EROI values tend to increase with turbine size. They provide three reasons for this difference:

1. Small turbines are often of older design and can be less efficient;
2. Large turbines have larger rotor diameters and can operate at reduced wind speeds thus capturing wind energy for a larger part of the time and hence operating at higher efficiency;
3. Large turbines are taller enabling them to take advantage of increased wind speeds occurring farther above the ground.

So, despite their larger initial capital investment, large turbines appear to compensate for this with proportionally greater energy outputs. Other factors influencing wind EROI estimates include costs of energy storage, grid connection dynamics and variations in construction and maintenance costs associated with turbine location. For example, off-shore turbines, while located in areas with more consistent wind, are also located in wet salty areas requiring far more maintenance and replacement. Turbines located in windy but remote mountainous areas require long distance grid connections that

result in energy loss and reduced usable energy values (Kubiszewski and Cleveland, 2010).

### 3.6 Solar (PV)

An examination of the EROI literature on solar (photovoltaic) energy generation systems is often contentious. Much of this derives from inconsistencies in the assumptions and methodologies employed and hence the EROI values estimated. The values, assumptions, and parameters included are often ambiguous and differ from study to study, making comparisons between PV and other energy EROI values difficult and fraught with potential pitfalls. In particular, the EROI of PV and other renewables is often estimated without converting the electricity generated into its “primary energy-equivalent” (Kubiszewski et al. 2009).

Additionally, PV EROI calculations appear to reflect some disagreement on the role of technological improvement. Raugeri and Fthenakis (2012) attribute low published PV EROI values to the use of outdated data and direct energy output data that represents obsolete technology that is not indicative of more recent changes and improvements in PV technology. EROI values that do reflect technological improvements are calculated by combining “top-of-the-line” technological specifications from contemporary commercially available modules with the energy output values obtained from well-calculated experimental field data. Other researchers contend that values derived using this methodology do not represent adequately the

“actual” energy cost to society and the many energy costs associated with this delivery process. For example Prieto and Hall (2012) and Palmer (2013) calculate EROI values that incorporate these energy costs using data from existing installations and with more inclusive boundaries. Their EROI values tend to be considerably lower.

Proponents making EROI assessments based on actual operating systems believe that in order to portray PV technology accurately it is necessary to appreciate that at present these systems are constructed almost entirely using high EROI fossil fuels. Also of concern is that PV technology is not a base load technology, meaning that any large scale deployment of PV technology beyond 20 percent of the grid capacity will likely require the construction of large, energy intensive, storage, “smart grid”, or regional sharing infrastructure which, if included within EROI assessments, would likely reduce EROI values considerably

Raugei and Fthenakis (2012) compare the  $EROI_{el}$  (EROI for electricity production) of PV electricity to the  $EROI_{el}$  ranges for oil and coal power thermal electricity production. Their results suggest that the electricity generated by PV has a similar range ( $EROI_{el}$  of roughly 6–12) as the  $EROI_{el}$  of conventional oil-fired electricity systems ( $EROI_{el}$  of about 4–11). Since few locations use oil anymore to generate electricity, the  $EROI_{el}$  of coal-fired electricity systems ( $EROI_{el}$  of approximately 12–24), seems a more appropriate comparison, approximately double that of PV. However it is

probable that their calculations do not take into account the much higher life-cycle greenhouse gas emissions that thermal electricity production, and coal-fired systems in particular, produce (Raugei and Fthenakis, 2012). The energy intensive carbon capture and storage (CCS) required to reduce these emissions to levels equivalent with that of PV electricity production, were they undertaken, might reduce the final coal  $EROI_{el}$  value to values similar to those for PV electricity (e.g. Akai et al. 1997 in Dale, 2010 and Lund and Biswas, 2008). In other words, coal’s higher EROI values are probably subsidized by its atmospheric pollution. The EROI of coal would likely be considerably less if the energy cost associated with future climate change remediation measure were included within the boundaries of EROI calculations. Study of the impact of CCS on the EROI of carbon emitting fossil fuels is required.

Kubiszewski et al. (2009) calculated EROI values using data from 13 analyses of 51 PV systems. These values resulted in an average PV EROI of 6.6:1. Prieto and Hall (2012) examined operational energy costs and gains from a series of PV collector installations in Spain. Their findings suggest a considerably lower EROI value (2 to 3:1 or three times this if corrected for the quality of the electricity). Palmer (2013) and Weissbach et al. (2013) found similarly low values for PV in Australia and for Europe when using comprehensive boundaries and including backup technologies. While some solar advocates have argued that these authors used larger boundaries

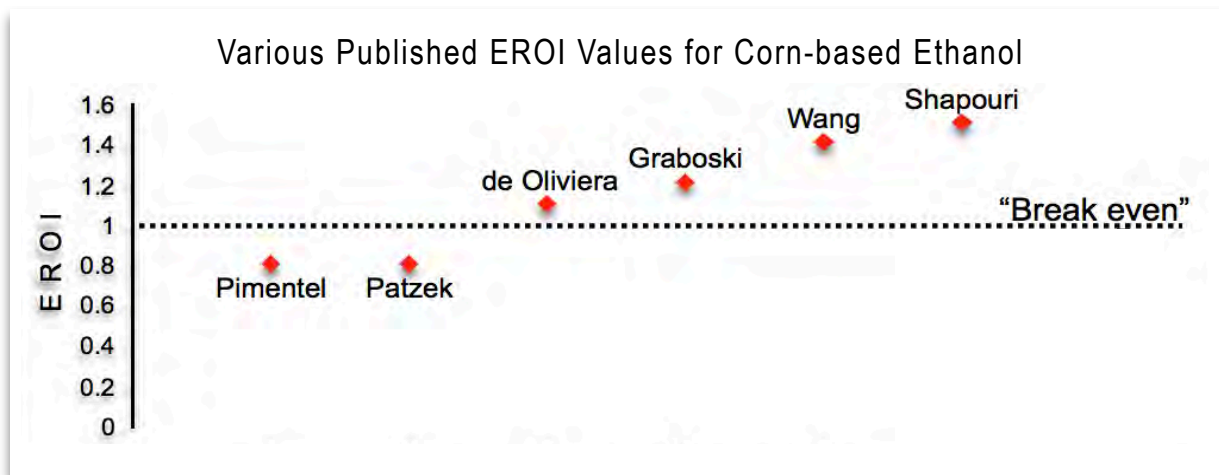


Figure 3.20: Various values published on the EROI of corn-based ethanol for what are purportedly the same fuel production processes.

when examining solar PV vs oil or coal in fact this is not the case since Hall and colleagues attempted to include all energy costs (except labor) in each previous analysis of fossil fuels through analysis of all indirect costs.

### 3.7 Biofuels

According to Murphy and Hall (2010) at least three different methods of net energy analysis have been utilized in the corn-based ethanol energy literature, resulting in three disparate EROI calculations that are “mutually incommensurable.” Patzek (2004) and Pimentel and Patzek (2005) have published EROI figures for ethanol from corn with a less than 1:1 ratio, suggesting that more energy investment is required for corn-based ethanol production than is gained in the fuel produced. Other researchers, outlined in Farrell et al. (2006) and Hammerschlag (2006), have published EROI figures that suggest an energy surplus, with values ranging from 1.2 to 1.6:1. The debate among ethanol researchers has revolved around whether the ethanol pro-

duction process results in a net gain or loss in energy from corn, which appears due principally to methodological assumptions, such as whether or how to include by products (Hall et al. 2011). All of these values are much too low to contribute significant net energy to society (Hall and Klitgaard, 2012). The variation in these findings is typically a result of the choice of which direct and indirect energy costs associated with energy production/extraction are to be included within the EROI calculations: i.e. the boundaries of the numerator and denominator (Hall et al. 2011). Within the ethanol debate, the question is whether one should adjust for:

- non-fuel co-products (such as residual animal feed—e.g. dry distiller’s grains),
- the quality of the fuels used/produced, and
- the boundaries of the denominator (i.e. whether or not to include the energy required to compensate for

environmental impacts in the future) (Hall and Klitgaard, 2012). A more complete discussion of boundary conditions can be found in Murphy et al.'s recent paper, *Order from Chaos: A Preliminary Protocol for Determining the EROI of Fuels*.

Much of the current EROI analysis literature tends to focus on net surplus for a given project, industry, nation, fuel, or resource. Present-day discussions within the field of energy research focus on the "energy break even" point of EROI, i.e. whether the EROI is greater than 1:1.

These arguments are likely to play an important role in the future as other, comparatively low quality, fuels (e.g. oil sands) are increasingly considered or developed to replace rapidly diminishing recoverable supplies of conventional oil and gas (Hall and Klitgaard, 2012). If such non-conventional or alternative energy resources use high quality energy inputs (e.g. conventional oil and gas) for their production, then decreased oil and gas availability would increase the cost of the alternative fuel since high quality (high EROI) energy is used to produce low quality (low EROI) energy. This would reduce its viability and negate possible prospective advantages. On the other hand the EROI of some other biological energy sources (such as sugarcane in Brazil or perhaps biodiesel, especially if used on the farm) may be considerably higher than corn-based ethanol (Dale, 2010).

We believe that the quantity of energy delivered over a specific period of time (the

numerator in the EROI equation) for most fuels, especially alternative fuels, is reasonably well understood. Unfortunately, the boundaries of the denominator, particularly when dealing with environmental issues, are not adequately understood and are poorly quantified (Gupta and Hall, 2011). Another important issue is whether or not to include the energy cost of labor, and if so how. Thus these difficult issues are normally left out of analyses. We believe that most published EROI values, including those we derive here, appear higher (i.e. more favorable) than they might be had better and/or more complete information been available at the time of publication (e.g. on energy required to compensate for environmental costs).

### 3.8 Summary

Fig. 3.21 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 deliver 99 percent of the useful energy (vertical axis) from that fuel to society (Murphy and Hall, 2010). Conversely, lower EROI fuels deliver substantially less useful energy to society (e.g. a fuel with an EROI of 2:1 will deliver only 50



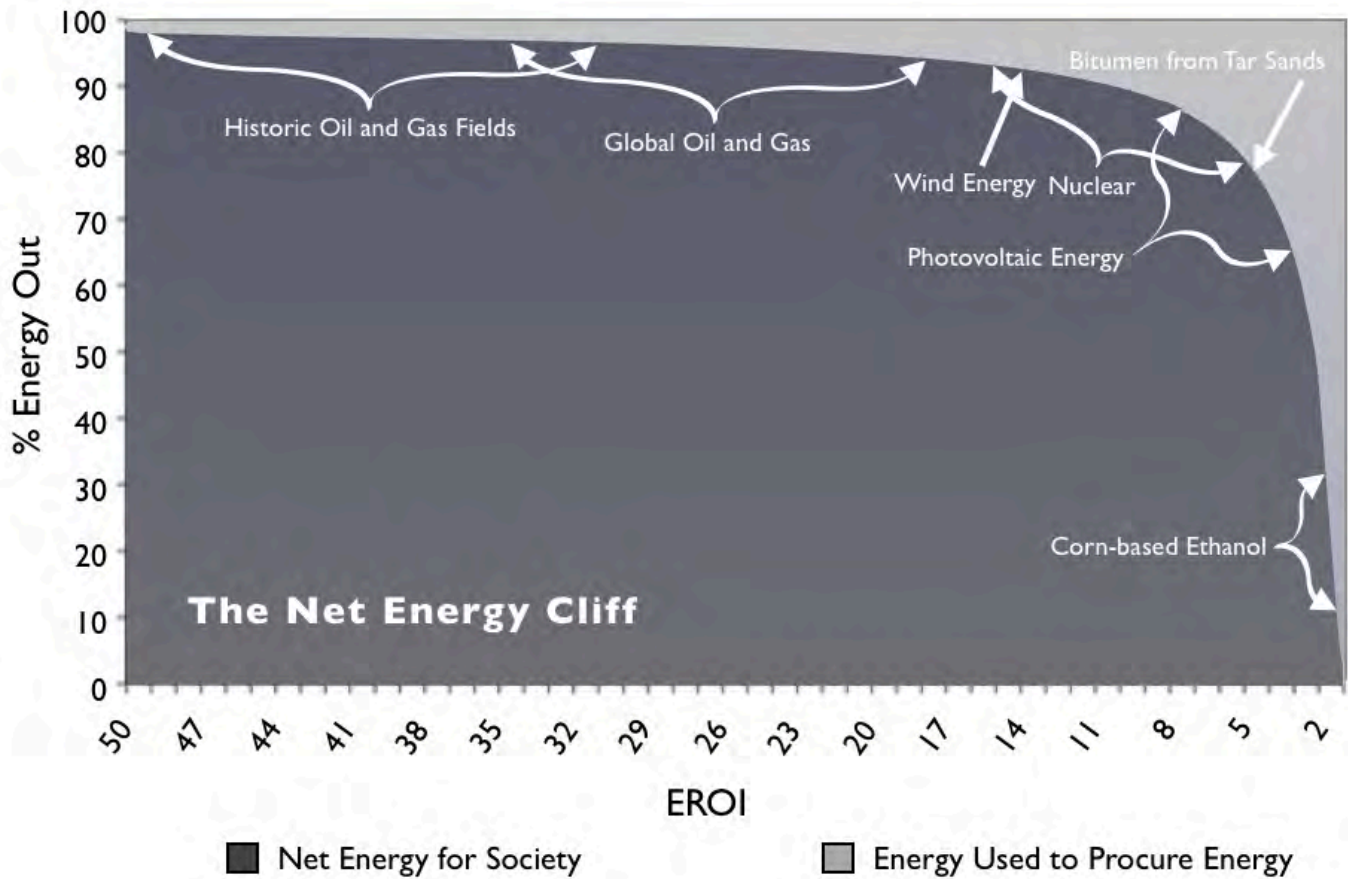


Figure 3.21: The “Net Energy Cliff” (figure adapted from Lambert and Lambert, in preparation and Murphy and Hall, 2010, concept courtesy of Nate Hagens and Euan Mearns).

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 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, 2013). 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. 2013).

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 and 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 transfer-

ring 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 and 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).





# 4. Energy Availability: VULNERABILITIES AND IMPACT



*“Overall, our analysis suggests that having, or having access to, large quantities of high EROI energy appears to contribute substantially to social well-being.”*



# Energy Availability: Vulnerabilities and Impacts

## 4.1 Introduction

*Humans, as well as their 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 many authors have concluded that surplus or net energy is the most important factor in determining the long-term survival and well-being of humans and society (Tainter, 1988, Hall and Klitgaard, 2012, Lambert et al. 2013). The history of human cultural advancement and decline has been examined frequently and powerfully from the perspective of the development of energy resources and the evolution of energy conversion technologies. In particular the energy provided by the burning of fossil fuels has fostered the expansion of economic, social and environmental development (e.g. Cottrell, 1955, White, 1959, Odum, 1972, 1973, Munasinghe, 2002). The availability of high EROI (i.e. cheap) energy and the increased efficacy with which it is used has enabled humans to devote more human effort to e.g. a higher quality diet, more education and medical technology, resulting in an enhancement of their comfort, a longer life and an increase in their numbers. The result is that 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, it is not just the total energy but also the efficiency with which that energy is incorporated into the economic process (EROI<sub>SOC</sub>) and the distribution of energy to each economic actor (Gini index)) that are important for societal well-being. In this section we examine these relations.*

### 4.1.1 Quality of Life Indices

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 are associated with 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), White (1959), Odum (1972, 1973), and Smil (2003) have clearly developed the importance of net energy to societies, there has been little quantification to date 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 many 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 other 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, al-

though 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 (Smil, 2003, FAO, 2012). 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. 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 portion of the report, 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



Table 4.1.: The coefficient of determination ( $R^2$ ) for correlation of various measures of energy availability and quality of life indices. Table taken from Lambert et al. (2013).

Social Indicators	Energy per Capita	EROI <sub>SOC</sub>	Multiple Regression <sup>1</sup>	GDP per Capita <sup>2</sup>
HDI	0.49	0.55	0.84	n.a.
Percent Children Underweight	0.30	0.21	0.44	0.49
GII	0.45	0.52	0.79	0.73
Percent Female Literacy	0.31	0.22	0.26	0.51
Improved Rural Water Source	0.33	0.38	0.52	0.52
GDP per Capita <sup>2</sup>	0.16	0.49	0.78	n.a.

(1) Adjusted  $R^2$  values reported for multiple regression of the natural log of EROI<sub>SOC</sub> and energy per capita (unless otherwise specified).

(2) GDP per capita (in current USD) based on purchasing power parity (PPP) (World Bank, 2012).

availability of our traditional energy resources.

## 4.2 Energy Availability and Quality of Life Indicators

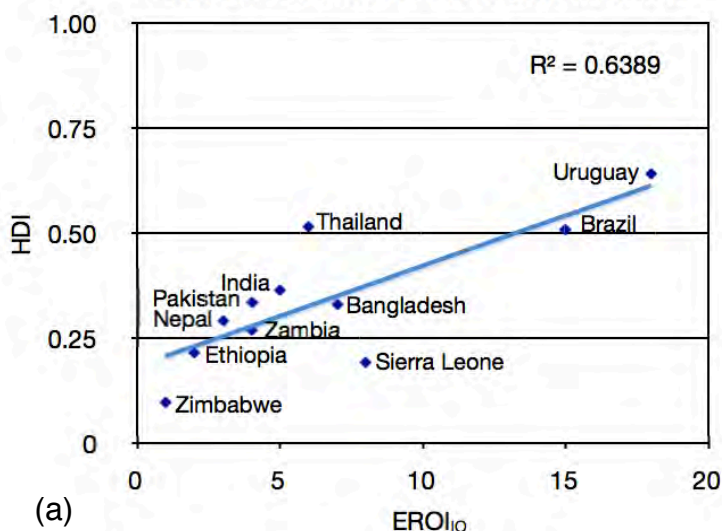
We find that many indices of human social well-being are well correlated with indices of energy availability (i.e. energy per capita and EROI<sub>SOC</sub>) and, as expected, GDP per capita (Table 4.1). EROI<sub>SOC</sub>, as a single measure of an energy system, is capable of addressing the mean quality of energy delivered per unit of energy used to get it, but not the total quantity of energy used by that country. Both energy per capita and EROI<sub>SOC</sub> appear to be correlated with quality of life indices, however, there is essentially no correlation between these two independent measures of energy availability. We performed a multiple regression analysis of energy use per capita and EROI<sub>SOC</sub> vs the dependent variables listed in Table 4.1 to determine which energy parameters are the most highly

correlated between energy use and social indicators of quality of life. The higher  $R^2$  generated in the multiple regression analysis suggests that the composite Lambert Energy Index (see Figure 2.2) is a more powerful indicator than its components. We next turn to analysis of specific components of the relations given above.

### 4.2.1 EROI<sub>IO</sub> for Developing Countries

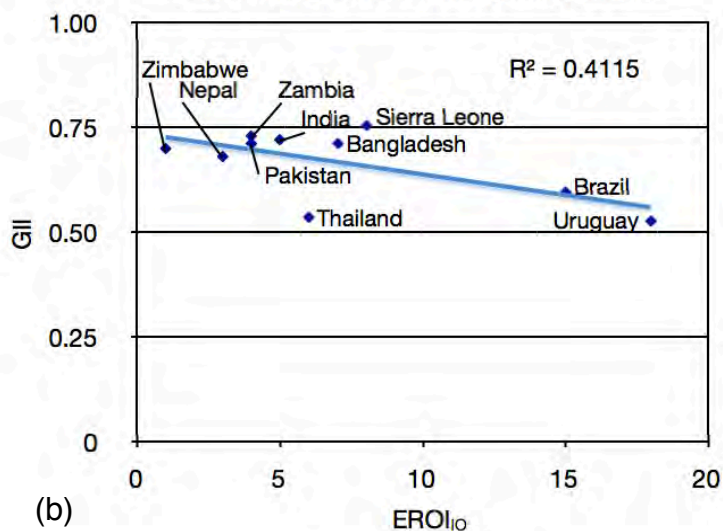
The EROI for imported oil is a moderately strong predictor of each society's indices of social well-being (i.e. of Human Development Index (HDI), Gender Inequality Index (GII), female literacy rate and health expenditures), especially for the twelve less affluent net energy importing countries. Most developing nations with EROI<sub>IO</sub> values below 8-10:1, are consistently below 0.50 on the HDI index (Figure 4.1a). The EROI<sub>IO</sub> for our selection of developing nations was also a good predictor of GII and per capita health expendi-

**EROI<sub>IO</sub> vs Human Development Index**



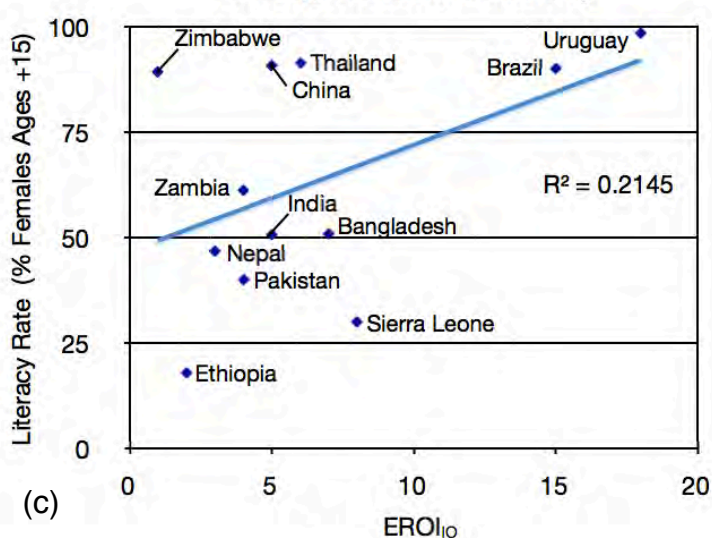
(a)

**EROI<sub>IO</sub> vs Gender Inequality Index**



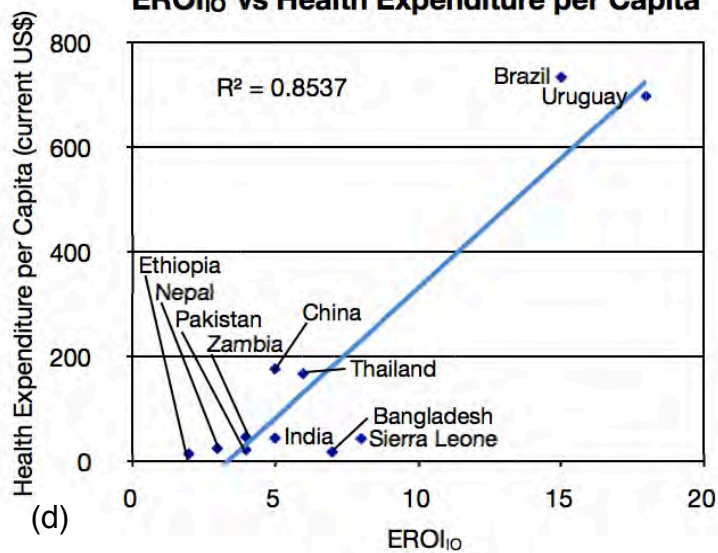
(b)

**EROI<sub>IO</sub> vs Female Literacy**



(c)

**EROI<sub>IO</sub> vs Health Expenditure per Capita**



(d)

Figure 4.1: Comparison of (a) HDI, (b) GII, (c) literacy (percent of females ages 15 and up) and (d) health expenditures per capita with EROI calculated for imported oil (EROI<sub>IO</sub>) (FAO, 2012, the World Bank, 2012).

ture (Figure 4.1b, d). but not female literacy (Figure 4.1c). Nations with high EROI<sub>IO</sub> values (Brazil and Uruguay) spent between six and seven hundred USD per person on health care. Nations with low EROI<sub>IO</sub> values (below 8:1) consistently spent less than two hundred USD per person on medical care. Whether this is due to regional priorities or something else is at this point an open question.

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<sub>IO</sub>) is changing over time (Figure 4.2). To do this we have selected a diverse list of develop-

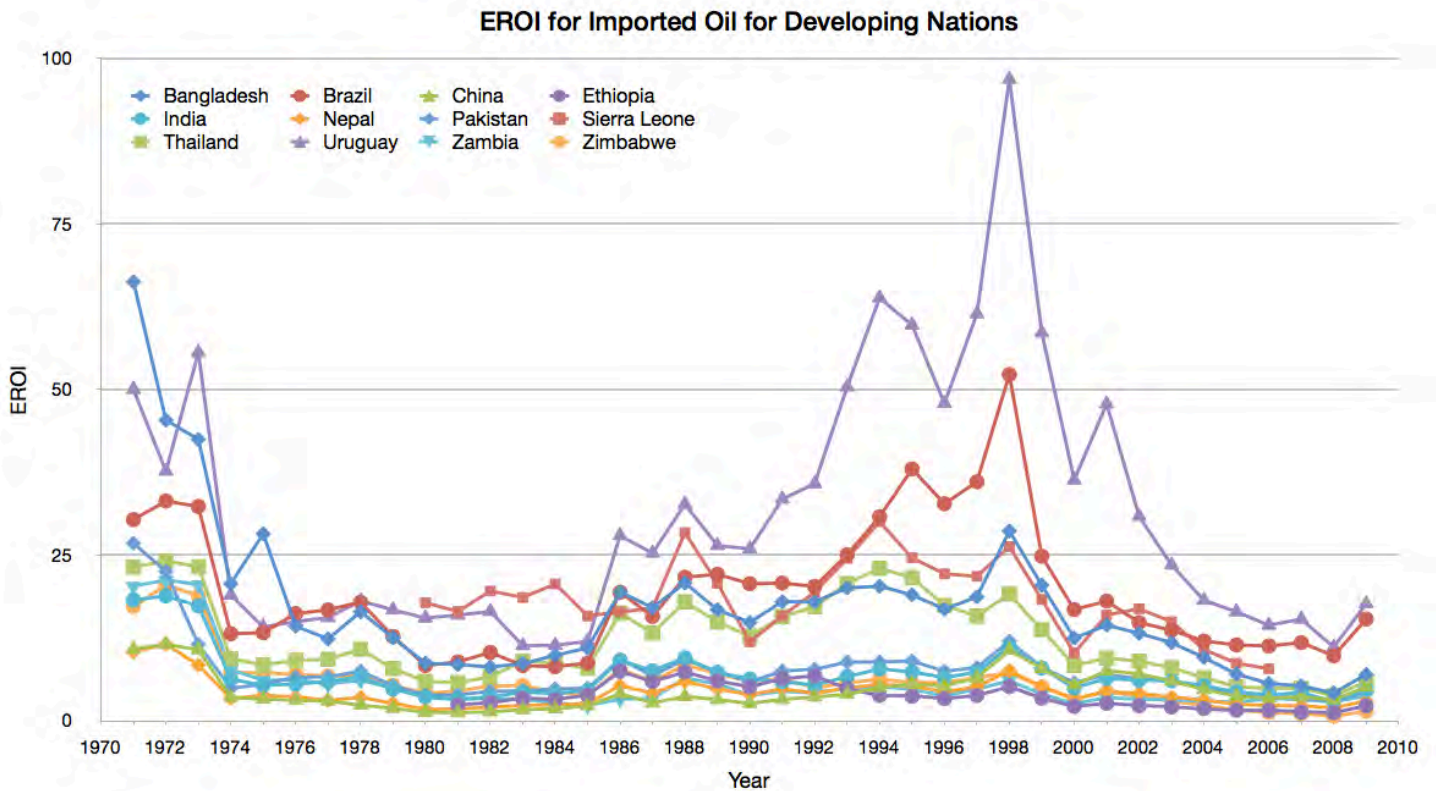


Figure 4.2: EROI calculated for imported oil ( $EROI_{IO}$ ) for select developing nations over time. Note the effect of oil price increases in the 1970s and the 2000s.

SOURCE: A. Gupta contribution to Lambert et al. 2013

ing 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 increases during “good times” of low oil prices (i.e. the late 1990s) and decreases during “bad times” of increasing oil prices (i.e. 2006-2008) (Figure 4.2). 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” of

the 1970’s the EROI declined and remained relatively low for each country through 1985-87, 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.

The next section of the report examines three main sections. Each section contains quality of life and societal well-being in one of the three generic developing country categories,

1. low income countries (LIC),
2. lower-middle income countries (LMIC) and
3. upper-middle income countries (UMIC).



## 4.3 Low Income Countries

**This section analyses the energy availability and social well-being of low income countries (LICs). LIC economies are classified by the World Bank, according to 2012 GNI per capita, as having low per capita annual income, \$1,035 or less. Our analysis is based largely on concepts developed by Smil (2003) and data drawn from the World Bank (2012) development indicators and US energy information Administration (EIA, 2012). Our sample includes 11 LIC countries that were net energy importers in 2009 and 1 LIC country that was a net energy exporter.**



Figure 4.3: Map showing location of LIC countries evaluated in this study.



Our results indicate each of the various nations have different reasons for low indices of social welfare, but at least one relatively high energy component is a minimal requirement for reaching a moderate quality of life (as measured by

quality of life indices). For example, all of the LICs we examined have low annual energy use per capita (below 24 GJ per capita), low EROI<sub>soc</sub> values (10:1 or less) although a wide range in income distribution (Gini index values range from 29.8 for Ethiopia to 59.5 for Haiti). All LIC nations examined have low LEI values (less than 0.12) and most of these countries also have correspondingly lower quality of life indicators (e.g. HDI below 0.35).

### 4.3.1 Key Economic and Energy Availability Indicators

This section presents key data on energy availability and economic and quality of life characteristics of low income countries. All of these indicators provide contextual data to evaluate a country's economic vulnerability and/or capacity to adapt to declining EROI.

#### Economic Indicators

Gross domestic product (GDP) is generally used as the indicator of a nation's economic health and well-being, although other indices such as HDI are used increasingly. The poorest among the LICs in terms of GDP per capita is Mozambique (\$867) followed by Ethiopia (\$953), and Togo (\$974) (Figure 4.4). Mozambique, the poorest of the LICs, was the only net energy exporter (exporting gas equivalent to 22 percent of its total energy use, World Bank 2012). The majority of LICs have large population densities and low total gross domestic product. Low GDP per capita, typical of LICs, suggests that because higher energy prices are inversely linked with low EROI values (King and Hall, 2011), any increase in the global price of oil or other imported fuels is likely to further reduce the EROI of imported fuels and hence reduce economic output.

Another important measure of a country's longterm economic stability when faced with declining EROI is that country's current account balance (the sum of net exports of goods and services, net primary income, and net secondary income) (World Bank, 2013). Large protracted deficits for

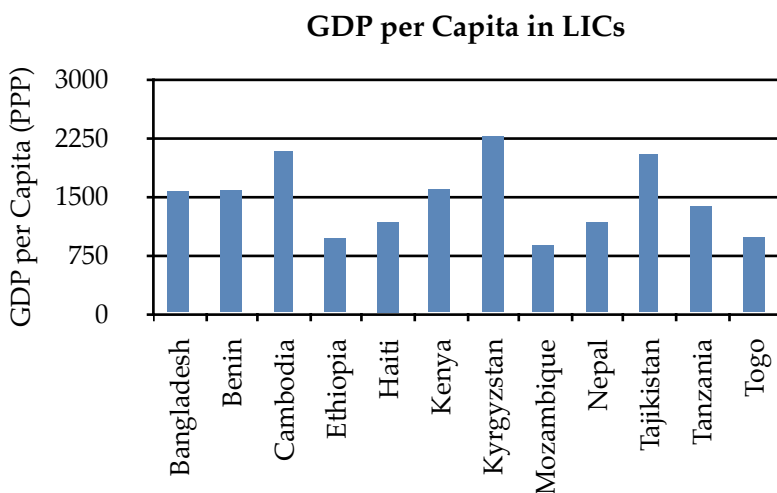


Figure 4.4: Gross domestic product (PPP) per capita in LICs, 2009 (SOURCE: World Bank, 2012)

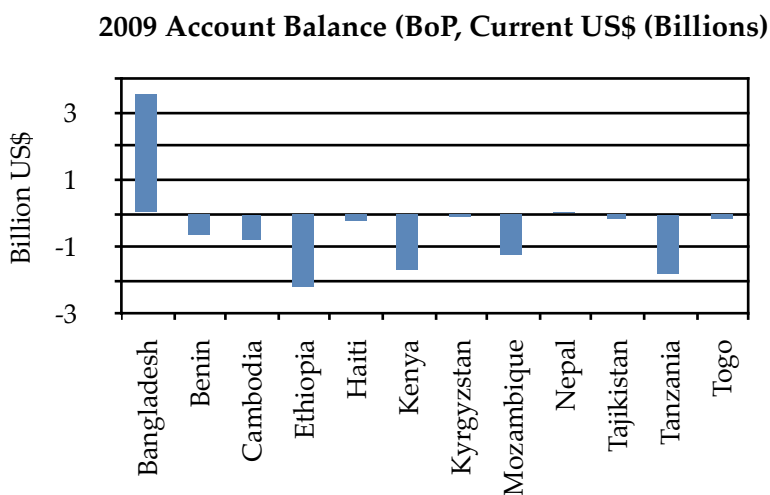


Figure 4.5: Account balance (BoP, Current USD) in LICs, 2009 (SOURCE: World Bank, 2012)

goods and services appear common to LICs (Figure 4.5) such as Ethiopia (-2.2 billion USD) and Tanzania (-1.8 billion USD). Declining EROI will likely exacerbate this trend as more discretionary income is allocated to paying for continued access to higher-priced energy resources.

### Energy Availability Indicators

Tables 4.2 and 4.3 give indicators of energy availability in 2009, based on formulas described in the methods section (Part 2). An important measure of the energy available to a nation is annual energy use per capita,

measured in giga joules. The annual energy use per capita of two of the LICs (Bangladesh and Haiti) is extremely low, below 12 GJ per capita. The energy use per capita of Mozambique, the only net energy exporter within our sample, is higher than the LIC average (mean) energy use (16 GJ per capita) but below the LICs with the highest energy use, Kyrgyzstan (23 GJ per capita) and Kenya (20 GJ per capita). The low energy use per capita typical of most LICs suggests that increasing costs associated with extracting lower quality, less accessible energy resources (low EROI fuels)

Table 4.2: Summary of energy availability indicators for net energy importing LIC nations (2009).

Country	Energy Use per Capita	EROI <sub>soc</sub>	Gini-Index	LEI
Bangladesh	8	9:1	31	0.08
Benin	17	5:1	39	0.09
Cambodia	15	5:1	44	0.09
Ethiopia	16	2:1	30	0.05
Haiti	11	6:1	60	0.06
Kenya	20	4:1	48	0.08
Kyrgyzstan	23	5:1	33	0.12
Nepal	14	4:1	47	0.06
Tajikistan	14	7:1	34	0.10
Tanzania minus Zanzibar	19	3:1	n.a.	n.a.
Togo	19	3:1	34	0.07
<b>Mean</b>	<b>16</b>	<b>5:1</b>	<b>40</b>	<b>0.08</b>
<b>Median</b>	<b>16</b>	<b>5:1</b>	<b>37</b>	<b>0.08</b>
<b>Standard Deviation</b>	<b>4</b>	<b>2</b>	<b>10</b>	<b>0.02</b>

Table 4.3: Summary of energy availability indicators for the net energy exporting LIC nation (2009).

Country	Energy Use per Capita	EROI <sub>soc</sub>	Gini-Index	LEI
Mozambique	18	3:1	46	0.05

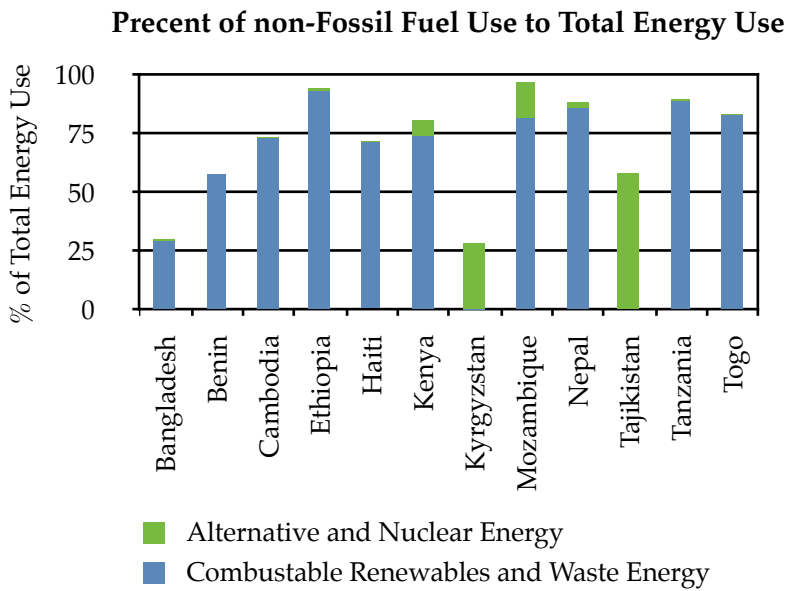


Figure 4.6: Contribution of alternative and nuclear energy (green) and combustable renewables and waste energy (blue) to total energy use. (SOURCE: World Bank, 2012)

are likely to further reduce the net energy available to LIC nations.

A second measure of the energy available to a nation is  $EROI_{SOC}$ , the ratio of energy returned per unit invested. This is also extremely low, below 10:1, for each LIC nation. The lowest  $EROI_{SOC}$  value was calculated for Ethiopia (2:1) and the highest for natural gas-rich Bangladesh (9:1). Declining  $EROI$  of traditional fossil fuels will likely further reduce the  $EROI_{SOC}$  values of LICs. However, 8 out of the 12 LICs included within our sample rely on combustable renewables and waste for greater than 70% of their total energy use portfolios (Figure 4.6). Several LICs, e.g. Kyrgyzstan and Tajikistan, rely heavily on hydroelectricity and other alternative energy sources. These LIC nations are less likely to face an acute decline in  $EROI_{SOC}$  associated with high energy prices and declining  $EROI$  of fossil fuels.

The Gini-index, a measure of the degree to which household income distribution varies from perfectly equal distribution, is highly variable among the LICs within our sample (Table 4.2) with values ranging from equitable income distribution (e.g. Ethiopia) to wide income distribution (e.g. Haiti). We use the Gini-index of income distribution as a proxy method for evaluating the distribution of energy within a national economy. Economic (or energetic) inequality is the degree of variation in the distribution of economic/energetic assets within a population. The issue of economic/energetic inequality impacts economic factors such as: equity, equality of outcome, equality of opportunity, and



has repercussions on social factors such as life expectancy. While some inequality may promote investment, excessive inequality is perceived as destructive. Researchers from the International Monetary Fund reported, in 2011, that income equality was a more accurate determinate of the duration of a nation's period of economic growth than free trade, low government corruption, foreign investment, or low foreign debt (FAO, 2006).

The Lambert Energy Index (LEI) is a composite of three statistical indices: the quantity of energy used, the efficiency of energy use ( $EROI_{SOC}$ ) and equitable distribution of energy (Gini-index). LEI can be viewed as an index of "potential" energy availability. LICs that rely on combustible renewables and waste as their primary energy source have the lowest LEI values (e.g. Ethiopia and Mozambique). These countries are also characterized as having high population growth rates (Figure 4.7) leading to further constraints on already limited renewable energy resources. While these nations are likely to continue to have difficulties providing sufficient energy per capita resources (especially with population growth rates in excess of 2 percent) a decline in the EROI of major fossil fuel energy sources is unlikely to have a substantial, direct impact on LIC economies (e.g. the  $EROI_{IO}$  for Mozambique declined only slightly during oil price shocks (periods associated with a decline in the EROI of oil) Figure 4.8).

Alternatively, the LICs with access to higher EROI energy have higher LEI values (e.g. electricity from hydroelectric

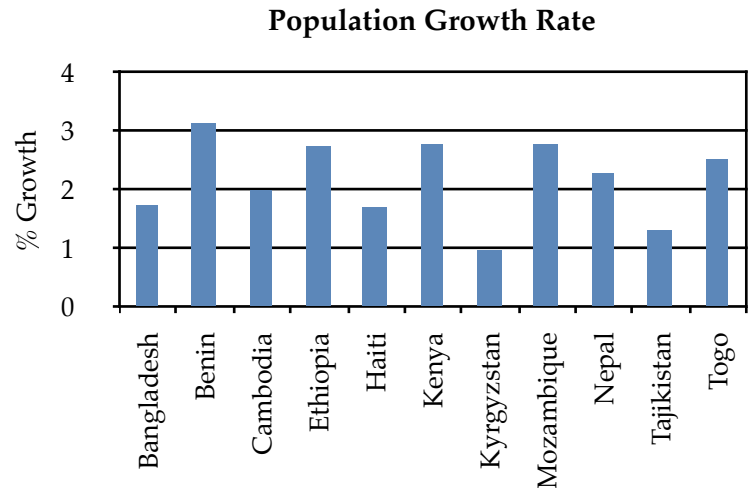


Figure 4.7: Annual percentage population growth in LICs, 2009 (SOURCE: World Bank, 2012)

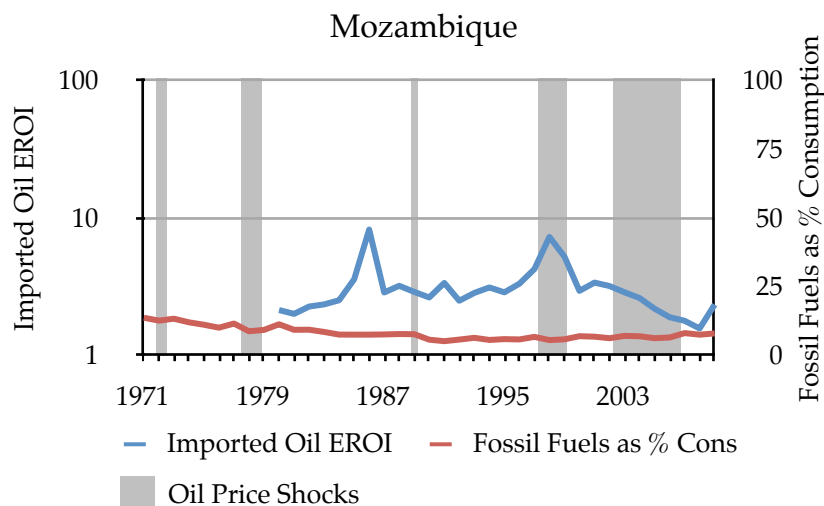


Figure 4.8:  $EROI_{IO}$  for Mozambique (log scale)  
(SOURCE: A. Gupta contribution to Lambert et al. 2013)

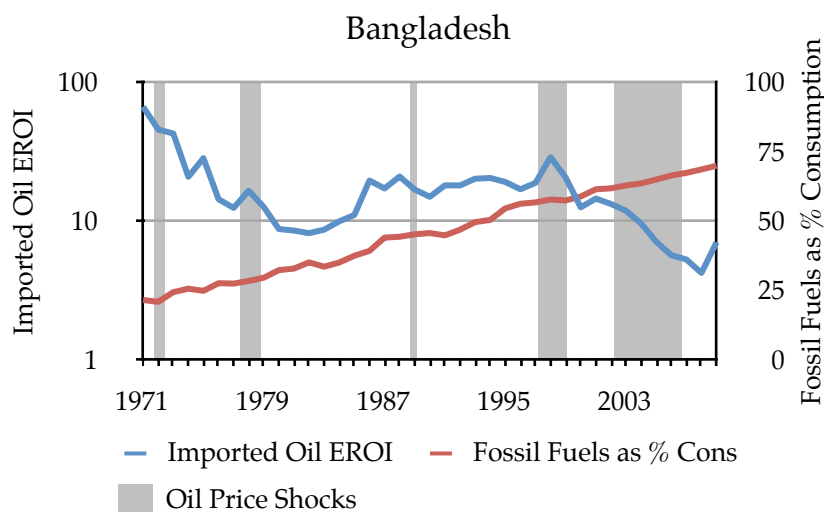


Figure 4.9:  $EROI_{IO}$  for Bangladesh (log scale).  
(SOURCE: A. Gupta contribution to Lambert et al. 2013)

plants makes up 79.9% of total installed capacity for Kyrgyzstan (CIA, 2012) or domestically-produced natural gas makes up roughly 53% of total energy consumption in Bangladesh (EIA, 2012)). These LICs also rely on imported fossil fuel to make up the difference in their energy portfolio. LICs that are forced to import fossil fuels (e.g. oil) are expected to experience economic turmoil when faced with declines in the EROI of major fossil fuel energy sources (e.g. the  $EROI_{IO}$  for Bangladesh declined several fold during oil price shocks Figure 4.9).

### General Pattern Over Time

A relative decline in EROI occurred during the “energy crises” of the 1970s followed by an irregular increase during the 1980s and 90s as oil prices declined relative to the price of other goods and services. For both countries there was a decline again during the 2000s, up to the peak international oil price in 2008. During all this period the  $EROI_{IO}$  was higher for Bangladesh (Figure 4.9) than for Mozambique indicating more favorable terms of trade (Figure 4.8), i.e. Bangladesh had to use less energy internally to trade for a barrel of oil than was the case for Mozambique. As was the case for Mozambique, countries subject to the whims of a increasingly volatile energy market are likely to suffer from similar volatility the EROI of imported oil.

### 4.3.2 Energy Availability and Quality of Life Indicators

While the economic and energy indices characteristic of LICs provide a general understanding for how a nation will be

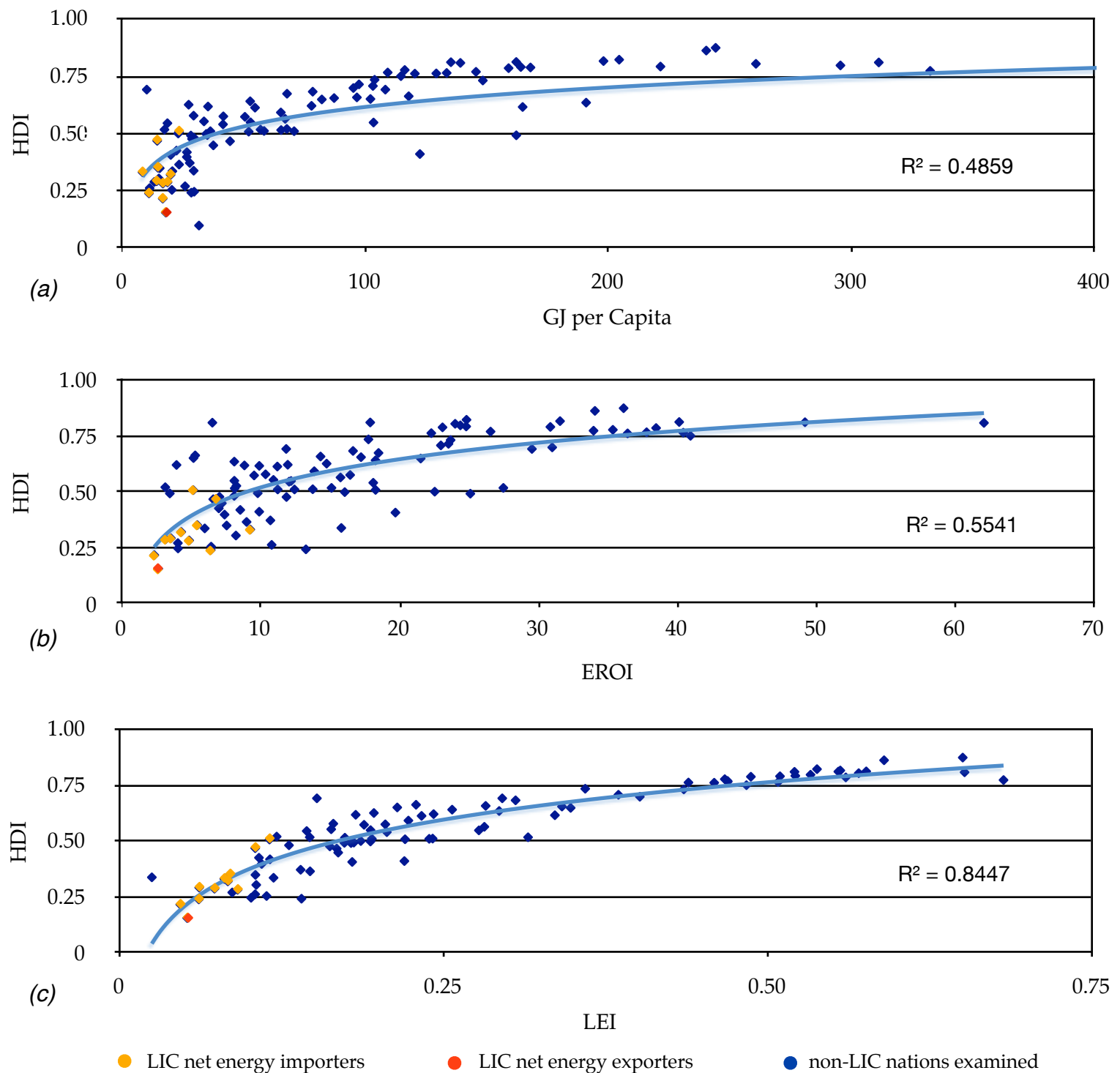


Figure 4.10: Regression of Human Development Index with (a) energy use per capita, (b)  $EROI_{SOC}$  and (c) LEI values for LICs (Lambert et al. 2013).

influenced by declining EROI and reduced energy availability, a more immediate concern lies in how energy availability is associated with the quality of human life as measured by various indices. This section examines data on measures of energy availability and quality of life for LICs.

### Human Development Index

The relation of HDI to all energy indices first increases together but then tends to saturate (Figure 4.10). The coefficient of determination ( $R^2$ ) is higher with LEI than with energy use per capita or  $EROI_{SOC}$ . LICs have HDI values at or below 1.5

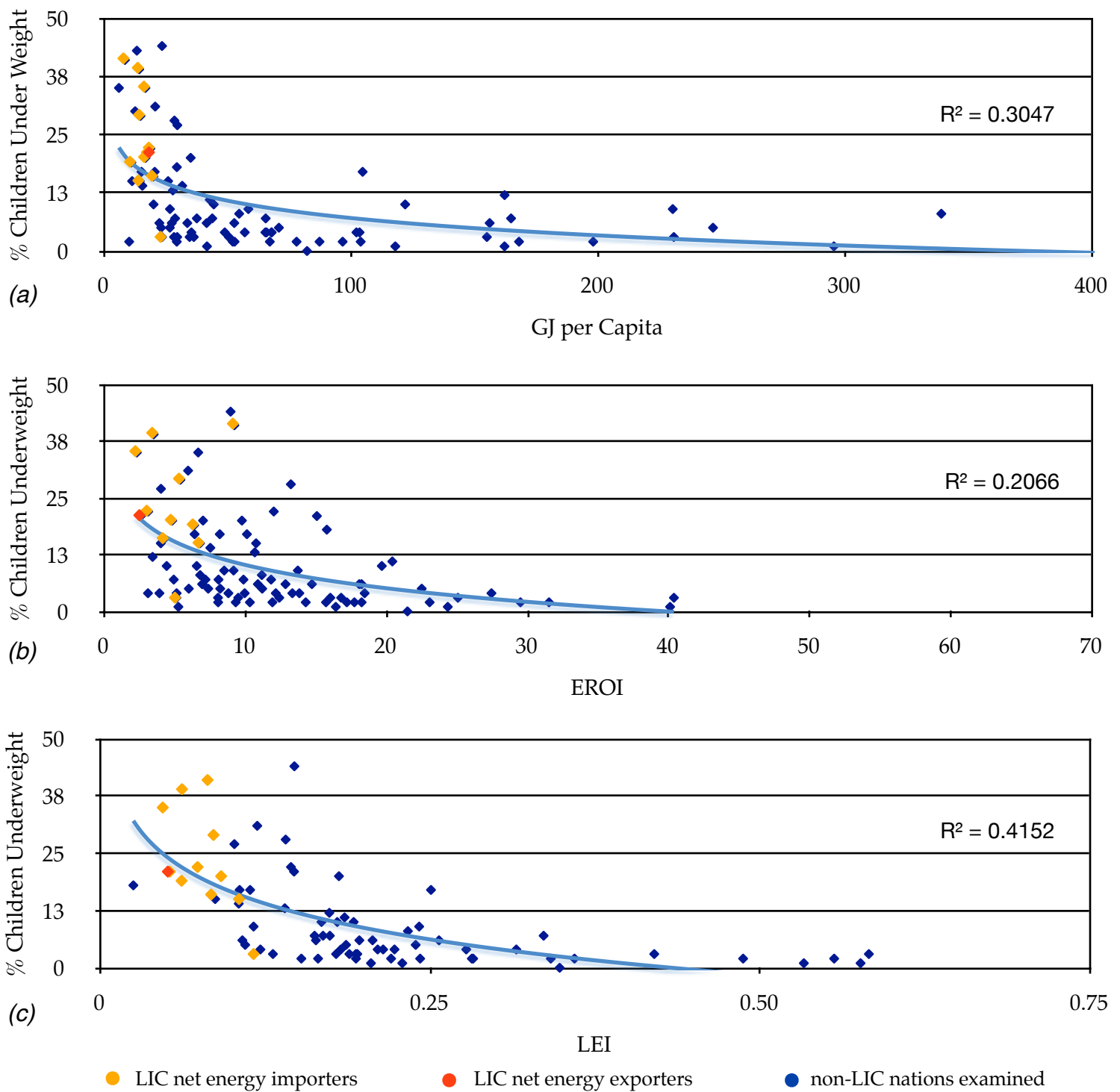


Figure 4.11: Regression of percent children (less than 5 years old) underweight with (a) energy use per capita, (b)  $EROI_{SOC}$  and (c) LEI values (Lambert et al. 2013).

(Figure 4.10). Of the LIC countries within our study, Kyrgyzstan has the highest HDI, 0.508 and the highest LEI, 0.12. Other indices of human well-being are also correlated with our three energy indices, although the relation is not quite as strong.

### Percent Children Underweight

Percent children under weight is a quantitative indicator of the availability of and access to food and healthcare. LICs tend to be impoverished and their populace tends to have limited access to adequate food

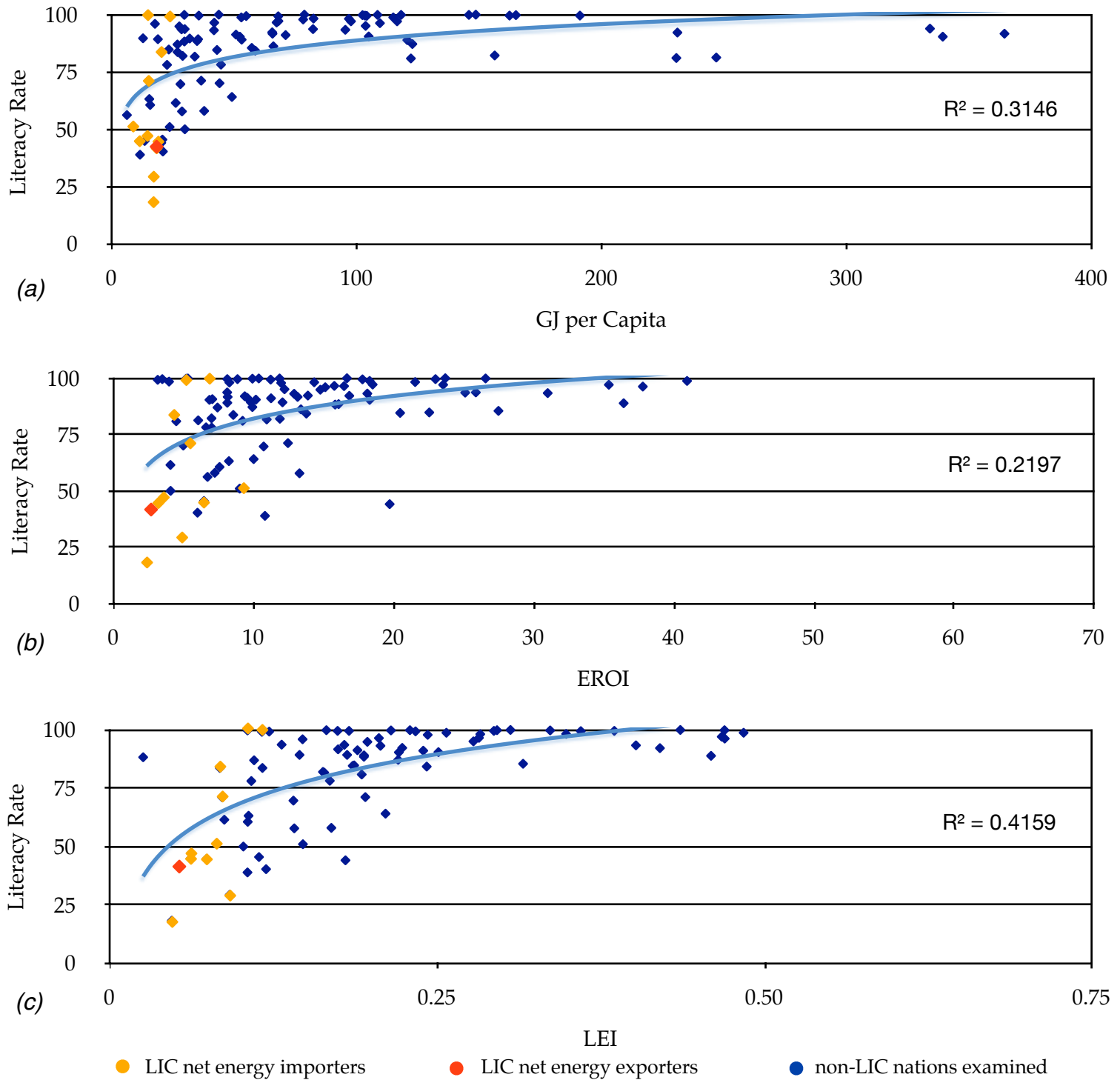


Figure 4.12: Regression of adult female literacy (% of females ages 15 and above) with (a) energy use per capita, (b)  $EROI_{SOC}$  and (c) LEI values (Lambert et al. 2013).

and modern healthcare facilities. Of the LICs included within our sample, Kyrgyzstan is the only country having less than 15% of its children under weight. On the opposite end of the spectrum we find Bangladesh with 41% of its children under weight, Nepal with 39% of its children

under weight and Ethiopia with 35% of its children under weight (Figure 4.11). These three LIC countries also have low LEI index values of between 0.05 and 0.08.

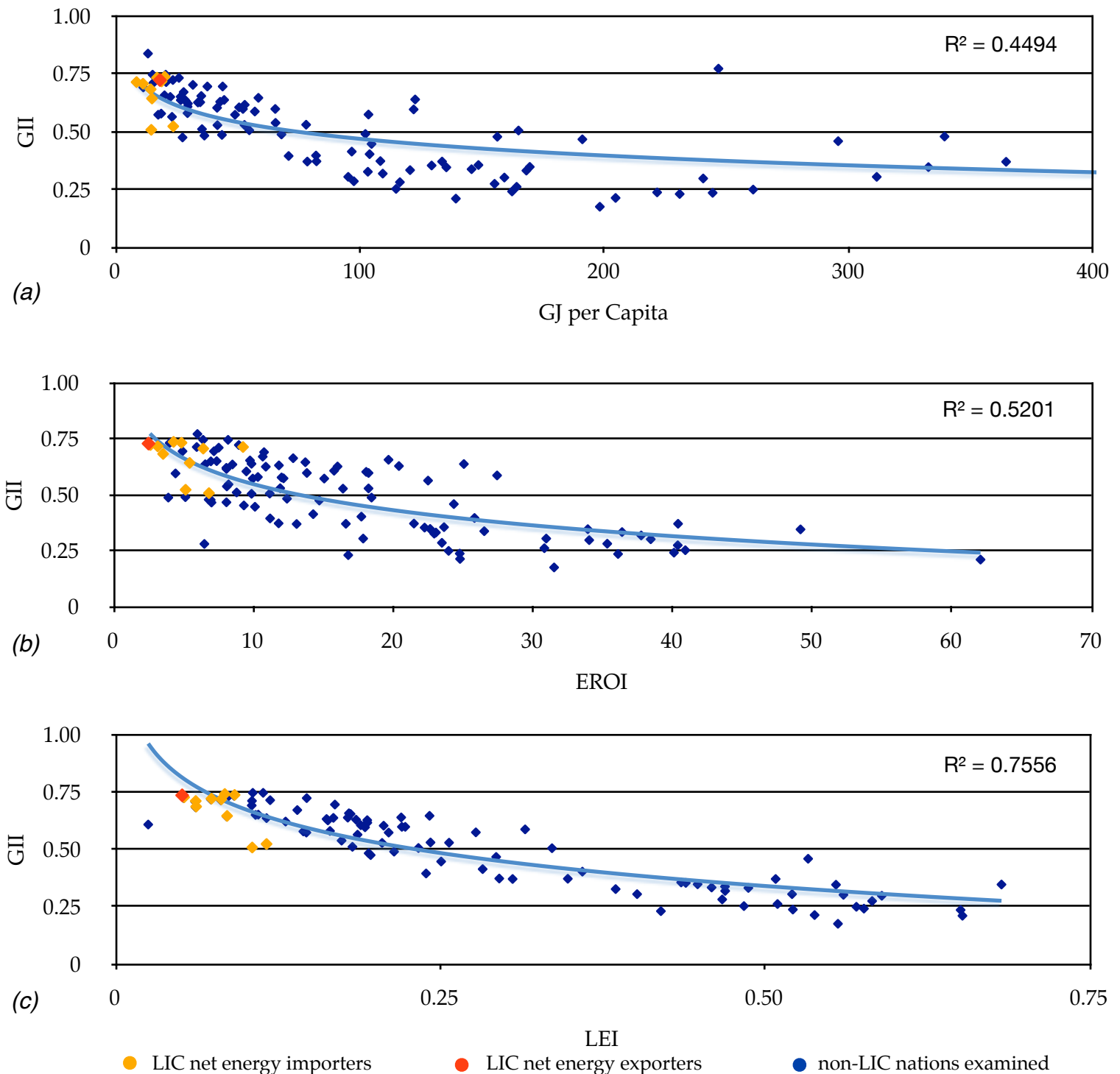


Figure 4.13: Regression of Gender Inequality Index with (a) energy use per capita, (b)  $EROI_{SOC}$  and (c) LEI values (Lambert et al. 2013).

### Female Literacy

Female literacy rates within LICs vary substantially (Figure 4.12). Kyrgyzstan and Tajikistan, former members of the Soviet Union, have the highest (99%) level of female literacy. Cambodia has a 71% female literacy rate and Nepal has a 47% female

literacy rate. Ethiopia on the other end of the spectrum, has the lowest (18%) female literacy rate of all of the LICs within our study.

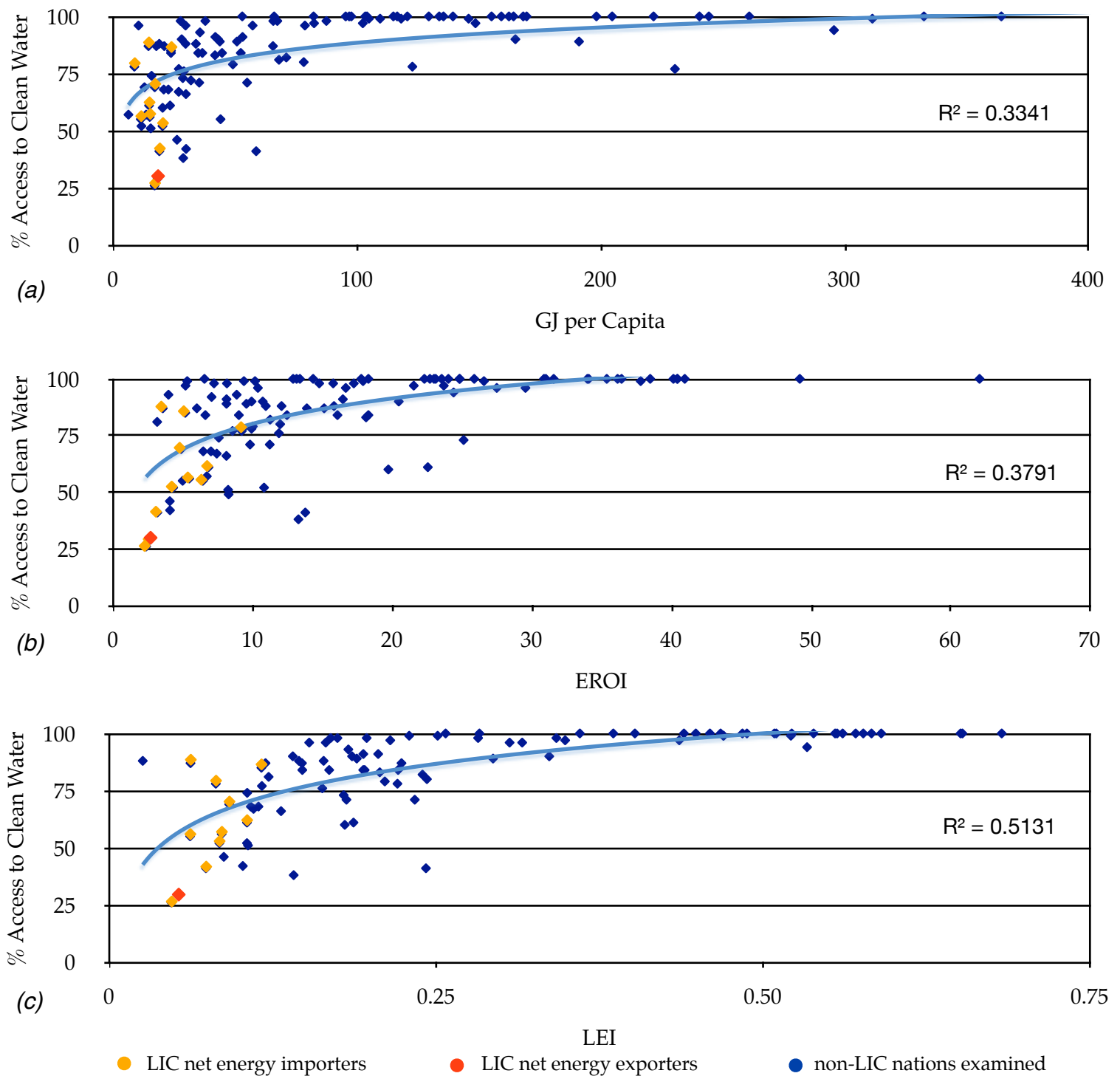


Figure 4.14: Regression of improved water source, rural (% of rural population with access) with (a) energy use per capita, (b)  $EROI_{soc}$  and (c) LEI values (Lambert et al. 2013).

### Gender Inequality Index

Kyrgyzstan and Tajikistan are the LICs with the greatest gender equality, 0.521 and 0.506, respectively (Figure 4.13). The African nations of Kenya (0.735), Benin (0.731) and Mozambique (0.721) are the

LICs within our sample demonstrating the least gender equality.

### Improved Water Source

Our last quality of life index, improved water source, measures the degree to which a country's rural population has ac-

cess to clean water (Figure 4.14). Eighty-seven percent of Nepal's rural population has access to clean water. This may be due, in part, to the proximity of seasonal glacial melt. Eighty-five percent of Kenya's rural populace also has access to clean water. Clean glacial melt from Mount Kenya in the highlands of Kenya and Kilimanjaro, in Tanzania, provides some of this water while seasonal rains provide the rest. On the extreme, only 29% of Mozambique's and 26% of Ethiopia's rural population have access to clean water.

Our results indicate that LICs have low energy use per capita, low to moderate energetic economic efficiency ( $EROI_{SOC}$ ) and a correspondingly low LEI. For example, Ethiopia and Mozambique have extremely low  $EROI_{SOC}$  values (2:1 and 3:1), extremely low energy use per capita (17 and 18 GJ per capita respectively) and equitable to moderate income distribution (Gini-index, 30 and 46), resulting in low LEI values (both having 0.05) associated with a poor quality of life indicators (e.g. HDI = 0.22 and 0.16 respectively).

### 4.3.3 Impact of Declining EROI

This section discusses the probable impacts of declining EROI on LICs, first in terms of fuel type, then with regard to domestic vs imported supply, and finally by focusing on four measures of energy availability and their association with quality of life.

### Fuel Type

It was noted in section 4.3.1 that the impact on LICs of the decline in EROI for our most important fossil fuels is likely to have less of an effect on LIC economies than on many developed nations as they tend to rely primarily on domestic sources of energy, that is renewable combustible and alternative energy sources. Those few nations that rely on domestic fossil fuel production (e.g. Bangladesh produces and consumes 20.13 billion cu m of natural gas (CIA, 2013)), are also less likely to feel the impact of declining EROI as acutely as nations that are forced to import large amounts of energy.

### Domestic and Imported Fuel

The majority of *fossil fuel* consumed by LICs was imported. This suggests that fossil fuel (e.g. oil) price shocks are likely to impact the portion of LIC economies that are directly or indirectly reliant on cheap and abundant fossil fuel for their continued function. The impact of declining EROI and its inverse relation with fuel price is more extreme for LICs that depend on imported fossil fuels (e.g. Haiti relies on fossil fuel for 28 percent of its total energy consumption (World Bank, 2012) and has no hydrocarbon resources of its own).

### Energy Availability and Quality of Life

Most measures of social well-being are correlated linearly to energy used per capita at low values, and also to  $EROI_{SOC}$ , up to a saturation point. Five of our major



findings that would appear to impact quality of life values for LICs are:

1. LICs use less than 24 GJ per capita per year and these values (excluding Kyrgyzstan and Tajikistan) are associated with low “quality of life.” Kyrgyzstan and Tajikistan have the highest energy use per capita of the LICs and the highest quality of life indices.
2. LICs have low EROI<sub>SOC</sub> values (from 2-9:1) which are correlated with a “low” standard of living. Ethiopia and Mozambique have the lowest EROI<sub>SOC</sub> of the LICs and the lowest quality of life indices, this trend is reflected in the lowest HDI values, 0.216 and 0.155 respectively.
3. Household income distribution is highly variable among the LICs within our sample with values ranging from equitable income distribution (e.g. Ethiopia) to wide (inequitable) income distribution (e.g. Haiti).
4. Improvement in well-being is correlated with increases in LEI value (LICs with high LEI values are associated with higher quality of life indicators).
5. An exception to these patterns, but one that is nevertheless consistent with our analysis, is that low population growth rate nations with large hydroelectric energy input, e.g. Kyrgyzstan and Tajikistan, have considerably higher quality of life indices.

#### 4.4.4 Summary

Overall, our analysis suggests that having, or having access to, large quantities of high EROI energy distributed equitably appears to contribute substantially to social well-being. The implications for this are that in a world where there is strong evidence, logically and empirically, for declining availability of fuel and its EROI there will be large pressures impacting the standard of living and the quality of life for people in poor developing countries. It is not clear that renewable energies, with their generally low EROI's and issues with intermittence will be able to compensate for this. One possible response to this situation would be a renewed focus on population issues. Another response would be to focus on plans to increase energy availability, its amount, EROI, sufficiency of production and equitable distribution.



## 4.4 Lower Middle Income Countries

**This section analyses the energy availability and social well-being of lower middle income countries (LMICs). LMIC economies are classified by the World Bank according to 2012 GNI per capita, as having income between \$1,036 - \$4,085. Our analysis is based largely on an extension of concepts developed by Smil (2003) and data drawn from the World Bank (2012) development indicators and US energy information Administration (EIA, 2012). Our sample includes 15 LMIC countries that were net energy importers in 2009 and 9 LMIC country that were a net energy exporter.**

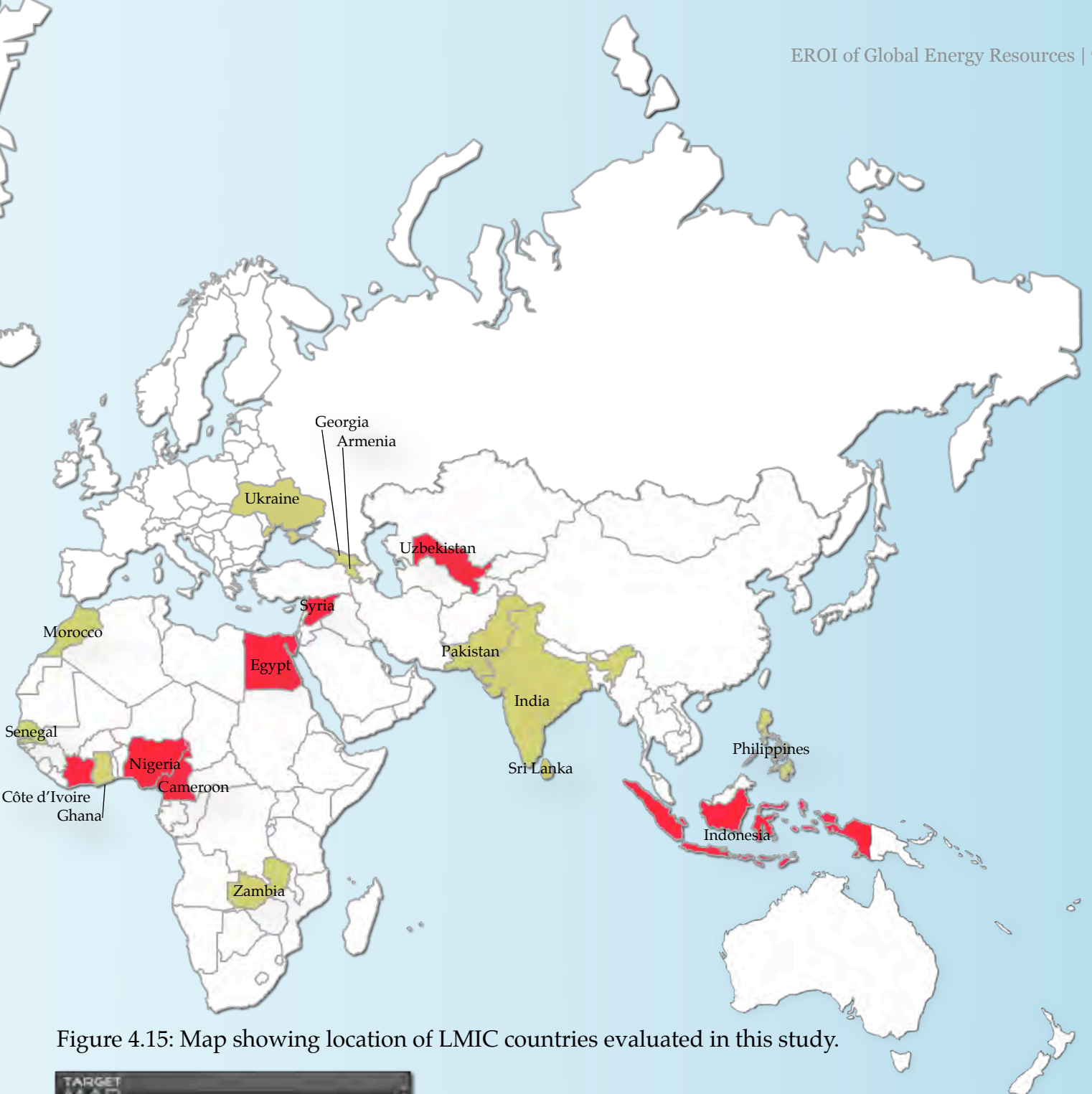


Figure 4.15: Map showing location of LMIC countries evaluated in this study.



Each of the various LMIC examined have different reasons for low to moderate overall energy availability and associated low to moderate quality of life (as measured by quality of life indices). These countries have relatively low

energy use per capita (averaging 30 GJ per capita), low EROI<sub>SOC</sub> values (20:1 or less) and a wide range in income distribution (Gini index values range from 27.5 for Ukraine to 57.7 for Honduras). However, all LMICs examined have low to moderate LEI values (between 0.09 and 0.21) and most of these countries also have correspondingly low to moderate quality of life indicators (e.g. HDI between 0.25 (Côte d'Ivoire) and 0.65 (Ukraine)).

#### 4.4.1 Key Economic and Energy Availability Indicators

This segment discusses data on energy availability and economic and quality of life features of nations defined as “lower middle income countries” (LMICs). Each of these indicators provides contextual information that assists in evaluating a country’s economic vulnerability and/or capacity to adapt to decreasing EROI.

##### Economic Indicators

Figure 4.16 presents the gross domestic product (GDP) per capita for the 24 LMICs included within our sample. The poorest among the LMICs in terms of GDP per capita is Zambia (\$1,455) followed by Ghana (\$1,542), and Côte d’Ivoire (\$1,856). The majority of LMICs have low GDP per capita and high population growth rates (averaging 2%, excluding countries previously within the USSR). The effect of higher energy prices (low EROI values) (King and Hall, 2011) on these already large and rapidly increasing populations is likely to be a further reduction in the EROI of imported fuels and hence reduced economic output.

Several LMICs have generated large net profits and currently have positive account balances. Indonesia (+11.6 billion USD), Nigeria (+13.8 billion USD) and Philippines (+9.4 billion USD) are examples. However, large protracted deficits for goods and services are found in 15 of the 24 LMICs (Figure 4.17). Declining EROI (observed as higher energy prices) will likely exacerbate this trend for these LMICs as more discretionary income is al-

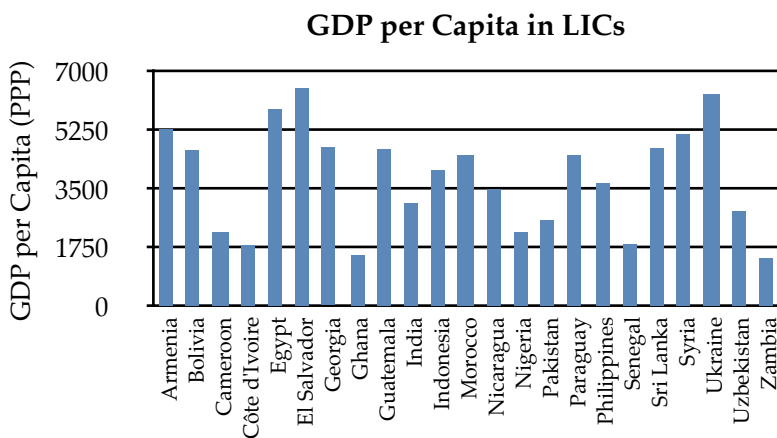


Figure 4.16: Gross domestic product (PPP) per capita in LMICs, 2009 (SOURCE: World Bank, 2012)

located to paying for continued access to higher-priced energy resources.

### Energy Availability Indicators

Tables 4.4 and 4.5 give quantitative indicators of energy availability in 2009. The mean energy use per capita of net energy exporters within our sample (34 GJ per capita, Table 4.5), is higher than the mean for net energy importers (28 GJ per capita, Table 4.4). The LMIC with the highest energy use per capita, Ukraine (102 GJ per capita), is a net energy importer (importing 40% of its total energy use). However the low energy use per capita, typical of

2009 Account Balance (BoP, Current US\$ (Billions))

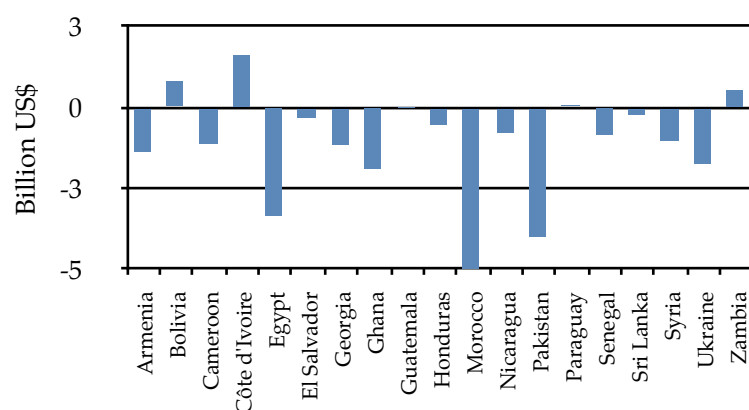


Figure 4.17: Account balance (BoP, billion current USD) in LMICs in 2009, excluding India (-25), Indonesia (+10), Nigeria (+14) and Philippines (+10). (SOURCE: World Bank, 2012)

Table 4.4: Summary of energy availability indicators for net energy importing LMIC nations.

Country	Energy Use per Capita	EROI <sub>soc</sub>	Gini-Index	LEI
Armenia	35	9:1	31	0.18
El Salvador	26	12:1	47	0.16
Georgia	29	10:1	41	0.17
Ghana	15	8:1	43	0.10
Guatemala	28	11:1	54	0.14
Honduras	27	9:1	58	0.12
India	23	9:1	37	0.15
Morocco	20	20:1	41	0.18
Nicaragua	22	7:1	52	0.11
Pakistan	21	6:1	33	0.12
Philippines	17	15:1	44	0.15
Senegal	11	11:1	39	0.10
Sri Lanka	19	12:1	40	0.14
Ukraine	102	5:1	28	0.21
Zambia	26	4:1	51	0.09
<b>Mean</b>	<b>28</b>	<b>10:1</b>	<b>43</b>	<b>0.14</b>
<b>Median</b>	<b>23</b>	<b>9:1</b>	<b>41</b>	<b>0.14</b>
<b>Standard Deviation</b>	<b>21</b>	<b>4</b>	<b>9</b>	<b>0.03</b>

Table 4.5: Summary of energy availability indicators for net energy exporting LMIC nations.

Country	Energy Use per Capita	EROI <sub>SOC</sub>	Gini-Index	LEI
Bolivia	27	7:1	57	0.11
Cameroon	15	8:1	45	0.11
Côte d'Ivoire	20	6:1	42	0.11
Egypt	37	7:1	32	0.17
Indonesia	35	10:1	37	0.18
Nigeria	30	4:1	43	0.10
Paraguay	30	8:1	52	0.13
Syrian Arab Republic	44	7:1	36	0.17
Uzbekistan	68	3:1	37	0.12
<b>Mean</b>	<b>34</b>	<b>7:1</b>	<b>42</b>	<b>0.13</b>
<b>Median</b>	<b>30</b>	<b>7:1</b>	<b>42</b>	<b>0.12</b>
<b>Standard Deviation</b>	<b>15</b>	<b>2</b>	<b>8</b>	<b>0.03</b>

most LMICs suggests that additional increases in costs associated with extracting lower quality, less accessible energy resources (low EROI fuels) are likely to further reduce the net energy available to LMIC nations.

The average level of EROI<sub>SOC</sub> among the LMICS was 10:1 for net energy importers and 7:1 for net energy exporters in 2009. Probably the lower EROI<sub>SOC</sub> of net energy exporters reflects the large amount of energy required to extract and export energy. A continuation of the current trend of a decline in the EROI of traditional fossil fuels would likely further reduce the EROI<sub>SOC</sub> values of LMICs. There was, however, a high degree of variability, ranging from lows of 3 to 4:1 in Uzbekistan and Zambia, to highs of 20:1 in Morocco. Ten of the LMICs included within our sample rely on combustible renewables and waste

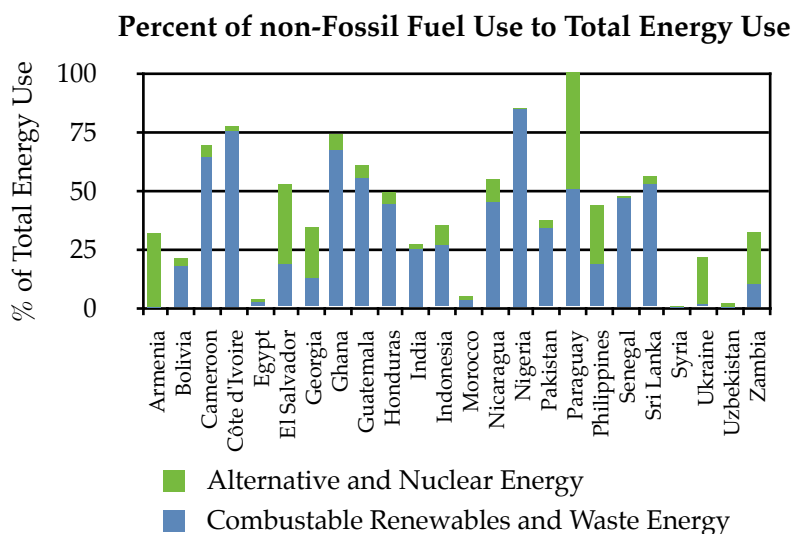


Figure 4.18: 2009 account balance (BoP, Current USD) in LMICs, 2009 (SOURCE: World Bank, 2012)

and/or alternative and nuclear energy for more than 50% of their total energy use portfolios (Figure 4.17) and several LMICs rely heavily on high EROI domestically produced fossil fuels (e.g. Indonesia produced 82.8 billion cu m and consumed only 41.35 billion cu m natural gas in 2010, CIA, 2013). The  $EROI_{SOC}$  for these LMICs will be influenced more heavily by the EROI of their domestic sources.

The LMICs within our sample have considerable variation in household income distribution. Gini Index values range from extremely equitable income distribution in Ukraine to wide income disparity in Honduras. While some inequality may encourage investment, severe inequality, such as that experienced in Honduras, is likely to be detrimental especially during periods of resource scarcity.

The Lambert Energy Index (LEI) is a composite of three statistical indices: the quantity of energy used, the efficiency of energy use ( $EROI_{SOC}$ ) and equitable distribution of energy (Gini-index). As with LICs, LMICs that rely on combustible renewables and waste as their primary energy source have the lowest LEI values (e.g. Nigeria and Ghana, Figure 4.18). These countries are also characterized as having burgeoning populations, with a present average growth rates in excess of 2 percent (Figure 4.19). High population growth rates and limited ability to compete in the global energy market is likely to constrain already limited renewable energy resources further. LMICs with limited access to sufficient higher EROI energy from domestic sources (e.g. im-

ported petroleum made up roughly 62% of total energy consumption for Zambia (EIA, 2012)) and those with high population growth rates (e.g. Zambia has a population growth rate of 2.6 in 2009 (World Bank, 2012)) are likely to experience economic turmoil when faced with declines in the EROI of major fossil fuel energy sources.

Alternatively, a decline in the EROI of fossil fuel energy sources is unlikely to have a substantial, direct impact on LMIC economies able to meet most of their energy requirements with domestic energy sources. LMICs with access to higher EROI energy and limited or negative population growth rates (e.g. Ukraine has a -0.64% population growth rate and electricity from hydroelectric and nuclear power plants supply the Ukraine with roughly 20% of total energy consumption (EIA, 2012) or Indonesia has a +1.33% population growth rate and domestically produced oil and natural gas 49% of total energy consumption (EIA, 2011)) tend to have higher LEI values. Those LMIC with domestic high EROI energy sources are expected to experience far less economic turbulence during periods of declining EROI (e.g. the  $EROI_{IO}$  for Indonesia declined only slightly during oil prices shocks Figure 4.20)

### General Pattern Over Time

When the EROI for imported oil is low or when it declines the economies of nations highly dependent upon oil, which includes most developing nations tend to suffer substantially as more of their do-

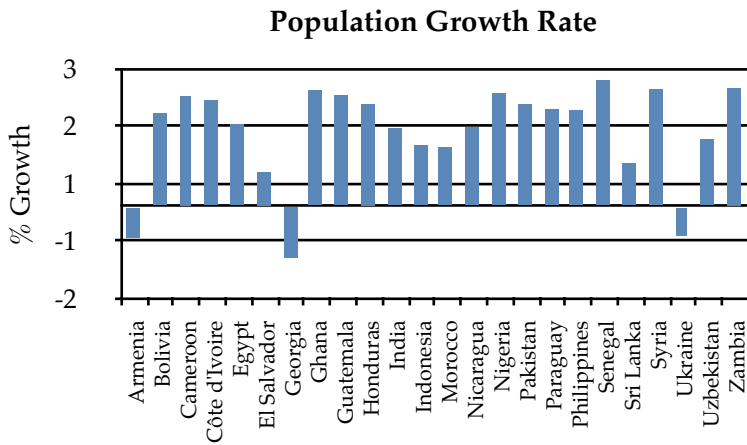


Figure 4.19: Annual percentage population growth in LMICs, 2009 (SOURCE: World Bank, 2012)

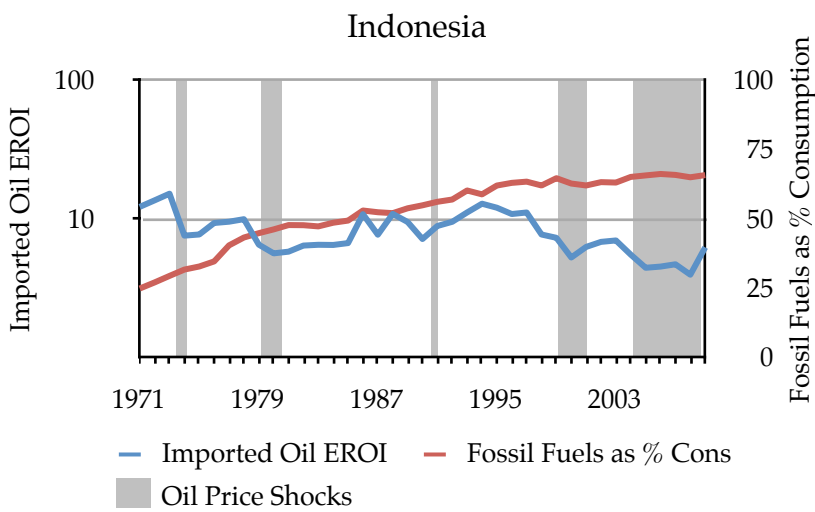


Figure 4.20:  $EROI_{IO}$  for Indonesia (log scale). (SOURCE: A. Gupta contribution to Lambert et al. 2013)

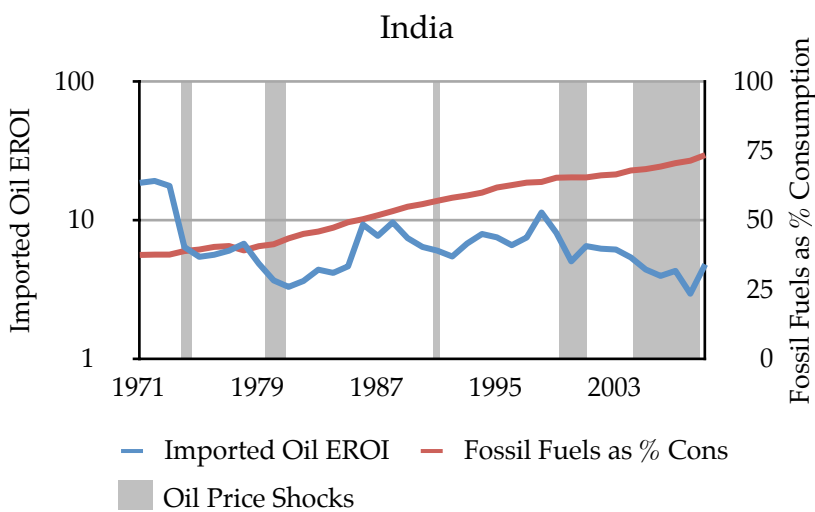


Figure 4.21:  $EROI_{IO}$  for India (log scale) (SOURCE: A. Gupta contribution to Lambert et al. 2013)

mestic production of goods and services must be diverted to gaining the same amount of oil. Thus if and as the EROI of global oil continues to decline, which we think likely, this will tend to contribute to the impoverishment of countries already poor.

India, as a perhaps typical country of this genre, has like Indonesia become more and more dependent on fossil fuels (Figure 4.21), in this case primarily coal. This enormous use of fossil fuel has created a world of two Indias. Roughly 31 percent of the people are considered “urban population” in 2011 (CIA, 2012) while many live in impoverished villages following a life style relatively unchanged from their ancestors. Thus the affluence from industrialization has disproportionately intensified the wealth of the relative few while marginally effecting the majority. Meanwhile the  $EROI_{IO}$  of the mostly imported oil has fluctuated with the world pattern, including the overall downward trend. Thus for coal-rich India it seems that increasing amounts of coal must be burned to generate the foreign exchange (through exports) necessarily to purchase oil from foreign sources.

#### 4.4.2 Energy Availability and Quality of Life Indicators

A pressing matter, particularly for LMICs, is the impact of decreasing energy availability on the quality of human life experienced by these burgeoning populations. This next portion of our study examines data gathered using various quality of life indices.



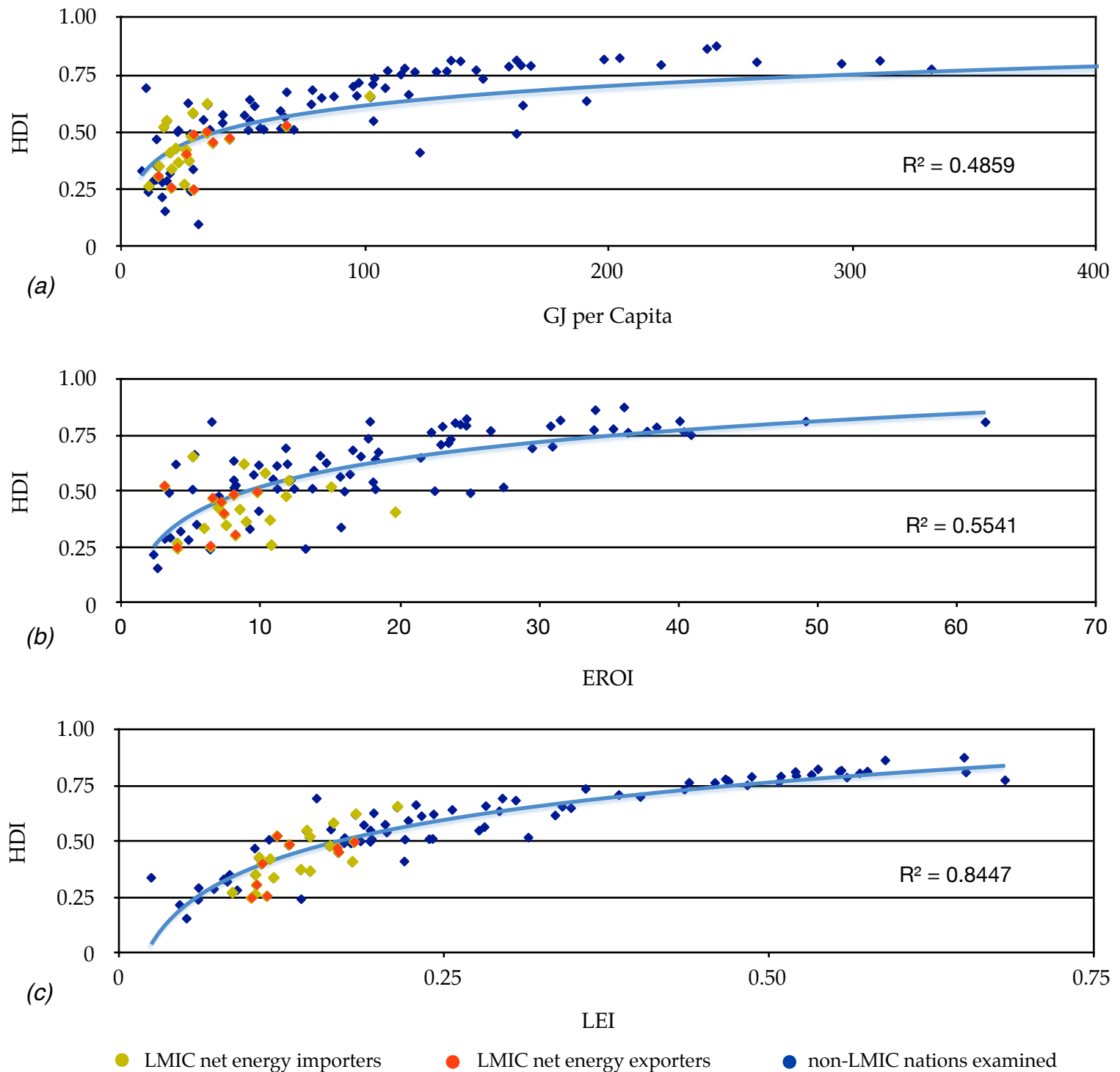


Figure 4.22: Regression of Human Development Index with (a) energy use per capita, (b)  $EROI_{SOC}$  and (c) LEI values (Lambert et al. 2013).

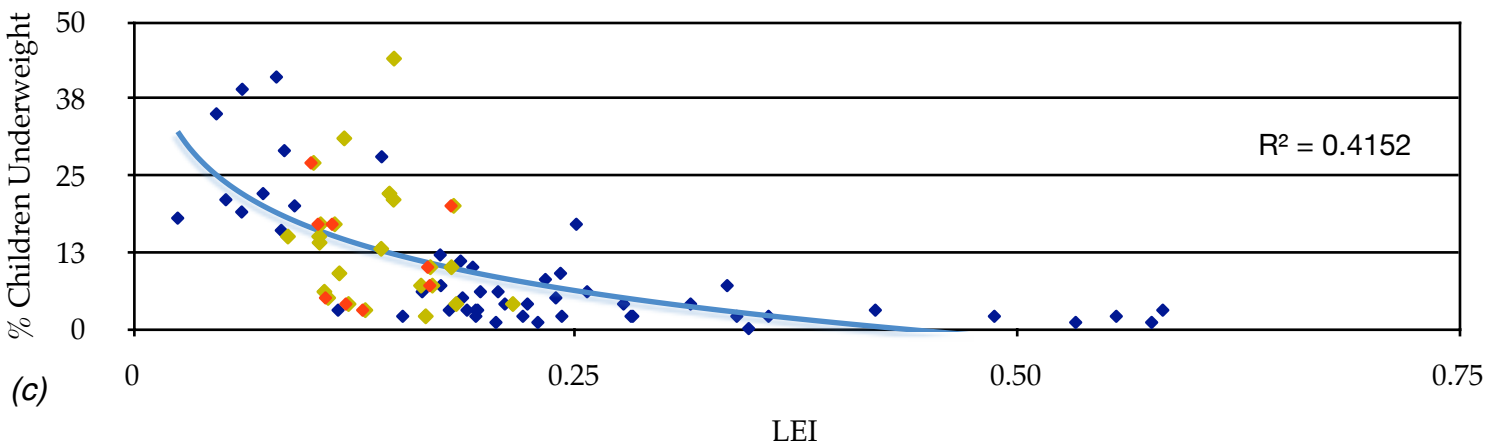
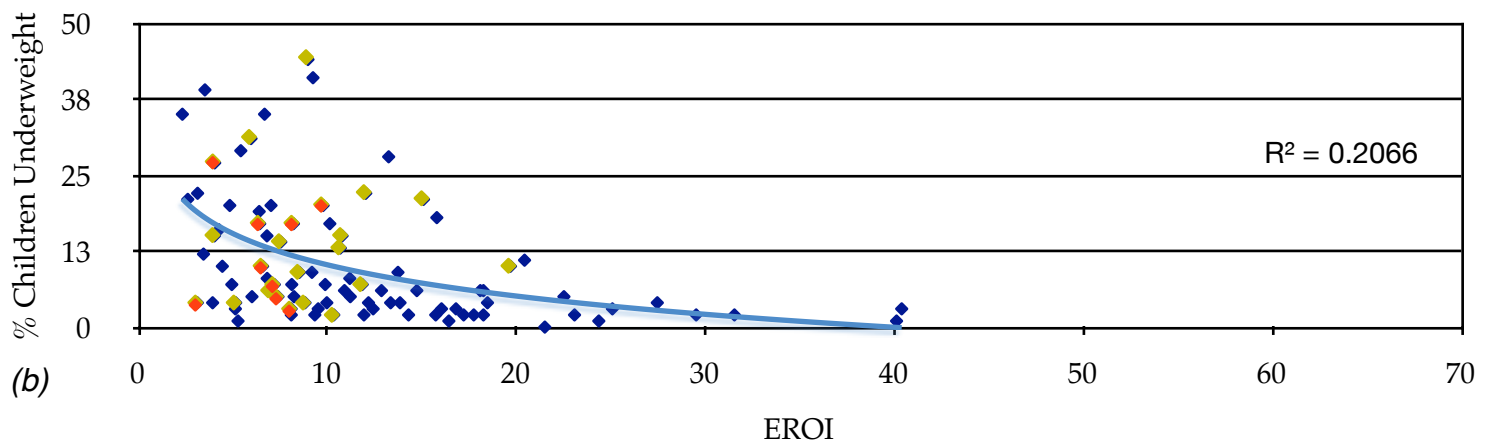
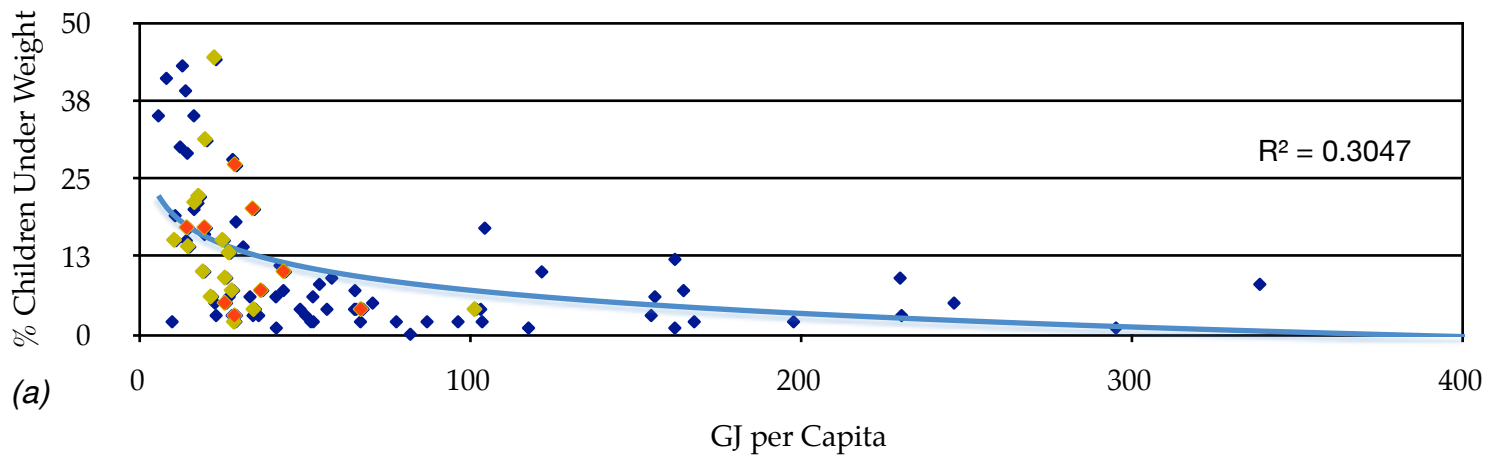
### Human Development Index

The relation of HDI with each of the energy indices employed first increases but then tends to saturate (Figure 4.22). LMICs have HDI values that range between 0.25 and 0.65. Of the LMIC countries within our study, the Ukraine has the

highest HDI, 0.652 and the highest LEI, 0.21.

### Percent Children Underweight

LMICs, although tending to have more food and better healthcare than LICs, are likely to be impoverished and their gen-



● LMIC net energy importers      ● LMIC net energy exporters      ● non-LMIC nations examined

Figure 4.23: Regression of percent children (less than 5 years old) underweight with (a) energy use per capita, (b)  $EROI_{SOC}$  and (c) LEI values (Lambert et al. 2013).

eral public is apt to have inadequate access to sufficient food and modern healthcare facilities. Armenia, Bolivia, Georgia, Paraguay, Ukraine and Uzbekistan are the only LMICs that have less than 5% of their children under weight. On the other end of the spectrum we find India with 44% of its children under weight. Pakistan is

slightly better with 31% of its children under weight and Nigeria has 27% of its children under weight (Figure 4.23). Each of these three LMICs also have low LEI index values of between 0.10 and 0.15.

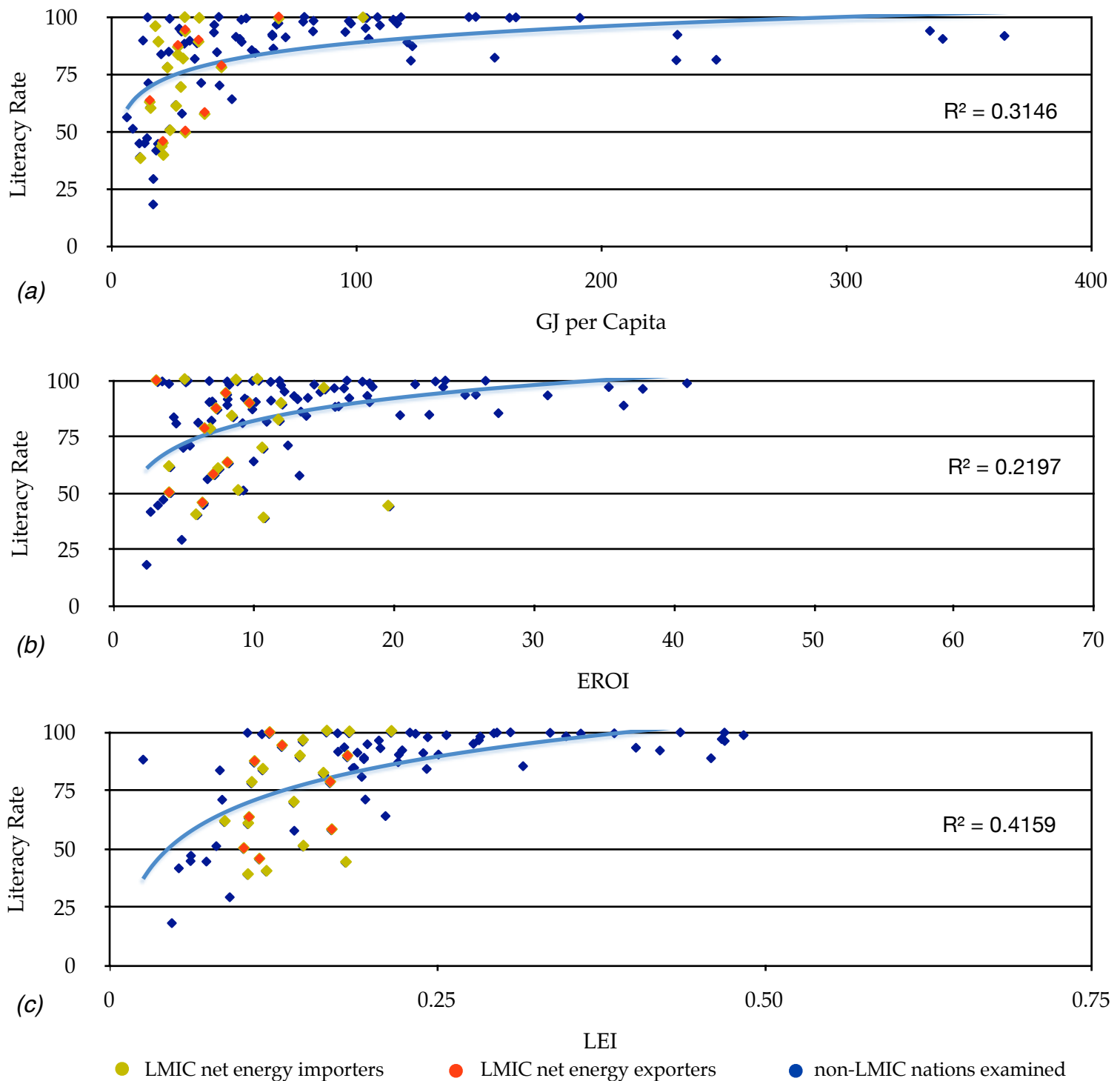


Figure 4.24: Regression of adult female female (% of females ages 15 and above) with (a) energy use per capita, (b)  $EROI_{SOC}$  and (c) LEI values (Lambert et al. 2013).

### Female Literacy

Female literacy rates within LMICs vary substantially (Figure 4.24). LMIC members formerly members of the Soviet Union (Armenia, Georgia, Ukraine and Uzbekistan) have the highest (99%) level of female literacy. India on the other end of the

spectrum, has the lowest (51%) female literacy rate of all of the LMICs within our study. Its neighbor to the east, Pakistan has a 40% female literacy rate and Senegal has similarly low (39%) female literacy rate.

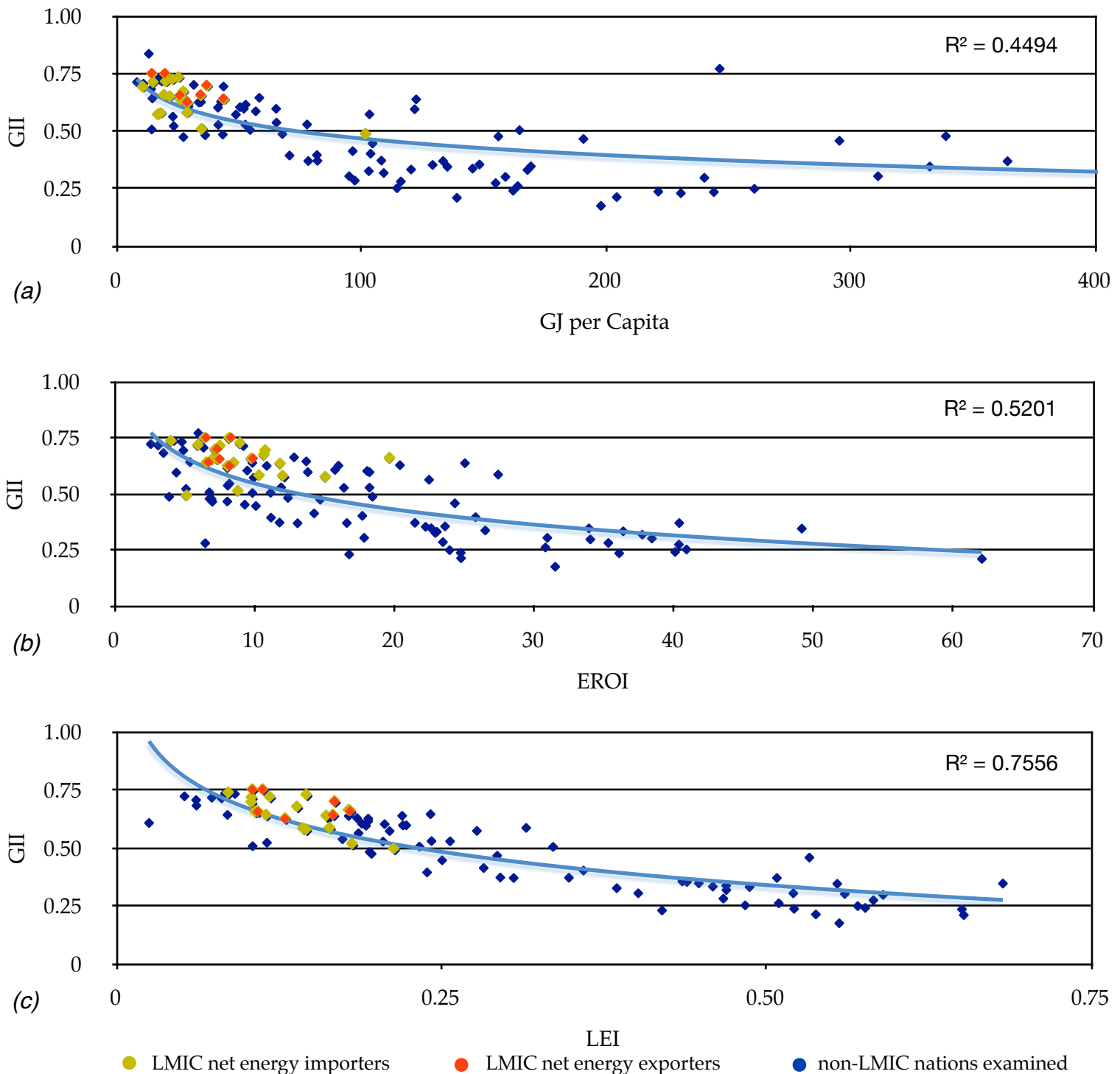


Figure 4.25: Regression of Gender Inequality Index with (a) energy use per capita, (b)  $EROI_{SOC}$  and (c) LEI values (Lambert et al. 2013).

### Gender Inequality Index

Ukraine and Armenia are the LMICs with the greatest gender equality, 0.488 and 0.506, respectively (Figure 4.25). The African nations of Cameroon (0.744), Côte d'Ivoire (0.744) and Zambia (0.730) are the

LMICs within our sample demonstrating the least gender equality.

### Improved Water Source

As with percent children underweight and female literary, percent access to improved water within LMIC varies substantially

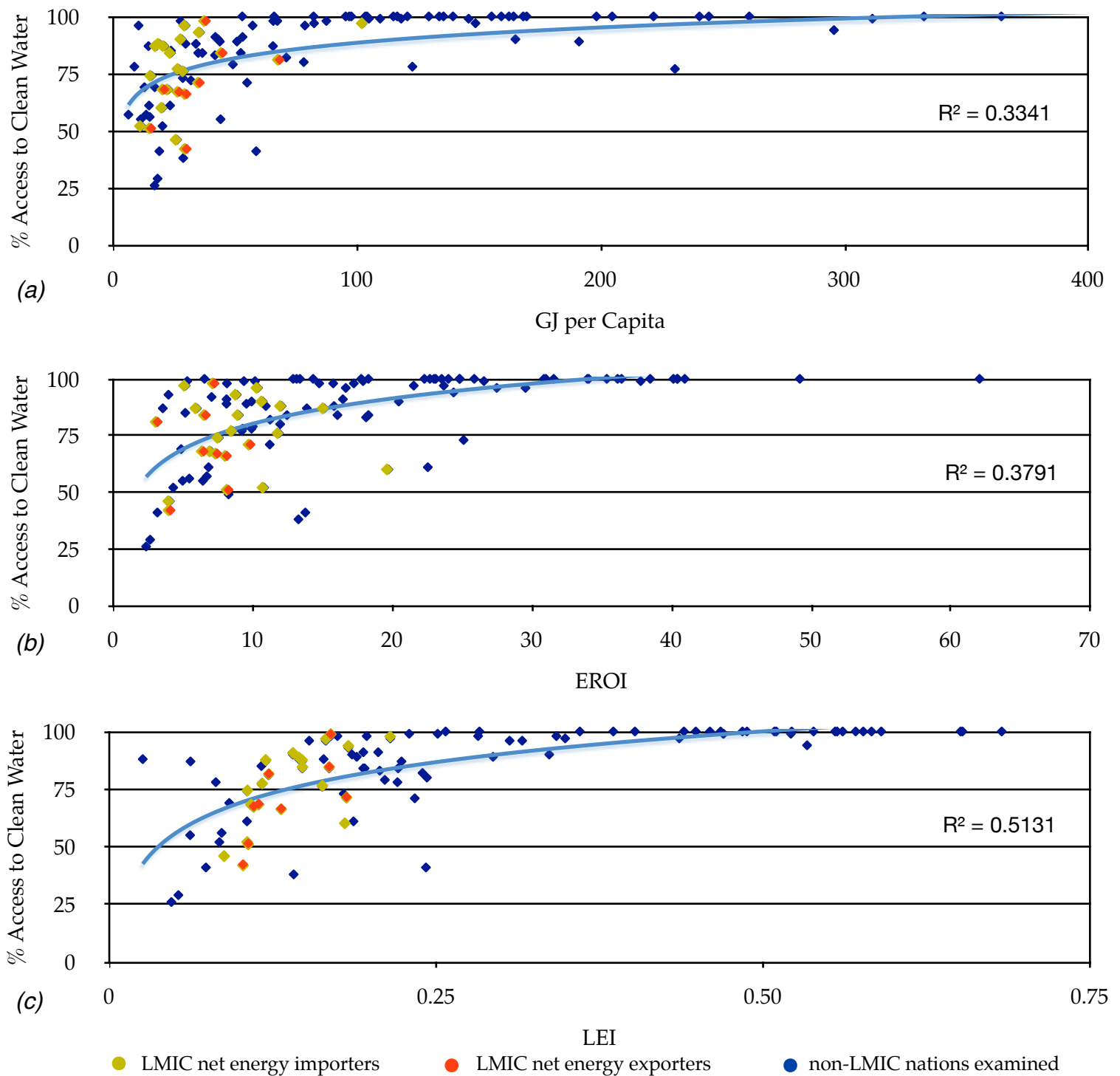


Figure 4.26: Regression of improved water source, rural (% of rural population with access) with (a) energy use per capita, (b)  $EROI_{SOC}$  and (c) LEI values (Lambert et al. 2013).

(Figure 4.26). Armenia, Egypt, Georgia, Guatemala and Ukraine are the LMICs that have greater than 90% of their rural populations with access to “clean” water. On the opposite extreme we have Zambia with 46% of its rural populations with access to improved water. LMICs with the greatest access to improved water also

have the highest LEI index values of between 0.14 and 0.21; the opposite is also true.

Our results indicate that LMICs generally have low energy use per capita, low to moderate energetic economic efficiency ( $EROI_{SOC}$ ) and a correspondingly low LEI.

### 4.4.3 Likely Impact of Declining EROI

This section discusses the probable impacts of declining EROI on LMICs, first in terms of fuel type, then with regard to domestic versus imported supply and then focuses on four measures of energy availability and their association with quality of life.

#### Fuel Type

A decline in EROI for our most important fossil fuels is likely to have a greater direct impact on LMIC economies than on many of their more impoverished LIC counterparts. This is primarily because LICs tend to rely more heavily on domestic sources of renewable combustibles and waste energy sources while LMICs nations tend to rely, at least in part, on domestic and imported fossil fuels. Nations currently importing fossil fuels (e.g. Sri Lanka) and those most likely to require non-domestic fossil fuel to meet their future energy needs, are expected to experience the greatest impact of declining EROI. This impact will be felt more acutely than in nations that are able to meet the majority of their energy needs via domestic energy sources.

#### Domestic and Imported Fuel

Most of the LMICs examined are pursuing large-scale construction and development projects, developing enterprises and increasing agricultural productivity in an effort to spur economic growth. These activities require ever increasing amounts of

fossil fuel. LMICs typically meet at least some of this demand with domestic energy sources (e.g. India produced 897,300 Bbl per day of crude oil, but required an additional 2.8 million Bbl per day of imported crude oil (CIA, 2013)). Fortunately India is an exception; the average LMIC examined imports just over 7% of their total energy used. This suggests that declining EROI of our most prominent fossil fuel resources are likely to adversely impact the portion of LMIC economies that are directly or indirectly reliant on cheap and abundant coal, oil and natural for their continued function, especially the transportation and electricity sectors and heavy industries.

#### Energy Availability and Quality of Life

Our major findings show that changes in energy availability would appear to impact quality of life values for LMICs:

1. LMICs use on average less than 30 GJ per capita per year. This level of use is typically associated with low to moderate “quality of life.” The Ukraine has the highest energy use per capita of our LMICs and the highest quality of life indices.
2. LMICs typically have low EROI<sub>SOC</sub> values (from 3-20:1). Unlike LICs, the link between EROI<sub>SOC</sub> and quality of life values appear to be largely non-predictive. Nigeria and the Ukraine have some of the lowest EROI<sub>SOC</sub> values (4:1 and 5:1) of the LMICs but highly divergent quality of life indices (e.g. HDI values, 0.246 and 0.652). This variability is not seen when the

pattern is reversed; those nations with the lowest HDI values nearly always have low  $EROI_{SOC}$  values. This suggests that some other factor (e.g. energy use per capita) is positively influencing these nations, allowing them to attain a better quality of life in spite of their low energetic efficiency.

3. Household income distribution ranges widely among LMICs. The most equitable nations include Armenia and the Ukraine. These LMIC nations also have the highest human development indices. Conversely UMICs with the poorest quality of life values typically have the least equitable income distribution (Gini index values greater than 40).
4. As with LICs, improvement in standard of living is linked with increases in LEI values. This suggests that a high value for one or more of the variables used to make up the LEI composite statistic may be able to compensate for low values for the remaining variables. For example, the Ukraine has the highest energy use per capita of LMICs and the most equitable income distribution, but it is energetically inefficient. The two extreme values (energy use per capita and income distribution) counteract the effect of low  $EROI_{SOC}$  resulting in relatively high LEI value. On the other hand, the Philippines has one of the lowest energy use per capita values and only modestly equitable income distribution, but it is en-

ergetically efficient. In this case, one extreme value ( $EROI_{SOC}$ ) offsets the effect of the other two values (energy use per capita and income distribution) leading to a moderately high LEI value.

5. Population growth rates predict current and future strains on existing energy resources. Nations with low population growth rates (Armenia, Georgia and Ukraine) have considerably higher quality of life indices.

#### 4.4.4 Summary

In summary, our analysis of LMICs suggests that those nations with access to large quantities of domestic, high EROI energy that is distributed equitably tend to experience a higher standard of living. Nations with high values in one or more energy category may still be able to achieve the relatively high overall energy availability (i.e. LEI) associated with high quality of life. The implications for this are clear. Even in a world experiencing declining availability of high EROI energy per capita, nations may be able to maintain or grow their overall energy availability by increasing their energetic efficiency. Similarly, those nations unable to increase energetic efficiency may be able to achieve similar results by increasing their per capita energy availability or the equitability of energy distribution.

## 4.5 Upper Middle Income Countries

This section analyses the energy availability and social well-being of upper middle income countries (UMICs). The World Bank classifies UMIC economies as having between \$4,086 - \$12,615 GNI per capita according to World Bank (2012). Our analysis is based largely on concepts developed by Smil (2003) and data drawn from the World Bank (2012) development indicators and the US Energy Information Administration (EIA, 2012). Our sample includes 21 UMIC countries that were net energy importers and 16 UMIC countries that were net energy exporters in 2009.





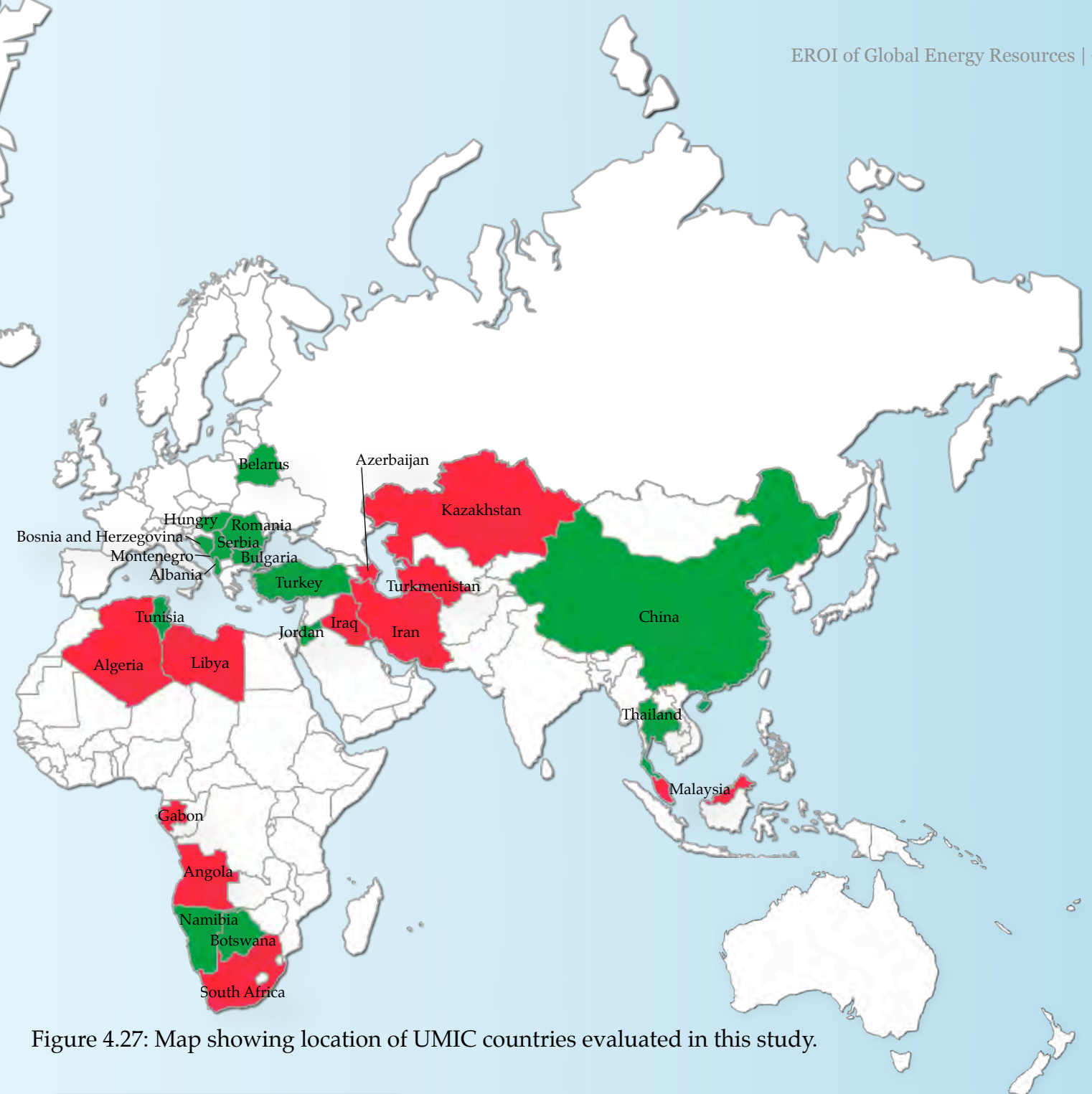


Figure 4.27: Map showing location of UMIC countries evaluated in this study.



Each of the UMICs examined have diverse resource and economic situations that result in low to moderate energy availability and an associated low to moderate quality of life (as

measured by quality of life indices). More specifically, the UMICs we examined have low to moderate energy use per capita (averaging 69 GJ per capita), low  $EROI_{SOC}$  values (averaging 14:1) and a wide range in income distribution (Gini index values range from 28.2 for Serbia to 74.3 for Namibia). However, all UMICs examined have low to moderate LEI values (between 0.03 and 0.34) and most of these countries also have correspondingly low to moderate quality of life indicators (e.g. HDI between 0.24 (Angola) and 0.74 (Hungary)).

## 4.5.1 Key Energy Availability and Quality of Life Indicators

This section presents key data on energy availability and economic and quality of life characteristics of upper middle income countries. Each of these indicators provides contextual data to evaluate a country's economic vulnerability and/or capacity to adapt to declining EROI.

### Economic Indicators

Figure 4.28 gives gross domestic product (GDP) per capita for the 38 UMICs within our sample. Among the UMICs, the poorest in terms of GDP per capita is Iraq (\$3,590). This is followed by Angola with \$5,657, and Jordan with \$5,770. It is noted that Iraq, the poorest of the UMICs, may have an anomalously low GDP per capita due to conflict within the region. In general the economic and other statistics of countries engaged in war are highly distorted by the war and are probably quite unreliable.

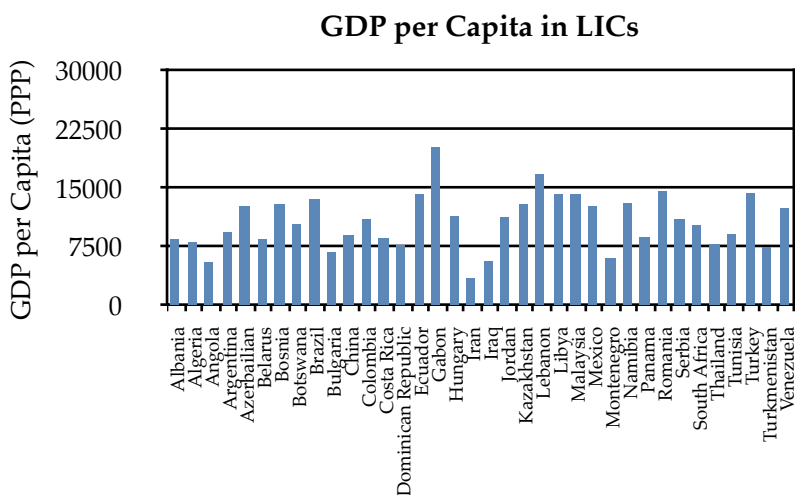


Figure 4.28: Gross domestic product (PPP) per capita in UMICs, 2009 (SOURCE: World Bank, 2012)

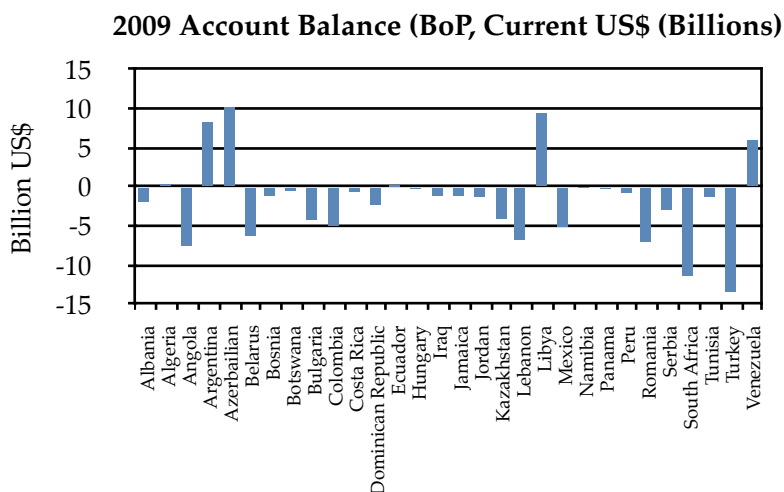


Figure 4.29: Account balance (BoP, billion current USD) in UMICs in 2009, excluding Brazil (-24), China (+243), Malaysia (+32) and Thailand (+22). (SOURCE: World Bank, 2012)

Twenty five of the UMICs examined had account deficits on goods and services in 2009 (Figure 4.29) (e.g. Brazil (-24.3%) and Turkey (-13.4%)). Alternatively a few UMICs have high account balances, most notably China (+243.3%). Countries with a positive balance of payment, such as China, have a much greater ability to respond to any future increase in the price of oil (and hence decline in  $EROI_{10}$ ) simply because they have foreign exchange "in the bank" and could pay for it, at least for a while. Conversely lending countries are likely to be averse to loaning additional

money to countries already highly indebted. Thus probable increases in the price of oil are likely to have severe impact on those developing nations that are “poor” and have already a negative balance of payment.

### Energy Availability Indicators

Sixteen of the 37 UMICs were net energy exporters in 2009 (Table 4.6 and 4.7). The energy use per capita for UMIC varies greatly among UMIC examined, averaging 56GJ per capita for net energy importers and 86GJ per capita for net energy export-

Table 4.6: Summary of energy availability indicators for net energy importing UMIC nations.

Country	Energy Use per Capita	EROI <sub>soc</sub>	Gini-Index	LEI
Albania	27	15:1	35	0.20
Belarus	118	5:1	27	0.23
Bosnia and Herzegovina	67	16:1	36	0.28
Botswana	43	20:1	61	0.19
Brazil	52	18:1	54	0.22
Bulgaria	97	14:1	45	0.28
China	71	11:1	42	0.24
Costa Rica	42	16:1	50	0.21
Dominican Republic	35	16:1	48	0.19
Hungary	104	18:1	31	0.36
Jamaica	50	9:1	46	0.19
Jordan	53	8:1	38	0.19
Lebanon	66	13:1	n.a.	n.a.
Montenegro	44	29:1	30	0.32
Namibia	29	16:1	74	0.03
Panama	41	18:1	52	0.21
Peru	23	22:1	48	0.19
Romania	68	18:1	n.a.	n.a.
Serbia	87	17:1	28	0.34
Thailand	65	8:1	54	0.17
Tunisia	36	12:1	41	0.19
Turkey	57	27:1	40	0.32
<b>Mean</b>	<b>58</b>	<b>16:1</b>	<b>44</b>	<b>0.23</b>
<b>Median</b>	<b>53</b>	<b>16:1</b>	<b>44</b>	<b>0.21</b>
<b>Standard Deviation</b>	<b>26</b>	<b>6</b>	<b>12</b>	<b>0.07</b>

Table 4.7: Summary of energy availability indicators for net energy exporting UMIC nations.

Country	Energy Use per Capita	EROI <sub>SOC</sub>	Gini-Index	LEI
Algeria	49	10:1	35	0.21
Angola	28	13:1	59	0.14
Argentina	78	12:1	46	0.24
Azerbaijan	55	11:1	34	0.23
Colombia	28	25:1	58	0.18
Ecuador	34	11:1	49	0.16
Gabon	58	14:1	41	0.24
Iran	122	4:1	38	0.19
Iraq	44	5:1	n.a.	n.a.
Kazakhstan	165	10:1	31	0.34
Libya	156	7:1	n.a.	n.a.
Malaysia	105	10:1	46	0.25
Mexico	65	14:1	52	0.22
South Africa	122	13:1	58	0.25
Turkmenistan	162	3:1	41	0.17
Venezuela	103	12:1	44	0.28
<b>Mean</b>	<b>86</b>	<b>11:1</b>	<b>45</b>	<b>0.22</b>
<b>Median</b>	<b>72</b>	<b>11:1</b>	<b>45</b>	<b>0.23</b>
<b>Standard Deviation</b>	<b>48</b>	<b>5</b>	<b>9</b>	<b>0.05</b>

ers. Several UMIC (Albania, Angola, Namibia and Peru) have low energy use per capita, below 30GJ per capita. This extreme low energy use per capita suggest that these nations will likely act as LICs when faced with increasing costs associated with low EROI fuels. Alternatively, many UMICs are high energy users (most of these are classified as net energy exporters), exceeding 100 GJ per capita.

A second measure of the energy available to a nation is EROI<sub>SOC</sub>, the net energy produced by a society. This is also extremely variable for UMICs examined, ranging

from 3:1 to 29:1. The lowest EROI<sub>SOC</sub> value was calculated for Turkmenistan (3:1) and the highest for Montenegro (29:1). As with the LICs and LMICs, declining EROI of traditional fossil fuels is expected to further reduce the EROI<sub>SOC</sub> values of UMICs. However, all but 4 of the UMICs included within our sample rely on combustible renewables and waste and alternative and nuclear energy for less than 40% of their total energy use portfolios (Figure 4.30). This means that the remaining 60% of total energy use is currently contingent on continued access to traditional fossil fuels (of

which many are imported). Consequently, those UMICs unable to meet their energy needs using domestic sources are likely to face a decline in  $EROI_{SOC}$  associated with high energy prices and declining EROI of fossil fuels.

As with previous income categories, the Gini-index is highly variable among the UMICs within our sample with values ranging from extreme equitable income distribution (e.g. Belarus) to extreme inequitable income distribution (e.g. Namibia). The ability to distribute resources in an energy constrained world equitably will likely have direct and indirect repercussions on social factors e.g. life expectancy.

LEI can be viewed as an index of “potential” energy availability. Several UMICs have low LEI values typically associated with LICs or LMICs (e.g. Namibia,  $LEI = 0.03$ ). And, like LICs and LMICs, these countries are characterized as having high population growth rates (Figure 4.31). These nations are likely to have difficulties providing sufficient energy resources (especially with population growth rates greater than 2 percent) in an energy constrained world. Therefore, a decline in the EROI of traditional fossil fuel energy sources is likely to impact these lower LEI UMIC economies adversely. However, the majority of UMICs have high LEI values relative to LIC and LMIC economies and lower population growth rate (averaging 1.3%). These UMICs typically rely on fossil fuel to run their economy. Large net energy exporters (e.g. Venezuela) are likely to experience few adverse effects when faced with declines in the EROI of major

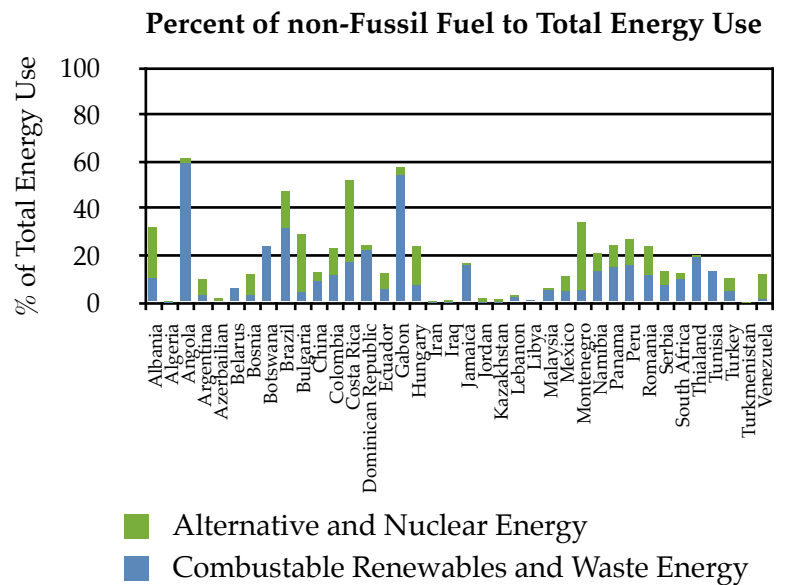


Figure 4.30: Contribution of alternative and nuclear energy (green) and combustible renewables and waste energy (blue) to total energy use.

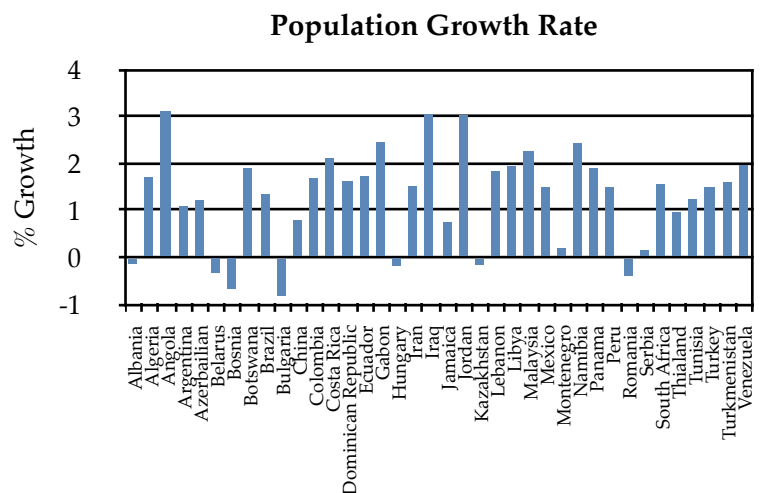


Figure 4.31: Annual percentage population growth in UMICs, 2009 (SOURCE: World Bank, 2012)

fossil fuel energy sources (assuming they are able to maintain access to domestic sources of high EROI fuel).

### General Pattern Over Time

Countries with a positive balance of payment, such as China, have a much greater ability to respond to any future increase in the price of oil (and hence decline in  $EROI_{IO}$ , Figure 4.32) simply because they have foreign exchange “in the bank” and could pay for it, at least for a while. Nevertheless, China has a certain vulnerability because of its heavy energy use and because of its exhaustible oil and coal reserves (Hu et al. 2013). Conversely lending countries are likely to be averse to loaning additional money to countries already highly indebted.

Malaysia has considerable natural gas which it has used to generate relatively high standard of living for its people. However, Malaysia is still dependent on imported oil for its energy. For Malaysia the  $EROI_{IO}$  has declined sharply since 1998 (Figure 4.33). Thus a substantial and increasing proportion of the goods and services generated using e.g. natural gas must be diverted to paying for imported oil, reducing the social benefit of that gas to the people of Malaysia.

### 4.5.2 Energy Availability and Quality of Life Indicators

This subsection discusses important energy availability and quality of life characteristics of upper-middle income countries.

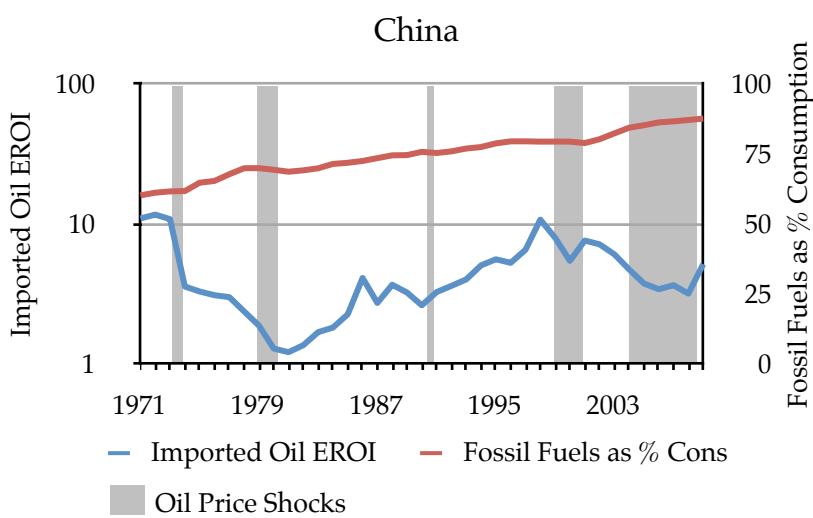


Figure 4.32:  $EROI_{IO}$  for China (log scale)  
(SOURCE: A. Gupta contribution to Lambert et al. 2013)

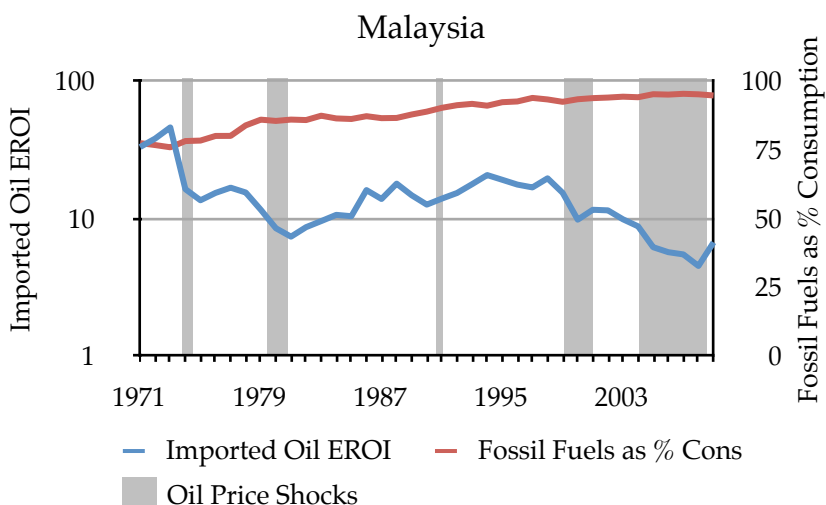


Figure 4.33:  $EROI_{IO}$  for Malaysia (log scale).  
(SOURCE: A. Gupta contribution to Lambert et al. 2013)

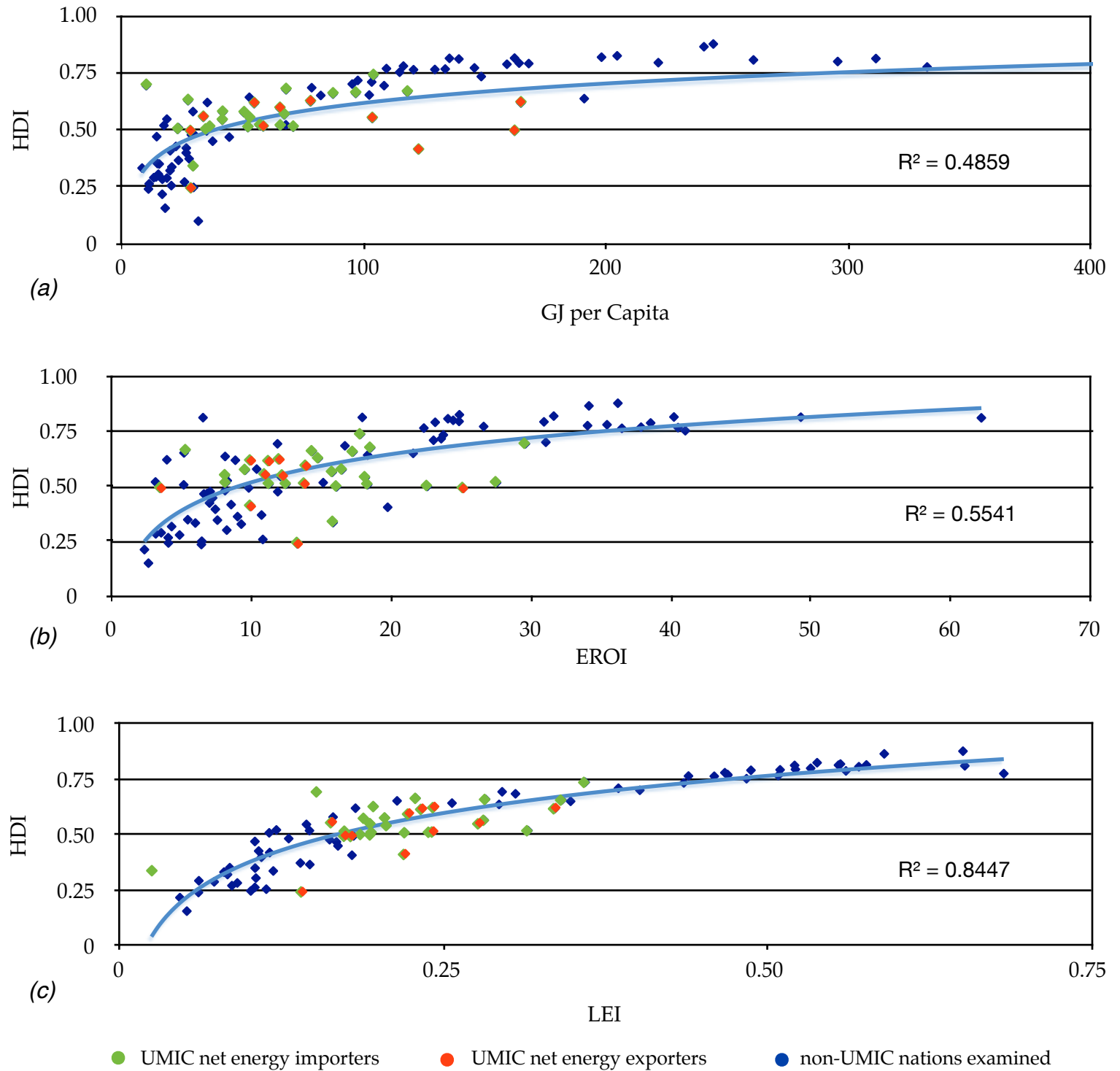


Figure 4.34: Regression of HDI with (a) energy use per capita, (b)  $EROI_{SOC}$  and (c) LEI values (Lambert et al. 2013).

### Human Development Index

Excluding Angola and Namibia, two extreme outliers, UMICs have HDI values that range between 0.40 and 0.74 and LEI values from 0.15 and 0.36 (Figure 4.34). Of the UMIC countries within our study, An-

gola (0.242) and Namibia (0.338) have the lowest HDI, 0.242 and 0.338 and the lowest LEI, 0.14 and 0.03. Alternatively, Hungary, the UMIC with the highest HDI value (0.736) also has the highest LEI value (0.36).

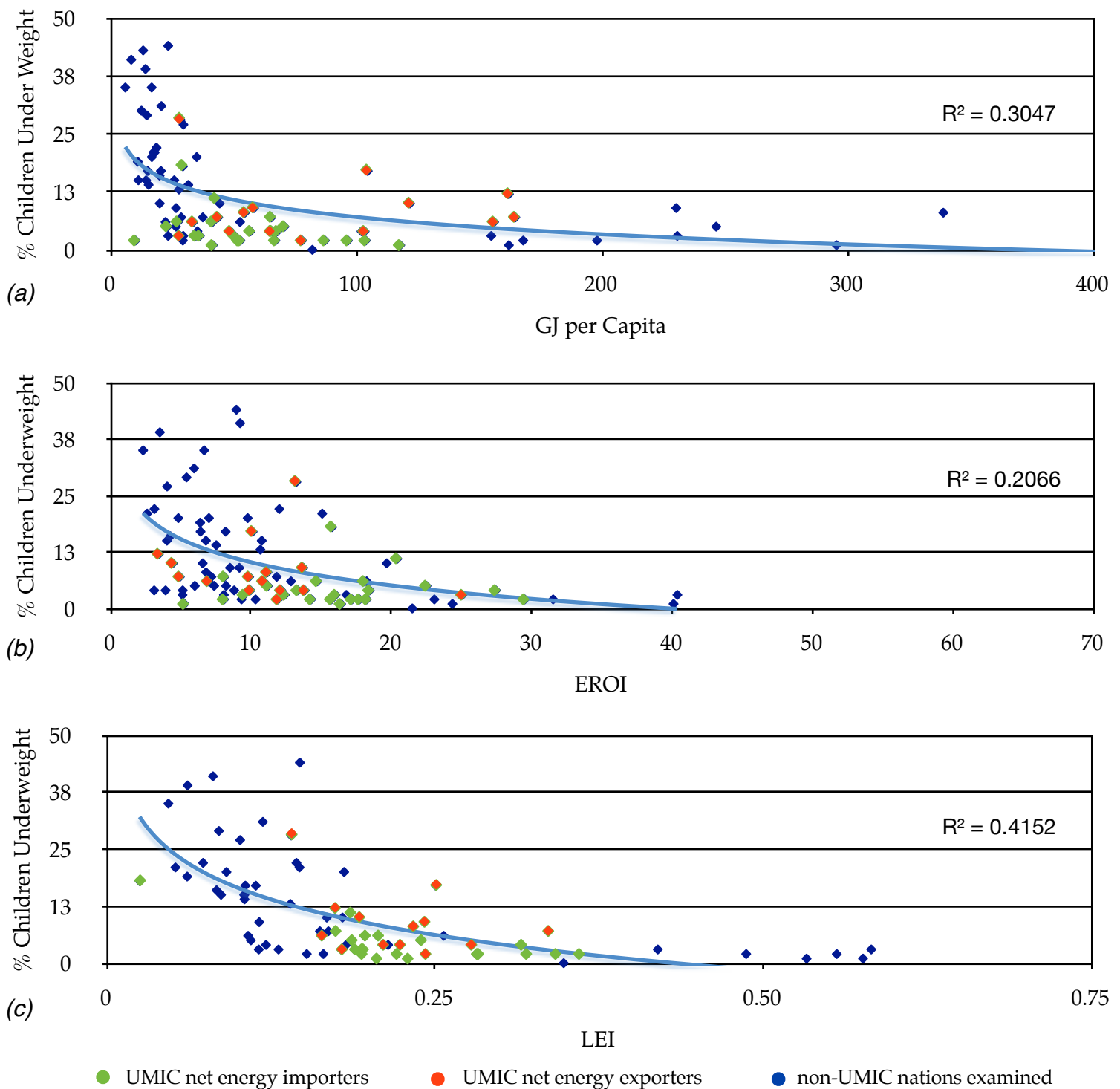


Figure 4.35: Regression of percent children (less 5 years old) underweight with (a) energy use per capita, (b)  $EROI_{SOC}$  and (c) LEI values (Lambert et al. 2013).

### Percent Children Underweight

Of the income groups examined, UMICs tend to have best access to food and healthcare. All but three UMICs examined (Angola, Malaysia, and Namibia) have less than 13% of their children under weight.

Each of these three UMICs also has a low LEI value (between 0.03 and 0.25).

### Female Literacy

The average UMIC female literacy rate is 89% with several countries approaching 100% (Figure 4.36). Some UMIC have



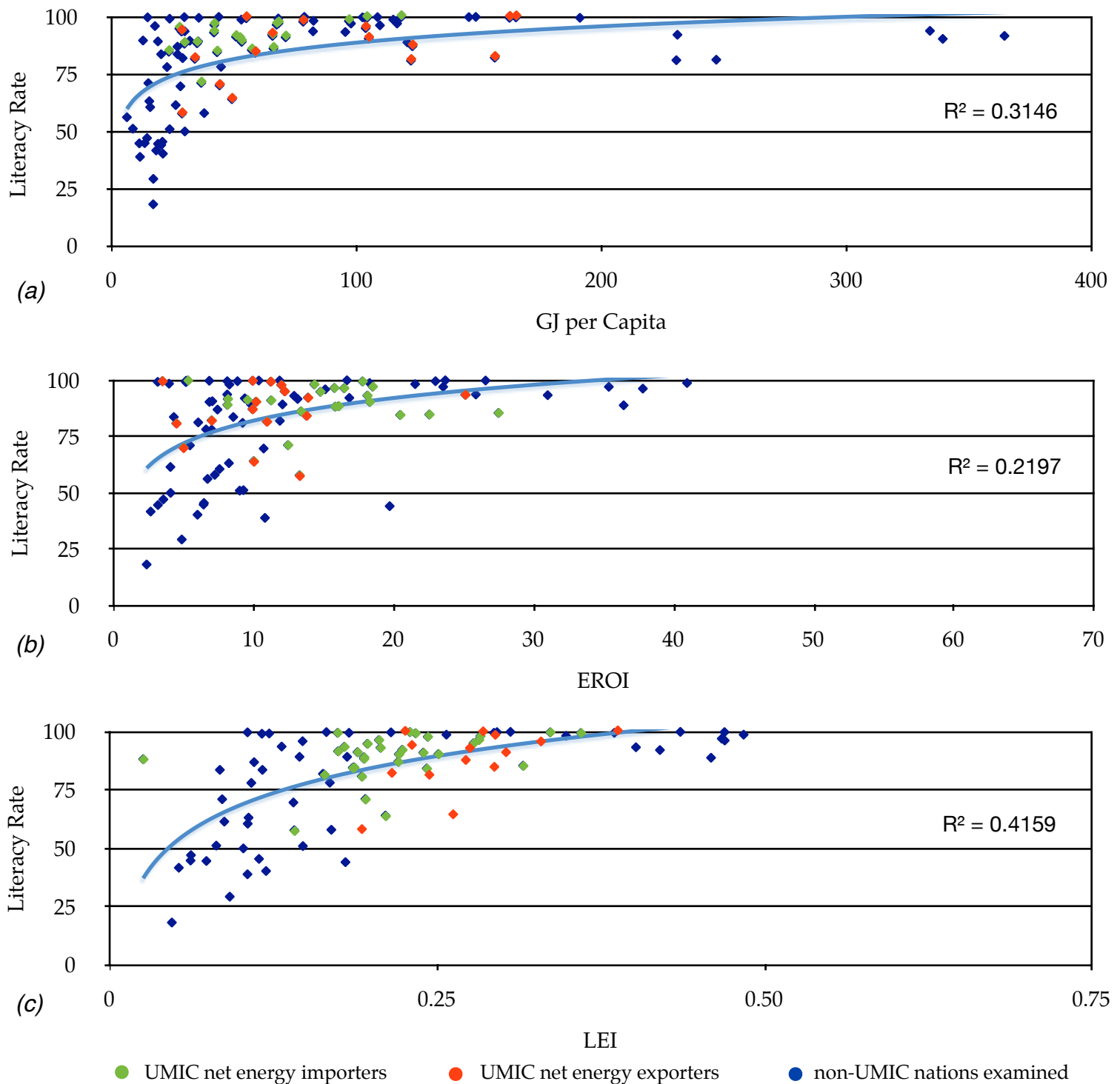


Figure 4.36: Regression of adult female female (% of females ages 15 and above) with (a) energy use per capita, (b)  $EROI_{SOC}$  and (c) LEI values (Lambert et al. 2013).

much lower adult female literacy rates. Algeria, Angola and Iraq have the lowest female literacy rates (64%, 58% and 70%) of all of the UMICs. Algeria is characterized as having poor socioeconomic conditions (e.g. large-scale unemployment) and societal instability (e.g. continuous dis-

ruptive activity by extremist militants). Angola is rebounding after economic trauma associated with 27 years of civil war that ended in 2002. A US-led invasion of Iraq began in 2003 and continued through 2011. The recent violence and economic instability experienced by each

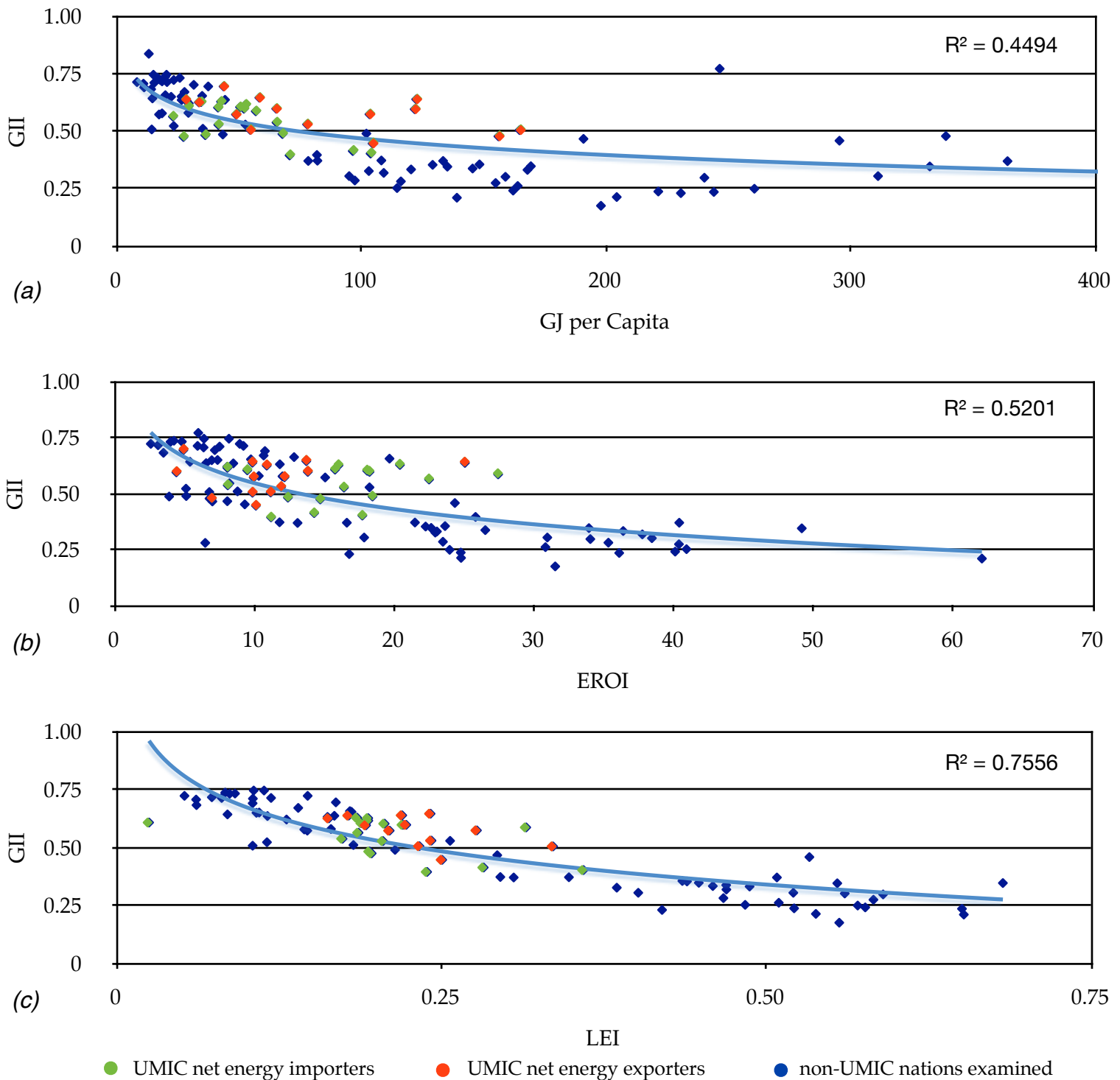


Figure 4.37: Regression of GII with (a) energy use per capita, (b)  $EROI_{SOC}$  and (c) LEI values (Lambert et al. 2013).

of these nations likely has a negative influence on female literacy.

### Gender Inequality Index

China with a 0.393 GII value and Hungary with a 0.401 GII value are the two UMICs with the greatest gender equality (Figure

4.37). The UMICs within our sample demonstrating the least gender equality include Botswana (0.627), Colombia (0.636), Iraq (0.693) and South Africa (0.637). These nations are also characterized as having low energy availability.

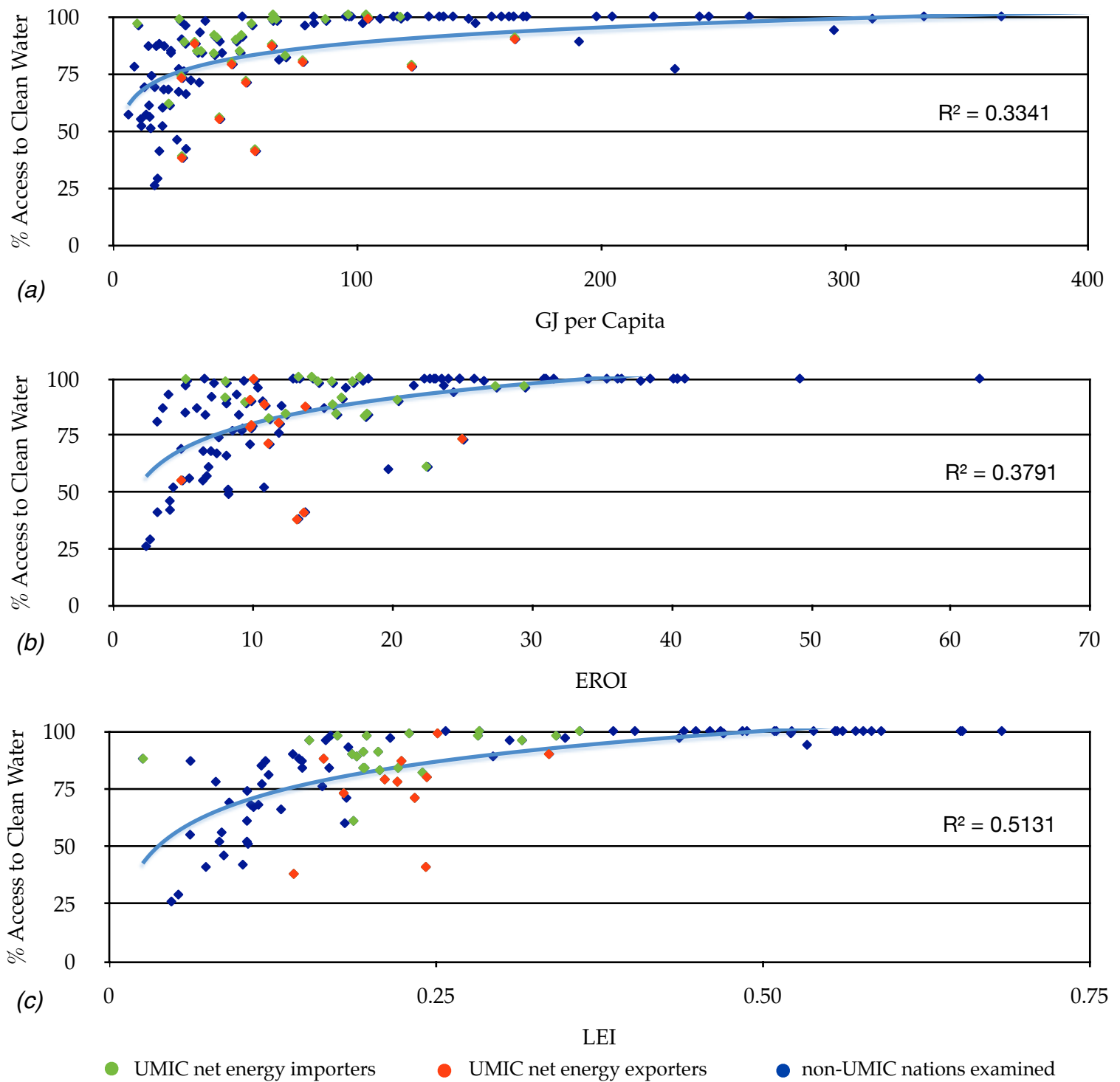


Figure 4.38: Regression of improved water source, rural (% of rural population with access) with (a) energy use per capita, (b)  $EROI_{SOC}$  and (c) LEI values (Lambert et al. 2013).

### Improved Water Source

Access to improved water sources varies substantially among the UMICs examined (Figure 4.38). In all but five UMICs more than 75% of the rural population has access to “clean” water. The five, Angola

(38%), Azerbaijan (71%), Gabon (41%), Iraq (55%) and Peru (61%) exhibit a high degree of variation ranging from nearly average to a very low 38% in Angola. UMICs with rural populations having the least access to improved water typically

have low LEI values between 0.14 and 0.24.

Our results indicate that UMICs generally have relatively high energy use per capita, but retain low to moderate energetic economic efficiency ( $EROI_{SOC}$ ). This results in moderate LEI values and associated moderate quality of life indices. The highest correlations are with the most general indices: LEI and HDI.

### ***4.5.3 Impact of Declining EROI***

This section discusses the potential impact of declining EROI on UMICs in terms of fuel type, domestic versus imported energy supply, and four measures of energy availability and their association with quality of life indices.

#### **Fuel Type**

The impact of declining EROI for our most important fossil fuels is likely to have a direct and adverse effect on most UMIC economies, because the average UMIC relies on fossil fuels for more than 80% of its energy portfolio (World Bank, 2012). Oil makes up nearly 60% of the fossil fuel used (EIA, 2012). UMICs currently importing fossil fuels (specifically oil) are expected to experience negative economic impacts associated with oil price shocks and declining EROI in the coming decades. This may also be true for nations which are currently relying on imported natural gas and coal. This is because these energy sources will be increasingly drawn upon to reduce and replace reliance on an increasingly volatile international oil market.

#### **Domestic and Imported Fuel**

Over half of the UMICs examined are currently net energy importers that rely on a positive trade balance to ensure their continued ability to pay for fossil fuel imports. UMIC net energy importers generally meet some of their energy demands via domestic energy sources. For example, China, by far the largest UMIC energy consumer, produced 4.15 million Bbl per day of crude oil in 2012, but required an additional 5.42 million Bbl per day of imported crude oil (CIA, 2013). Hu et al.'s (2013) findings suggest that China's oil consumption will continue to rise and that these demands are unlikely to be satisfied by China's low EROI domestic oil resources. Many UMICs are expected to follow similar paths. This suggests that declining EROI for imported fossil fuels, especially oil, are likely to adversely impact UMIC economies that are currently directly or indirectly reliant upon international sources of cheap and abundant coal, oil and natural gas.

UMICs also include prominent net energy exporters (e.g. Libya, Iran, Iraq, Venezuela, etc.). These nations are unlikely to experience direct negative impacts as long as they continue to produce sufficient high quality energy. These net energy producers may, in fact, experience economic benefits associated with higher energy commodity prices that commonly accompany oil price shocks. Proactive national and international policy decisions will be necessary to minimize the economic, political and social impact of current and future volatility in the global energy market.

## Energy Availability and Quality of Life

Our findings show that decreased energy availability will negatively impact quality of life values for UMICs.

1. UMICs on average consume greater than 65 GJ per capita per year. Among the countries examined, this varies widely (from 23 GJ per capita in Peru to 164 GJ per capita in Kazakhstan). These energy values typically are associated with low to moderate “quality of life” indices.
2. UMICs exhibit a range of EROI<sub>SOC</sub> values (from 3-29:1). The link between EROI<sub>SOC</sub> and quality of life values appears to be moderately predictive. UMICs with high EROI<sub>SOC</sub> values tend to also have high quality of life indices. The opposite is not always evident. Nations with high quality of life indices do not necessarily have high EROI<sub>SOC</sub> values. Many net energy exporters with low EROI<sub>SOC</sub> values (e.g. Iran) have high quality of life indices. This suggests that either, (1) the free market price assumptions used in the study do not adequately represent prices associated with consuming domestic energy resources (in other words, it is cheaper for net energy producers to consume their own fuel rather than sell it on the open market) and/or (2) the production of energy is an energy intensive process that drastically reduces the energy efficiency of an economy. We believe the answer lies somewhere in the middle.
3. As with LICs and LMICs, income distribution ranges widely among UMICs. The most equitable nations include Belarus and Montenegro while the least equitable nations include Namibia and Botswana. As with LMICs, nations with the greatest income equality have the highest quality of life indicators and UMICs with the most inequitable income distribution have the lowest quality of life indicators.
4. A better standard of living is associated with a higher LEI value. Like the LMICs examined in section 4.4.3, a high value for one or more of the variables within the LEI composite statistic appears to be able to offset the affect of a low value for the remaining variable(s). For example, net energy producers such as Iran have high energy use per capita but are energetically inefficient. Their high energy use per capita balances the effect of low EROI<sub>SOC</sub>. This in turn results in a relatively high LEI value. Conversely, net energy importers who have relatively low energy use per capita, moderately equitable income distribution and are energetically efficient, also achieve a relatively high LEI values.
5. For UMICs the impact of population size and population growth rate on quality of life indices varies among countries. The relation between quality of life indices and population and population growth rate for UMICs falls into three distinct categories:

countries with low populations and low to negative population growth rates which tend to have higher quality of life indices (e.g. nations with the lowest population growth rates (Armenia, Georgia and Ukraine) have considerably higher quality of life indices); countries with large population bases and moderate expected growth rates which are most likely to experience greater constraints on energetic resources and countries with high populations and high population growth rates (greater than 2%) are most likely to have low quality of life indices. While declining EROI for important fossil fuels make increasing energy use per capita challenging, the added issues of large population size and growth rates exacerbate these challenges.

#### **4.5.4 Summary**

Our analysis of UMICs indicates that nations with access to large quantities of domestic high EROI energy (net energy exporters) that is equitably distributed within the population will have relatively high standards of living. Declining EROI of fossil fuels will have little negative economic impact on these energy exporters as long as the supply of energy remains plentiful. In fact, these net energy exporters may find themselves benefiting from volatile global energy markets. UMICs that are net energy importers, whose economies are dependent either wholly or in part on fossil fuels purchased on the global market will find that declining EROI will, depend-

ing on the severity of the EROI decline/availability make increasing energy use per capita challenging or impossible. UMICs with high values in one or more energy category may still be able to achieve a relatively high overall energy availability associated with high quality of life for a limited amount of time. In a world of declining availability of per capita high EROI fuels nations may find that the only means of maintaining or growing their overall energy availability is via increasing their energetic efficiency.

#### **4.6 Summary**

Traditionally, economists have viewed quality of life indices as a consequence of economic production. We find that EROI<sub>SOC</sub>, annual per capita energy use and LEI are as strong a statistical predictor as traditional economic indices. Both energy per capita and EROI<sub>SOC</sub> are independent measures of the influence of energy availability on the ability of an economy to do physical work, which is a very strong determinant of the generation of economic well-being and “quality of life.” Most measures of social well-being are correlated linearly to EROI<sub>SOC</sub>, energy used per capita and also LEI, 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<sub>SOC</sub> of less than 15-25:1 and/or an energy use of less than 100 GJ per capita per year tend to have a poor to moderate “quality of life.”

Table 4.8.: Summary of energy availability indicators for the three generic country categories

Indicators	Number of Nations	Energy per Capita	EROI <sub>SOC</sub>	LEI	GDP per Capita <sup>1</sup>
LIC average (s.d.)	12	16 (4)	5:1 (2)	0.08 (0.02)	\$1,464 (468)
LMIC average (s.d.)	24	30 (19)	9:1 (4)	0.14 (0.03)	\$3,834 (1547)
UMIC average (s.d.)	38	69 (40)	14:1 (6)	0.22 (0.06)	\$10,757 (3504)

(1) GDP per capita (in current USD) based on purchasing power parity (PPP) (World Bank, 2012).

LEI values below 1.3 also correspond with a poor quality of life.

2. A threshold is passed with countries that have an EROI<sub>SOC</sub> of from 20-30:1 and/or 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 0.3-0.4.
3. This improvement in well-being appears to level off at EROI<sub>SOC</sub> values above 30:1 and/or greater than 200 GJ per capita per year, observed in countries with LEI value greater than 0.4. There is little or no additional improvement in societal well-being above these levels (Lambert et al. 2013).

Overall, our analysis suggests that having, or having access to, large quantities of high EROI energy appears to contribute substantially to social well-being. Conversely, the declining availability of these fuels and the growing global population will most likely constrain economic development and improvements in well-being for most nations striving to do so.

Our results indicate that the energy surplus from fossil fuels, the increases in the efficiency of energy use in economic systems (EROI<sub>SOC</sub>) and especially their combination in LEI are strong predictors of the social indicators we tested, at least as strong as the economic variables more commonly used (in fact we think the economic variables as well are determined in large part by EROI). Different nations have different reasons for high or low indices of social welfare, but all with high values require some relatively high energy components.

Low income countries (LIC) such as Ethiopia or Nepal have low energy use per capita (17 and 14 GJ per capita), low EROI<sub>SOC</sub> values (2:1 and 4:1 respectively) but may range in income distribution equity (e.g. 29.8 and 47.3 respectively). Ethiopia and Nepal have low LEI values (both 0.06, Table 4.8). These countries also have correspondingly lower quality of life indicators (e.g. HDI = 0.22 for Ethiopia and 0.29 for Nepal).

Lower-middle income countries (LMIC) (e.g. Bolivia, Pakistan and India) have low energy use per capita (27, 21 and 23 GJ per capita), low EROI<sub>SOC</sub> values (7:1, 6:1 and

9:1) but a range of income equitability (Gini-index, 57.3, 32.7 and 36.8 respectively). LMIC nation's minor improvement in access to energy are reflected in slightly higher LEI values, however overall energy availability remains low (LEI = 0.11, 0.12 and 0.15). These values are associated with low quality of life indicators (e.g. HDI = 0.40, 0.34 and 0.37).

Upper-middle income countries such as Mexico or Brazil have moderate energy use per capita (65 and 52 GJ per capita respectively) and moderate  $EROI_{SOC}$  values (13:1 and 18:1 respectively) and a wide gap in income distribution (51.74 and 53.9 respectively). Mexico and Brazil have low LEI values (both 0.22). These countries

also have correspondingly lower quality of life indicators (e.g. HDI = 0.59 for Mexico and 0.51 for Brazil).

In other words, greater energy availability (high LEI values) appears to correspond with higher "quality of life" (Lambert et al. 2013, Table 4.8).







# 5. Policy Implications and Mitigation Strategy



*“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.”*



# Policy Implications and Mitigation Strategy

## 5.1 Introduction

*In order to meet our international humanitarian responsibilities for 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. 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). This part of the report investigates potential policy implication and mitigation strategies for adjusting to and countering the potentially harmful impacts of declining energy availability (specifically declining EROI) on the quality of life for developing nations. We develop policy recommendations and mitigation strategies across the three generic country categories using a regional approach, to allow for the variability of economic, environmental, and social aspects among different nations within each generic income category.*

## 5.2 Significance of EROI

EROI is perhaps the single most important property of energy that allows it to contribute to human welfare. As such it is a gauge of the effectiveness of energy's ability to satisfy fundamental physical needs, assist in achieving a sense of mental and psychological well-being, and accomplishing the higher aspirations associated with the best (and worst) 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 had a relatively large energy surplus (i.e. an EROI of 10:1), which allowed them to

spend a great deal of time in leisure activities. 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. 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.

The question that remains is, "What is the minimum EROI required for a typical "developed" society? And, where do de-

veloping nations lie on this spectrum?" 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 net energy for its maintenance metabolism.

### 5.3 Minimum EROI

The concept of a hierarchy of "energetic needs" required for the maintenance and perhaps growth of a typical "western" society (Figure 5.1) 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 physiological and 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 (e.g. education and health-care) become important or even possible at a societal level.

Consider a civilization on an island with one oil well as its only energy source (besides the sun). If the EROI for oil was 1.1 to 1 (1.1:1) then one could pump the oil

out of the ground and look at it (Hall et al. 2009). If it were 1.2:1 you could both extract it and refine it. At an EROI of 1.3:1 it could be distributed to where it is useful as well but, once again, all you could do is look at it. Hall et al. (2009) examined the EROI required to run a truck. They found that an EROI of at least 3:1 at the wellhead was necessary to build and maintain the truck and the roads and bridges required to use one unit of energy (oil), including depreciation (Hall et al. 2009). 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). In a thought experiment Hall and Klitgaard (2012) estimated that in order to deliver a product in the truck, such as grain, an EROI of roughly 5:1 is required to include growing and processing the grain to be delivered. To include depreciation (i.e. death and replacement) of the oil field worker, the refinery worker, the truck driver and the farmer, as well as their equipment, it would require the support of the families and an estimated EROI value of approximately 7 or 8:1 (Hall and Klitgaard, 2012). If the children of these families were to be educated an EROI value in the region of 9 or 10:1 might be required. If the families and workers receive health care and higher education then an estimated EROI value of perhaps 12:1 at the wellhead is required (Hall and Klitgaard, 2012). The authors guessed that an EROI value of at least 14:1 would be needed to provide the performing arts and other social amenities for these families and workers.

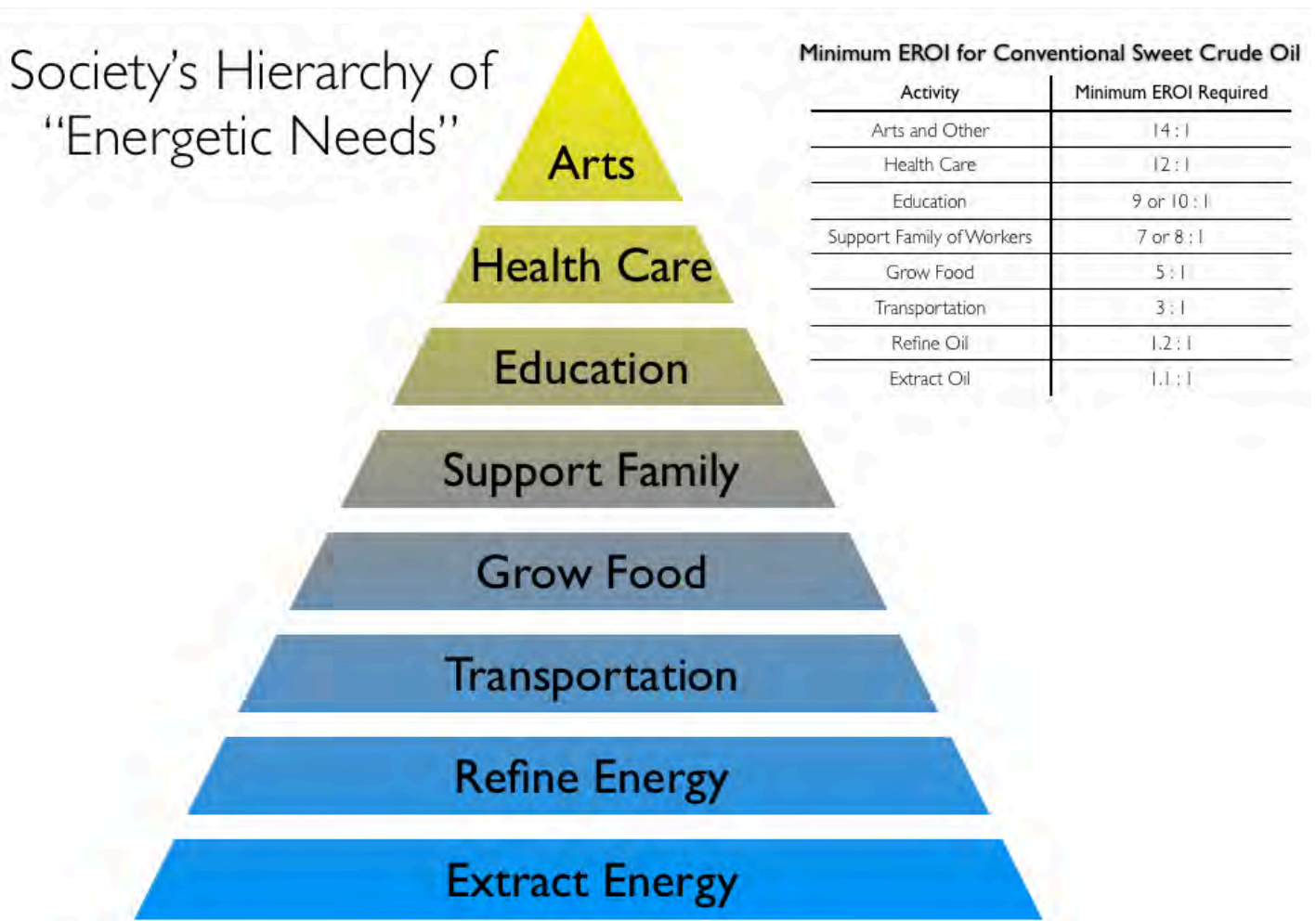


Figure 5.1: "Pyramid of Energetic Needs" representing the minimum EROI required for conventional oil, at the well-head, to be able to perform various energetic task required for civilization. The blue values are published values: the yellow values are increasingly speculative (calculations from Hall and Klitgaard, 2012, figure adapted from Lambert and Lambert, in preparation).

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 (or conceivably a huge supply of lower EROI fuels, Lambert et al. 2013) 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 that have satisfied the lower tiers of the financial and energy pyramid. In other words to have a modern civilization, one needs not simply surplus energy but lots of it, and that requires either energy sources with a high EROI or massive sources of moderate EROI fuels (Lambert et al. 2013).

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 quantity 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 in surplus energy.

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 to 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 a moderate to high HDI value. 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.

## 5.4 Energy and MDGs

*“Universal energy access is a key priority on the global development agenda. It is a foundation for all the Millennium Development Goals.”* UN Sec. Gen., Ban Ki-Moon (2010)

The eight strategic Millennium Development Goals (MDG) published in 2000 did not feature energy concerns. While energy is not typically regarded as a primary development goal, it is a vital enabler and multiplier of these and other goals. Energy is the principle agent for surmounting poverty, providing education and health-care services and generating enterprises, which in turn generate employment and incomes.

Since its publication, many have acknowledged the critical role that energy plays in reducing extreme poverty and improving standards of living (e.g. in 2002 the Johannesburg Plan of Implementation (JPOI) agreement at the World Summit on Sus-



Table 5.1: Role of energy in achieving millennium development goals (UNDP, 2005, Arranz-Piera and Velo, 2011).

## Energy and Millennium Development Goals

1	<b>Eradicate extreme poverty and hunger</b>	<p>Increased energy is required to:</p> <ul style="list-style-type: none"> <li>• create jobs, expand industry, transportation, and modernized agriculture</li> <li>• process, conserve, cook and refrigerate foods</li> <li>• reduce time collecting fuel (firewood)/increase time for income-generating activities</li> <li>• provide lighting – expanding productivity period</li> </ul>
2	<b>Achieve universal primary education</b>	<p>Electricity is necessary to:</p> <ul style="list-style-type: none"> <li>• provide educational facilities with teaching aids, educational IT, access to Internet</li> <li>• light the homes of students and teachers for evening study</li> <li>• attract teachers to rural schools</li> <li>• free-up time spent collecting wood for cooking</li> <li>• assist girls in attending school instead of assisting family subsistence needs</li> </ul>
3	<b>Promote gender equality and empower women</b>	<p>Modern fuels and electricity:</p> <ul style="list-style-type: none"> <li>• assists women and girls with household activities leads to gender inequality</li> <li>• saves time that could be used for more productive activities</li> <li>• allows women and girls more time to gain an education or earn a living</li> <li>• leads to greater gender equality</li> </ul>
4	<b>Reduce child mortality</b>	<p>Modern fuels and electricity will:</p> <ul style="list-style-type: none"> <li>• reduce smoke inhalation from cooking and heating fires</li> <li>• decrease respiratory illness caused by indoor air pollutants</li> <li>• provide improved lighting – reducing injuries from fires</li> <li>• reduce diseases caused by poor quality water</li> </ul>
5	<b>Improved maternal health</b>	<p>Electricity in health clinics will:</p> <ul style="list-style-type: none"> <li>• provide adequate illumination during night deliveries</li> <li>• disproportionately impact women as they visit clinics more often for illness resulting from daily household chores, indoor air pollution and water- and food-borne illnesses</li> <li>• provide health clinics with energy for cooking, lighting, heating and refrigeration</li> </ul>
6	<b>Combat HIV/AIDS, malaria and other diseases</b>	<p>Electricity for communication (radio and television) will:</p> <ul style="list-style-type: none"> <li>• disseminate important public health information to combat deadly diseases</li> </ul>

# Energy and Millennium Development Goals

7	<b>Ensure environmental sustainability</b>	<p>Access to clean fuels will:</p> <ul style="list-style-type: none"> <li>• reduce adverse effects of fossil fuels on the local, regional and global environment</li> <li>• reduce indoor and outdoor air pollution</li> <li>• reduce land degradation</li> <li>• reduce deforestation and increase environmental sustainability</li> <li>• provide fuels for improved cook-stoves</li> <li>• reduce greenhouse gas emissions</li> </ul>
8	<b>Develop a global partnership for development</b>	<p>The World Summit for Sustainable Development called for:</p> <ul style="list-style-type: none"> <li>• partnerships between public entities, development agencies, civil society and the private sector</li> <li>• support for sustainable development</li> <li>• delivery of affordable, reliable and environmentally sustainable energy</li> <li>• information exchange and dialogue</li> <li>• access to communications and Information Technologies</li> </ul>

tainable Development (WSSD) stated the need for the international community to work together to improve access to energy services to facilitate the successful achievement of the MDGs). The European Union Energy Initiative's (EUEI) stated objective is to improve access to energy needed to reach the MDGs. However the EUEI's lofty goals: (1) to aid in the effort to improve access to energy and (2) to aid in the effort to halve the number of people in extreme poverty by the year 2015, have fallen short of their desired outcome. In the ten years following this show of initiative, energy use per capita has increased by less than 10% for LICs and less than 20% for LMIC (World Bank, 2012), the nations targeted by the EUEI's poverty reduction program. And as of 2010, less than 30% of people living in LICs have access to electricity (World Bank, 2012). Electricity is

a crucial, if not primary requirement, for economic growth and reducing extreme poverty (MDG 1). Yet, in spite of the widely acknowledged importance of energy infrastructure financing remains extremely low.

According to an MDG Africa Steering Group 2008 report, roughly 700 million people in sub-Saharan Africa (excluding South Africa) are forced to share a combined electricity generation capacity equal to that of Argentina (a country of less than 40 million people). Consequently, only 25% of Africans, and less than 10% of rural Africans have access to electricity (MDG Africa Steering Group, 2008). This is not to say that energy improvement efforts have not contributed to poverty reduction in impoverished regions. Since 1990, the percentage of the population living on less

than \$1.25 a day (2005 international prices) has been reduced by 26% for LICs, 42% for LMICs and 79% for UMICs (World Bank, 2012). This suggests that efforts to reduce extreme poverty have met with greater success in LMICs and UMICs. What this tells us is that in spite of the obvious connection between energy availability, the EROI of the energy available and the level of poverty experienced, little headway has been gained in the efforts to effectively ameliorate the energy needs and thus poverty levels particularly in LICs; and, with less than two years remaining to meet the Millennium Development Goals, it seems unlikely that halving the number of people living in extreme poverty in LICs will be possible by the year 2015.

In the next section of the report we examine potential vulnerabilities and policy implications for each of the three generic developing country categories, low income countries (LIC), lower-middle income countries (LMIC) and upper-middle income countries (UMIC).

## 5.5 Low Income Countries

The following subsections deal with potential policy implication and mitigation strategies for adjusting to and countering impacts of declining and low energy availability (specifically declining EROI) for LICs. To do this we use a combination of energy type and regional approach, to allow for the variability of economic, environmental, and social aspects among different nations within each generic income category.

### 5.5.1 Vulnerabilities

Apart from low energy consumption per capita, and unsustainable reliance on low EROI bio-mass (wood-fuel), most LICs are confronted with wide-spread challenges in the search for sufficient domestic high-EROI energy alternatives. Thus, the fundamental energy challenge facing LICs is the task of procuring and maintaining consistent, dependable, reasonably-priced environmentally “friendly” energy that is available to a wide swath of their populace so that their economies have the energy necessary for sustained economic growth and widespread improvement in standard of living. Four important issues complicate solutions to this critical energy issue:

1. Most LICs examined within this study currently acquire greater than 75% of their energy from renewable combustibles and waste, inherently low EROI fuels.
2. The remaining 25% of their necessary energy is currently attained via imported fossil fuel, usually oil. Ever increasing prices of non-domestic fossil fuel result in trade deficits making this practice increasingly unsustainable over the long run.
3. These countries are often not considered economically viable. As a result, they have difficulty obtaining foreign financial investment.
4. Most LICs are currently experiencing a relatively high population growth rate. Renewable energy resources are

already strained and are not likely to keep pace with population growth.

Those LICs that appear energetically and financially “better off” than their fellow LICs seem to have several common characteristics. Most importantly, they have lower population density, lower population growth rates and high EROI domestic energy alternatives (e.g. domestic hydroelectric energy in Kyrgyzstan) or sufficient domestic fossil fuel sources (e.g. domestic natural gas in Bangladesh). Kyrgyzstan and Tajikistan have higher standard of living indices and higher LEI values than Bangladesh. This is probably due to lower population density coupled with established domestic energy sources that require only maintenance funding. This frees them from the fiscal constraints of constant financial investment for attaining and producing the energy required to run their society.

### ***5.5.2 Policy Recommendations***

The factors that drive per capita energy availability appear to include: per capita access to energy resources, energy resource quality and type (e.g. high or low EROI fuels), energy efficiency of the economic process ( $EROI_{SOC}$ ) and energy distribution among economic actors.

#### **A “catch 22” situation**

The need to elevate per capita access to energy creates pressure for LICs to grow their net energy resources. Their impoverished economies, however, limit the domestic capital funding available for energy resource projects. Policy guidelines for in-

ternational development aid are aimed at promoting private sector participation in the development of energy infrastructure (e.g. OECD Principles for Private Sector Participation in Infrastructure in 2007). However, the disadvantaged economic profiles and comparatively small economies of LICs adversely impact foreign private investment.

For example, the “Energy and the Millennium Development Goals in Africa” report developed by the Forum of Energy Ministers of Africa (FEMA) states that 20 billion USD per year (roughly twice the historic levels of financing) is required to meet the Millennium Development Goals (MDG) for African nations. The report estimates that need in the electricity sector will account for 20% (\$4 billion USD per year) of the estimated aid requirements (FEMA, 2006). However, as a whole, foreign direct investment (FDI) into Africa has been low. This is also true for LICs; foreign direct investment for all LICs makes up less than 1% of global investment (World Bank, 2012) and little, if any, of this aid has been directed toward improving per capita energy availability.

The World Bank surveyed 20 Poverty Reduction Strategy Papers (PRSPs) for countries in Sub-Saharan Africa, South Asia, East Asia, and Latin America (UNDP, 2005). FEMA (2006) summarized their findings:

“It was found that energy was hardly given attention; the limited mentions tend to be focused on large infrastructure. Energy access issues were

absent and important linkages with productivity and cross-sectoral applications were not addressed. Also traditional energy receives very little attention. The report concluded that the PRSPs tend to focus on traditional, larger-scale infrastructure solutions and that smaller-scale energy inputs that can be useful to poverty reduction were ignored.”

Lopsided aid efforts, directed at improving quality of life without providing aid for the development and improvement of energy infrastructure appear to meet with limited success.

This study has shown that those LICs with relatively high quality of life indices also have greater access to domestic high EROI energy and have social and economic policies geared toward more equitable energy distribution.

Unsurprisingly we suggest that LICs which are currently economically constrained by limited access to high EROI domestic energy, have poor quality of life indices and inequitable energy distribution embrace economic, social and political reforms that will ameliorate these chronic and ever worsening conditions.

Our recommended policy framework is made up of a core package of broad-based reforms with medium- to long-term pay-offs. The framework is comprised of three guiding principles for energy policy development. Each principle is valuable individually, but collectively they provide, what we believe is the best opportunity

for successfully mitigating the quality of life impacts of declining energy availability:

1. Increase LICs energetic efficiency (increase  $EROI_{SOC}$ ) by providing financial assistance for developing moderate EROI primary energy facilities (e.g. geothermal, hydroelectric, wind) that will provide much needed domestic energy resources making these countries less dependent on an increasingly volatile fossil fuel market. Often, but not always, insufficient domestic fossil fuel is a confounding factor in economic development for these nations. We recommend the development of PV, concentrated solar or wind resources and/or creating opportunities to produce biomass which can be turned into higher quality fuels by burning for cogeneration of heat and electricity.
2. Increase energy per capita by growing energy resources and establish programs that help reduce population growth (increasing the amount of energy per person).
3. Promote programs that promote greater income equality (better Gini index).

## 5.6 Lower Middle Income Countries

Lower middle income countries include a wide range of economic performers. Many are quite poor but some, such as the Phil-

ippines, are relatively stable economically and others such as Ghana have possible prospects for new oil wealth. Some are net energy exporters but the majority are energy import-dependent. What is characteristic of nearly all LMICs is that they have very high population growth rates and a large emphasis on industrialization. Thus, while the amount of total wealth produced is in many cases increasing rapidly, for the most part it is barely keeping pace with the population growth rate. These somewhat wealthier nations are different from LICs because they are much more reliant on fossil fuels. In an increasingly uncertain and unpredictable international fossil fuel market, they, like most nations, need to determine strategies for energetic and economic sustainability. We provide here some of the vulnerabilities and policy implications that we think are appropriate for these less poor yet potentially vulnerable countries.

### ***5.6.1 Vulnerabilities***

Aside from relatively low energy consumption per capita, and continued dependence on low EROI bio-mass (especially in rural areas), most LMICs are confronted with a growing reliance on fossil fuels purchased in an increasingly volatile international market. Therefore the energy challenge facing LMICs is the task of sustaining and growing domestic high EROI, dependable, reasonably-priced environmentally “friendly” energy that is compatible with existing infrastructure and is available to a wide swath of their populace. Six important issues complicate solutions to this critical energy issue:

1. Many LMICs still rely on energy from renewable combustibles and waste (low EROI fuels). This is especially true in rural areas. Large populations and high population growth rates will likely tax this already strained resource base.
2. The remaining energy is currently attained via imported and domestic fossil fuels. For these net energy importing LMICs the main issue is, and will continue to be, the price of fuel. This will probably, inflate more rapidly than the price for exports, lowering the EROI of their imports and hence greatly eating into their profitability (as happened in the 1970's and the late 2000's, see Figure 4.2). For those energy import-dependent countries the volatile fossil fuel market will probably lead to turmoil in the coming decades as, indeed, is already the case for some LMICs.
3. An immediate problem that many of these energy-exporting LMICs are facing (e.g. Indonesia, Syria and Egypt) is that they have hit and passed “peak oil”, that is the time at which the quantity of oil produced stops increasing and starts declining. This usually results in a large loss of revenue even with increases in energy prices.
4. Many of these countries are in the process of industrializing their own agriculture and also the production of goods and services. An important issue for all nations is the degree to

which oil exporting nations are using more and more of the energy that they internally produce (Hallock et al. 2004). As long as their domestic sources of energy remain abundant, these nations can, at least in principle, continue to flourish. When production begins to decline (post peak oil) these countries can be hit hard as their energy and economic expecta-

tions have increased substantially during the pre-peak times.

5. Many LMICs rely largely on income generated from tourism and the sale of luxury goods and, hence, are dependent upon global surplus energy in indirect ways. For example Ghana exports considerable cocoa, which requires affluent people to purchase it. The tourism trade and the sale of

## Peak Oil

Indonesia is a good example of a precautionary tale. It is a LMIC with large reserves of oil and natural gas and was formerly a member of OPEC. Peak oil occurred here approximately two decades ago and production has declined to about half of its former value (Figure 5.2). Oil consumption, on the other hand, has

continued to increase. Oil imports and their associated costs have increased dramatically, greatly decreasing the remaining amount of discretionary income. The growth of GDP, which had been increasing substantially prior to 1996, declined precipitously following the peak and the value of real GDP did not recover to pre-peak levels for a decade (World Bank, 2012). Recently energy prices have increased dramatically, resulting in widespread public protests and the Indonesian government has often had to increase subsidies for energy to reduce social unrest. However, rising national debt is forcing the Indonesia government to reduce oil subsidies and the price of oil is expected to increase 44%. As it stands, fuel subsidies are expected to cost 13.3% of Indonesia's revenue. The high price of oil in 2011 and 2012 helped to reduce Indonesia's foreign reserves by roughly \$20 billion and the rupiah has dropped by 15% against the dollar. 2012 marked Indonesia's first account deficit since 1998, brought about in part by high oil subsidies. The economic turbulence has already created schisms amongst political leaders unsure how to reduce per capita oil consumption and maintain socioeconomic stability (The Economist, 2013).

Indonesia Oil Production and Consumption

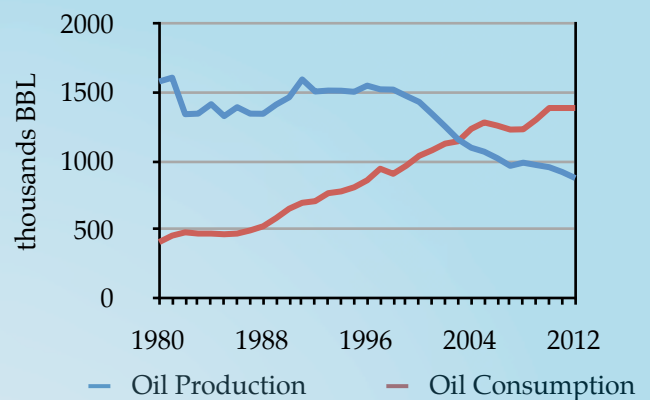


Figure 5.2: Peak oil in Indonesia (EIA, 2012)

luxury goods is likely to wane in an unpredictable, energy constrained world

6. The population growth tends to be far higher in LMICs compared to wealthier nations. LMICs also already have high population density (averaging 120 people per sq. km (World Bank, 2012)) and many are largely dependent on foreign economies for sufficient food.

### ***5.6.2 Policy Recommendations***

LMICs are already attempting to grow their energy portfolio to meet their need to reduce poverty, access high EROI energy and keep pace with their population growth rate. It is unlikely that most will have sufficient discretionary resources available to both grow existing energy resources and adjust their existing energy portfolio to include novel and different energy resources. That is, nations which currently rely on oil for production of electricity are likely to find it challenging to adjust their existing infrastructure to a cheaper more abundant fuel like coal. In an energy constrained world where nations must respond effectively to continuously declining EROI, LMICs as a group will find their options restricted.

Unlike LICs which are generally energetically inefficient due to use of low quality (EROI) fuels, LMICs have either domestic or imported fuels that are much higher in quality (greater EROI values) for use during production processes. Most of these LMIC economies are based on the energy-

intensive production of goods meant for export. Most of these nations are also reliant, at least in part, on non-domestic fossil fuel resources. They are, as a result, subject to both: (1) the volatile international energy market required for the production of goods for export and hence revenue production and (2) interruption in the continued ability of wealthier nations to consume their exported goods.

For LMICs with less available capital there are other headwinds to the alternative primary energy development pathway. As these technologies require a large up-front cost, many LMICs would need to find external sources of funding or make a significant investment of whatever government resources are available. The energetic benefit from these investments would be reaped over decades rather than over the short term. It would require sacrificing power output over the short haul for increased efficiency of energy production over the long haul. During the near future, while fossil fuels dominate the global energy mix, these countries may be out-competed in the global economy by those with access to higher EROI, higher power (useful energy/time) sources of energy. However, there is likely to be a long-term benefit to this strategy as nations with more efficient economic production (lower energy intensity, higher EROI<sub>net</sub>) will likely experience greater economic success as fossil fuels become scarce. Hence we recommend that if possible:

1. LMIC grow their own domestic economy making them less dependent on external purchasers.



2. Develop their own high quality domestic energy resources.
3. Increase their energy per capita by reducing their population growth rate and/or increase total energy consumption.
4. Increase the energetic efficiency of their economic process (EROI<sub>soc</sub>) by decreasing the production of energy intensive goods and services while increasing their share of the less energy intensive service industries.

prices. The challenge facing net energy importers is the task of growing sufficient domestic high EROI, dependable energy. Four issues complicate solutions to this critical energy issue:

1. Fossil fuels are the primary energy source for most UMICs. For these energy import-dependent countries a volatile fossil fuel market will likely lead to economic and possibly social turmoil. A related issue facing many of these countries (e.g. Mexico, Venezuela) is declining EROI associated with increasing production costs; the quantity of energy produced, specifically oil and gas, has been declining, so that revenue does not necessarily increase with increases in energy prices.
2. Many UMIC are currently in the process of industrializing their agriculture and production of goods and services. Industrialization requires an abundance of high/moderate EROI energy and many of these tasks may become difficult to support in an energy constrained world.
3. People living in UMICs have developed expectations for economic growth and social improvement expectations. Many of these are predicated on access to large quantities of high EROI fossil fuel (e.g. the ability to own a car). UMICs may find it challenging to meet these expectation in an energy constrained world and this, in turn, is likely to result in social unrest.

## 5.7 Upper Middle Income Countries

Upper middle income countries (UMIC) include a wide range of economic performers. Some such as Costa Rica are very stable economically, others such as China are growing at an intensive pace, some are net energy exporters but the majority are energy import-dependent. They, as will most other nations, face common issues in a global economy with a very uncertain future. We provide here some of the characteristic vulnerabilities and strategies that we think are especially appropriate for these relatively well off, but potentially vulnerable countries.

### 5.7.1 Vulnerabilities

Most UMICs have a growing reliance on fossil fuels purchased in an increasingly volatile international market. For net energy exporting nations, a decline in EROI will do little to directly impact their overall economies negatively because of increased revenues from increases in fuel

# Energy Importers

Societies that are net energy producers may be able to supply their own energy needs through using that energy directly. But 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 (or was) usually the fuel of choice as it is cheap, is extremely useful and the machines to use it are readily available. 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 energy and petrochemicals required for their production and cosmetic quality (Hall, 2000).

Falling EROI means higher fuel prices which is reflected in an increase in the cost of banana production. This cost is in turn passed on to the consumer. Higher prices at the market result in less discretionary income on the part of the consumer and fewer bananas purchased. To sell their bananas Costa Ricans are forced to sell their product for less money even if price for inputs are increasing. Hence declining EROI is likely to result in a lower profit margin for Costa Rican farmers. These production expenses consume a large portion of the economic "surplus" necessary to generate hard currency to pay for imported petroleum.

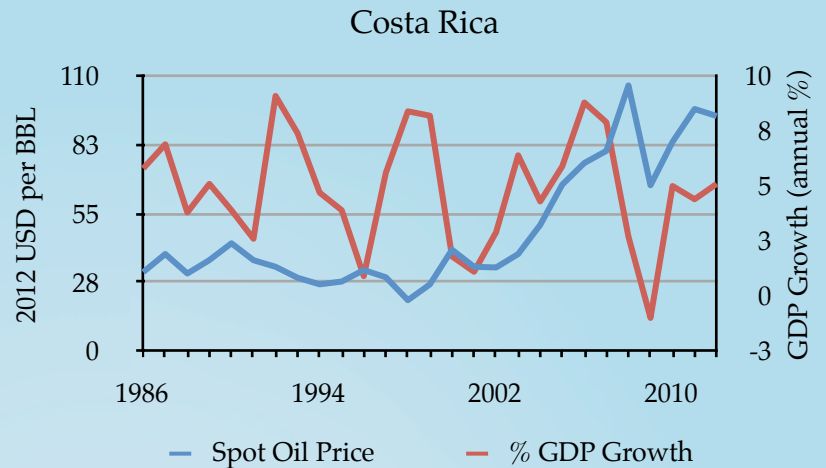


Figure 5.3: Costa Rica GDP growth (World Bank, 2012) and Cushing, OK spot price of oil (EIA, 2012)

4. Like LMICs, many UMICs have economies largely driven by both international and external tourism and as such are quite dependent upon global surplus energy. Tourism-dependent Costa Rica and the Cancun area of Mexico are examples. These countries, or some portion of them, have become accustomed to the benefits of a flourishing economy based largely on discretionary income of wealthy nations. When discretionary income from upper income countries (UIC) such as European nations and the United States, major sources of tourists for Mexico and Costa Rica, contracts, as occurred in 2009 and in general as energy prices increase, tourism driven economies are impacted as far fewer tourists visit these places.
5. Even though population growth rates for UMICs tend to be much lower when compared with less wealthy nations (LICs and LMICs), many already have a large population base. This makes them largely dependent on foreign economies for sufficient food and other resources.

### ***5.7.2 Policy Recommendations***

We suggest that broad policy recommendations for these countries focus on: development of domestic energy sources, reduction in energy intensive economic activities, education and reduction in population growth rate, and improved distribution of energy.

Some UMICs have the necessary capital required for encouraging renewable energy production/use thereby reducing fossil fuel consumption. In a future of almost certain declining fossil fuel EROI, renewed focus on expanding and enhancing alternative energy high EROI energy production, may be the best way for these countries to ensure future high standards of living. For even though the EROIs of these energy sources are lower than for fossil fuels historically, the net energy from these technologies may be greater in the future.

An issue for most UMICs is that of rising prices for imported fuel. This may limit the discretionary income available to make the required capital investments necessary to move from energy intensive industry to less intensive/service oriented industries, and for the citizenry to have adequate disposable income to spend on the discretionary goods and services produced in these “lighter” industries. Rising imported fuel prices is not the only challenge; UMICs must compete with discretionary goods and services produced in developed nations.

We recommend the following:

1. UMICs would be well served to develop domestic energy resources using available financial capital and foreign aid.
2. For those UMICs already invested in traditional heavy industry, reduction in energy intensive economic activities by continuing along the “tradi-

tional" economic development pathway, i.e. the progression from heavy industries to a service-oriented economy is recommended. Even though many higher income nations have successfully pursued this path, it is not clear that this development strategy is feasible in a world that has diminishing EROIs for global oil and natural gas production and with many countries already successfully employing these well-developed strategies. An example case is Malaysia. This UMIC is one of the leading exporter of semi-conductor devices, electrical devices and IT and communication products. It also exports natural, agricultural and petroleum resources. Tourism is Malaysia's 3rd largest source of foreign exchange. It is clear that this is hardly a transition strategy but rather one of a mix of strategies for Malaysia.

3. For those UMICs without an existing manufacturing base, policies should be implemented and foreign aid directed to improving the energy intensity of the economy directly through technology transfers, social capital building, and growing the service economy. There has been little precedent for this "leap-frog" development from a traditional to a service economy except, perhaps, in areas that have developed tourism and attract foreign currency influxes. This too may become more difficult as the cost of air travel increases and higher prices for food and energy reduce the

discretionary spending of global travelers.

4. The adoption of policies focusing on educating the general population to the probability of future energy resource constraints, the impact on the world to which they have become accustomed and on possible means of mitigating and adapting to these constraints. In these, as in all countries, policies directed to address issues related to population growth rates and education of the populace are essential.
5. Many UMICs need to address issues of equitable energy distribution within their populace. Consideration needs to be given to the idea, especially for the poorer of these countries, that the best way to increase social well-being may be to increase energy availability, use and equity per capita. Policies and programs that help reduce population growth may also help make more energy available per person.

## 5.8 Energy Exporters

For LMICs and UMICs that are net energy exporters the coming decline in EROI will likely have little immediate, direct, negative impact on their overall economies. This will result from probable increases in fuel prices and hence revenues. Unfortunately for these countries energy price increases are likely to lead to a greater disparity between those connected with the energy industries who are importing more

money and the poor who are likely to be paying more for their fuel. Thus policies for these countries might focus on distributional aspects. An important concern for all nations is the degree to which oil exporting nations are using more and more of the energy that they produce internally (Hallock et al. 2004). As long as domestic sources of energy are abundant, net energy exporters can, at least in principle, continue to flourish. However many of these fuel sources are expected to peak sometime in the coming decades. How these

nations are likely to react to declining EROI remains unclear. However, inability to meet their own internal energy demand and growing energy intensity suggests that this challenge will be met with socio-economic friction. This disparity is already evident in several net energy exporting countries (e.g. Mexico and Argentina).

## 5.9 Summary

A summary policy options for mitigation of declining energy availability for LICs, LMICs and UMICs is given in Table 5.2.

Table 5.2: Mitigation and policy options for LICs, LMICs and UMICs

Generic Income Categories	Policy Recommendations
LICs	<ul style="list-style-type: none"> <li>• Increase energetic efficiency (increase <math>EROI_{soc}</math>) by promoting development of domestic moderate EROI primary energy facilities (e.g. geothermal, hydroelectric, wind).</li> <li>• Grow existing energy resources and establish programs that help reduce population growth.</li> <li>• Promote programs that promote greater income equality.</li> </ul>
LMICs	<ul style="list-style-type: none"> <li>• Grow their own domestic economy making them less dependent on external purchasers and providers.</li> <li>• Develop their own high quality domestic energy resources.</li> <li>• Increase their energy per capita by reducing their population growth rate and/or increase total energy consumption.</li> <li>• Increase the energetic efficiency of their economic process (<math>EROI_{soc}</math>) by decreasing the production of energy intensive goods and services while increasing their share of the less energy intensive service industries.</li> </ul>
UMICs	<ul style="list-style-type: none"> <li>• Develop domestic energy resources using available financial capital and foreign aid.</li> <li>• Reduce of progression from heavy industries to a service-oriented economy.</li> <li>• Implement policies and foreign aid directed to improving the energy intensity of the economy directly through technology transfers, social capital building, and growing the service economy.</li> <li>• Develop further policies directed to address issues related to population growth rates and education of the populace are essential.</li> <li>• Address issues of equitable energy distribution within their populace.</li> </ul>



# 6. Conclusion



*“Our main message is that  
a future of declining  
energy availability need  
not be an undesirable  
future.”*





# Conclusion

*The availability of energy will become an increasingly important factor affecting the economic viability of developing nations in the 21st century. We began this report by pointing to the absolute necessity of energy and how this is a major driver of the global economy. Perhaps most importantly, resource quality, as measured by high EROI, provided the fuel required for the previously high level of economic growth and activity. Our main message is that a future of declining energy availability need not be an undesirable future. However, the process of declining EROI and subsequent outcomes can be adverse, at times highly so, and there is considerable necessity for improvements in policies and poverty reduction strategies at the national, regional and international levels. Our results call for a bold vision that suggests the need for a more energy-centric poverty reduction program and identifies ambitious long-term policy options for improving overall energy availability.*

*This will require engineers, politicians and economists to think very differently about what is important. We believe that very high on this new list needs to be a much greater emphasis on thinking about growth, including both economic and population, climate change, and tools and policies that lead to genuine sustainability.*

*Most of the recommendations we have made are not conditional on securing additional funding from aid organizations, rather they call for a change of focus and recognition of the necessary energy and material inputs that allow for high standards of living. The future prosperity of the nations we examined in this report will almost certainly depend on our ability to adjust and adapt to lower or negative growth of our principal fuels even while EROI values are likely to decline. This will require a more biophysically-based approach to our understanding of economics.*

*Our suggested policy options, if implement, could bring about substantial quality of life improvements. Advancing this agenda will require a coordinated and collaborative effort, proactively guided by committed senior-level leadership, with substantial stakeholder and public input and should be informed by and consistent with the best available science to move the debates and policy discussions forward.*

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