EROI of Global Energy Resources

Preliminary Status and Trends

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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), 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 relation to GDP. 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 from the middle of 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 less discretionary funds available for "non-essential" projects. The declining EROI of traditional fossil fuel energy sources and this 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 ERIO 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.

The increasing energy cost of oil: Drake's first well, Spindletop (Courtesy Texas Energy Museum), Thunderhorse (courtesy of Andyminicooper), a modern pumpjack and refinery.

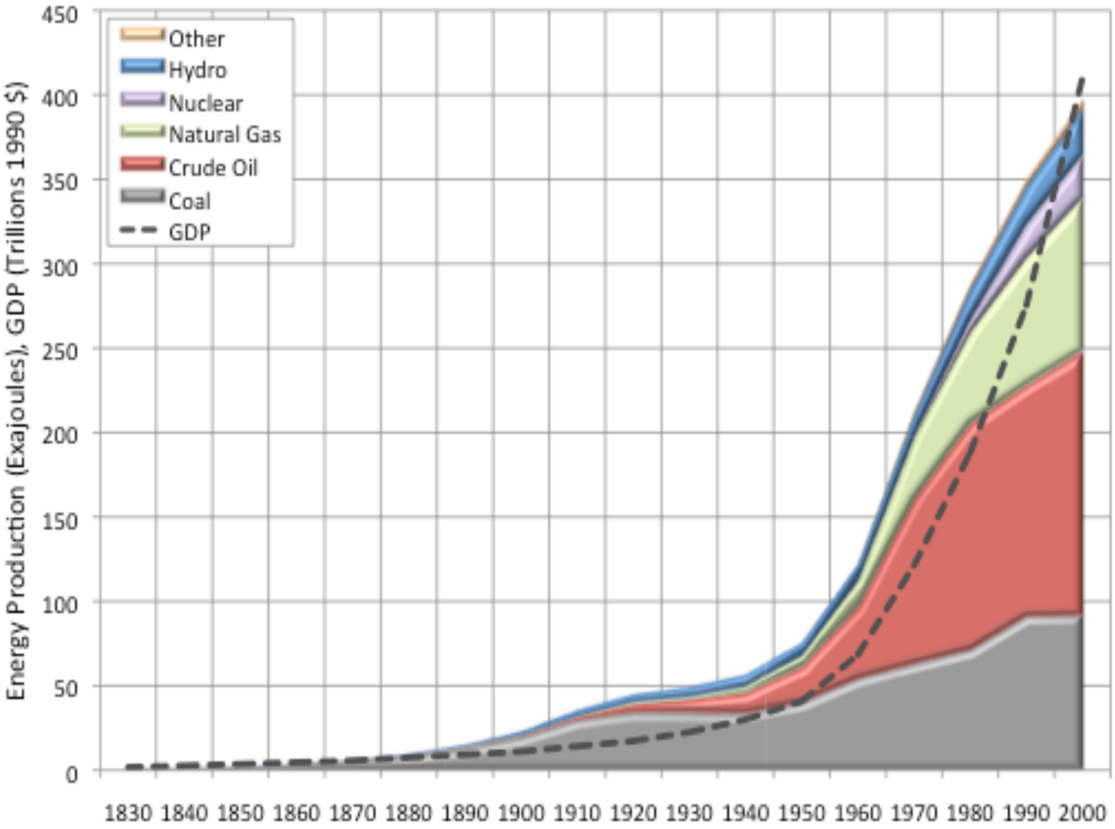


Figure 1: The global use of hydrocarbons for fuel by humans has increased nearly 800-fold since 1750 and about 12-fold in the twentieth century. The most general result has been an enormous increase in the ability of humans to do all kinds of economic work, as represented by the increase in GDP [6].

Introduction

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 [1]. 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 wide-spread wealth, art, culture and other social amenities. Economic fluctuations tend to result, directly or indirectly, from variations in a society's access to cheap and abundant energy [1, 2, 3].

Today, fossil fuel resources are among the most important global commodities and are essential for the production and distribution of the rest. Fossil fuels supply greater than 75 percent of the total energy consumed by society [4, 5]. The prosperity and stability of modern society is inextricably linked to the production and consumption of energy, especially oil [6].

Economic production and growth requires work and consequently a steady and consistent flow of energy (Appendix A). Intervals of economic growth have been punctuated by numerous oscillations; i.e. periods of economic expansion and recession. In general, the growth of real GDP is highly correlated with rates of oil consumption (Appendix B). Four out of the five recessions experienced since 1970 can be explained by increased oil prices [5, 7]. During periods of recession, oil prices decline eventually encouraging consumption. Alternatively, during periods of expansion oil prices increase and higher energy consumption and economic expansion are eventually constrained by these higher prices [7].

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. Jones et al.'s 2003 article, Oil Price Shocks and the Macroeconomy, reveals a clear relation between oil price and GDP [7]. The main conclusions drawn from this and similar discussions are:

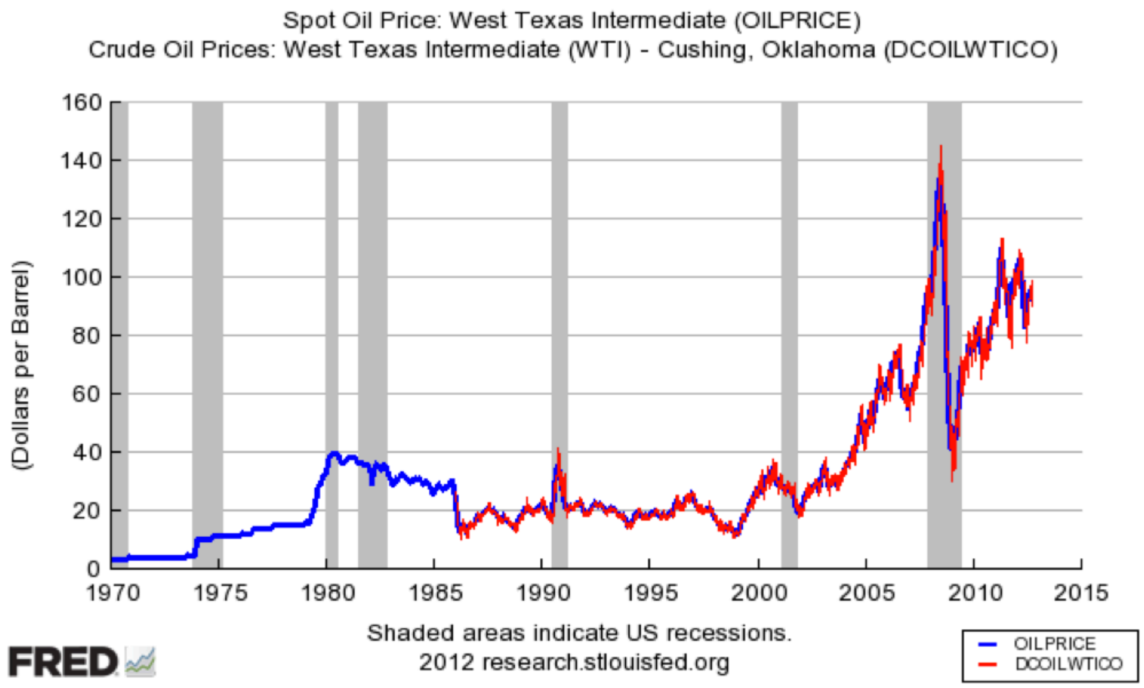


Figure 3: Spot oil price and crude oil price trend data from the west Texas Intermediate, for the United States from January 1970 through June 2012 and periods of economic recessions. Spot oil price and crude oil price data from the from the St. Louis Federal Reserve [8, 9].

1) Decreases in GDP during the post WWII period are chiefly attributable to oil price shocks, not government policy.

2) Oil price shocks are the only novel or surprising price movement observed in a two year window of time prior to a recession.

3) Oil price shocks lead to costly reallocations of people and industry as well as fluctuations and pauses in investment. This influences industrial output and subsequently GDP [7].

Economic Cost of Energy

It is possible to examine the ratio of the cost of energy compared to the benefits of using it to generate wealth. This is accomplished by dividing the money required to buy energy by the total gross domestic product:

$$\text{Economic cost of energy} = \frac{\text{Money to buy energy}}{\text{GDP}}$$

Equation 1: Hall and Klitgaard, 2011 [6]

When this ratio is low, typically around five percent, economies grow strongly [6]. When this ratio is high, about ten percent (and, historically, up to fourteen percent), recessions tend to occur. 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 mid-2008 “oil price shocks” [6]. Rapid increases in the economic cost of energy (e.g. from five to ten precent) result in the diversion of funds from what is typically devoted to discretionary spending to energy acquisition [6]. Consequently, large changes in energy price influence the global economy.

The energy and economic communities currently host strongly polarized discussions about the declining quantity and quality of fossil fuel resources ultimately available to society and the potential repercussions of declining energy availability of high quality energy for societal well-being and economic growth. Much of the argument used by the energy community revolves around 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.

Net Energy

Net energy analysis is a means of measuring the quality of various fuels by calculating the difference between the energy delivered to society and the energy invested in the capture and delivery of this energy. This technique enables the flow of energy in a society to be correlated with the growth and well being of that society. 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 [10].

EROI

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

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

Equation 2: Hall, Balogh and Murphy, 2009 [4]

The numerator and denominator in Equation 2 are usually defined using the same units. Sometimes corrections are required to adjust for the quality of the energy obtained or used. The boundaries of this relatively straightforward analysis are sometimes considered controversial and ambiguous and produce what appears to be different results. These concerns are addressed in Murphy et al.'s recent paper, *Order from Chaos: A Preliminary Protocol for Determining the EROI of Fuels* [12]. Hall and Klitgaard further clarify the boundaries used in EROI [6] calculations by delineating net energy analyses into the following categories:

Societal EROI (EROI_{soc})

Societal EROI is the overall EROI that might be derived for all of a nation's or society's fuels by summing all gains from fuels and all costs of obtaining them. To our knowledge this calculation remains theoretical because it is difficult, if not impossible, to include all the variables necessary to generate an all-encompassing societal EROI value [4].

$$\text{EROI}_{soc} = \frac{\text{Energy content of all fuels delivered}}{\text{All the energy costs of } \textit{getting} \text{ those fuels}}$$

Equation 3: Hall, Balogh and Murphy, 2009 [4]

Standard EROI (EROI_{st})

A standard EROI approach uses a simple standardized energy output divided by both the direct (i.e. on site) and indirect (i.e. offsite energy needed to make the products used on site) energy used to generate that output. This EROI calculation is applied to fuel at the point where it leaves the extraction or production facility (wellhead, mine mouth, farm gate, etc.). This approach allows the comparison of different fuels even when the analysts do not agree on the methodology that should be used [12].

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

Equation 4: Hall, Balogh and Murphy, 2009 [4]

For example, finding and extraction of oil 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 then the EROI = 1 and no net energy is produced to power society.

Point of Use EROI (EROI_{pou})

Point of use EROI is a more comprehensive EROI that includes the costs associated with refining and transporting the fuel (Appendix B). As the boundaries of the analysis are expanded, the energy cost of getting it to that point increases, resulting in a reduced EROI [4].

$$\text{EROI}_{pou} = \frac{\text{Energy returned to society at point of use}}{\text{Energy required to get } \textit{and deliver} \text{ that energy}}$$

Equation 5: Hall, Balogh and Murphy, 2009 [4]

Extended EROI ($EROI_{ext}$)

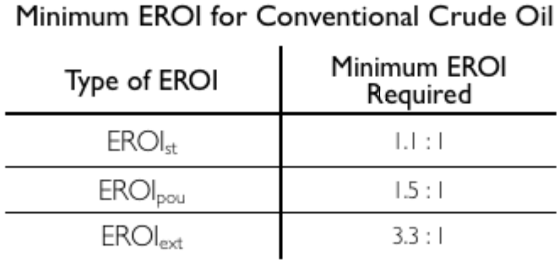
This expanded analysis considers the energy required not only to get but also to use a unit of energy (Appendix C). In other words, extended EROI is the required EROI energy at the mine mouth for that energy to be minimally useful to society [4].

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

Equation 6: Hall, Balogh and Murphy 2009 [4]

Each progressive EROI methodology extends the boundaries of an analysis to become ever more inclusive. Hence, the minimum standard EROI for crude oil production, 1.1 to 1, is less than a third of the extended EROI, 3.3 to 1 [4, 6, 11].

Table 1: Minimum EROI values to break-even for conventional sweet crude using EROI methodologies.



Minimum EROI for Conventional Crude Oil

Type of EROI	Minimum EROI Required
$EROI_{st}$	1.1 : 1
$EROI_{pou}$	1.5 : 1
$EROI_{ext}$	3.3 : 1

We employ methodology discussed by Murphy et al., 2010 to achieve the greatest possible degree of scientific rigor and replicability [12]. 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.

Energy Quality

The heat or energy content of a given fuel is only one of several important measurable characteristics of the energy quality of a fuel (the ability of a form of energy to do useful work) [6]; although energy content values form the backbone of any EROI analysis. However, energy equivalent values and subsequently EROI analyses do not assess the complex combination of physical, technical, environmental, economic, and social attributes that determine a fuel's usefulness to society [13]. No single measure of an energy system is able to evaluate this multitude of variables. Kaufmann's work (1994) validates this assumption that over time, market signals (prices) tend to reflect the perceived economic usefulness of a fuel (Appendix D) [14].

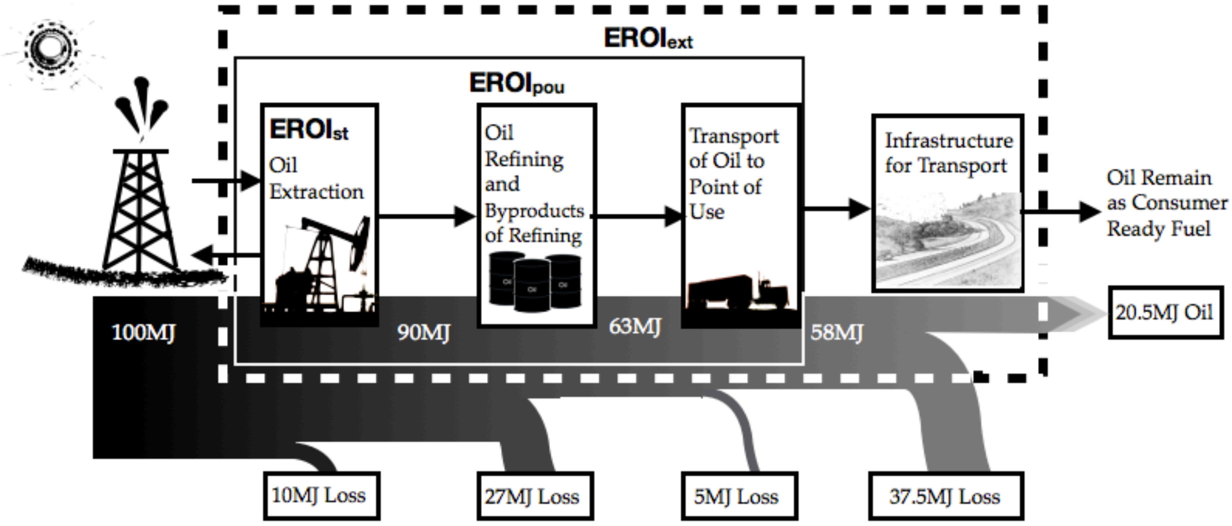


Figure 3: Boundaries of various types of EROI analyses (standard EROI ($EROI_{st}$), EROI at the point of use ($EROI_{pou}$) and extended EROI ($EROI_{ext}$)) and energy loss associated with the processing of oil as it is transformed from "oil at the well-head" to consumer ready fuels (figure adapted from Lambert and Lambert, in preparation [3]).

History of EROI

The theory of EROI was based on Howard Odum's teachings on net energy [15, 16]. The concept was first formally applied to fuels (as net energy) in Hall and Cleveland's 1981 paper on petroleum yield per effort, *Petroleum Drilling and Production in the US: Yield per Effort and Net Energy Analysis* [17]. Studies by Herendeen and Plant, 1981 [18] and Herendeen, 1988 [19] centered on the "Energy Cost of Energy," which is, for all intents and purposes, the same idea as EROI. Other early conceptions of net energy analysis can be found in publications by sociologist Leslie White [20] and economist Kenneth Boulding [21].

Hall et al., 1981 [22] 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 [23]. 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 [24].

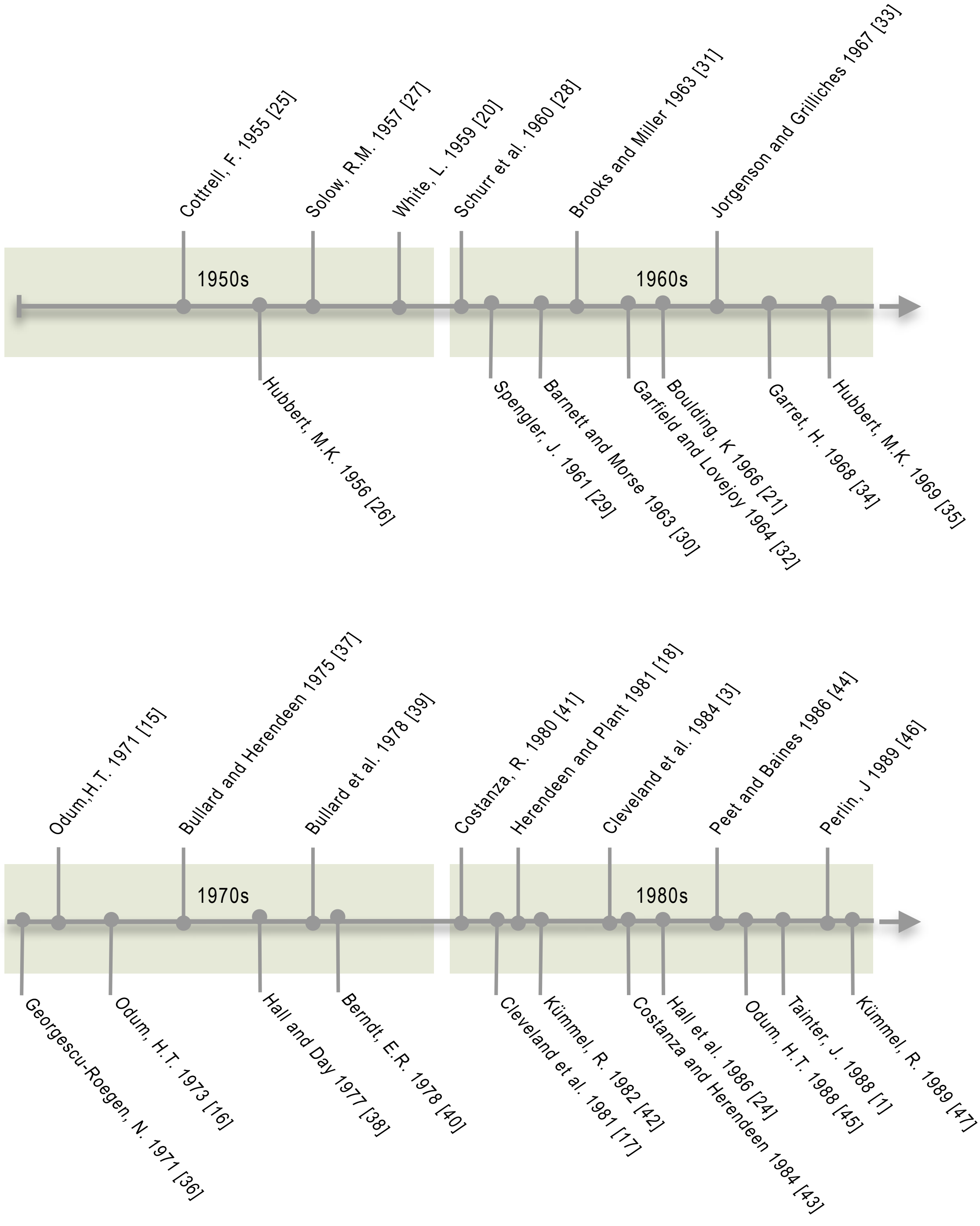


Figure 4a (top) and 4b (bottom): A timeline (not drawn to scale) of influential works in the fields of energy science, EROI, biophysical economics and net energy.

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

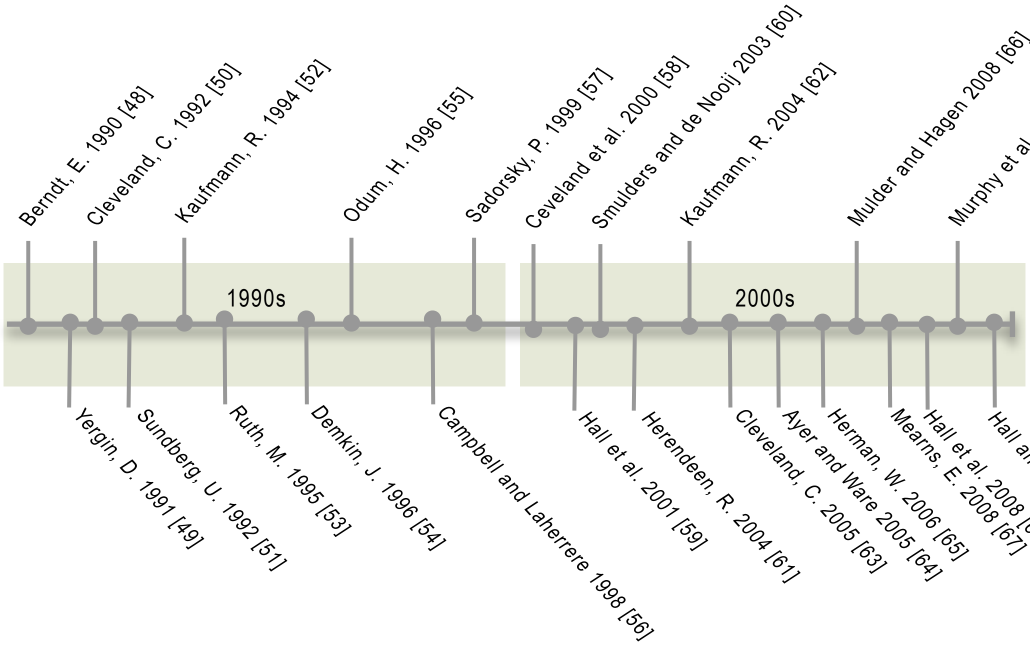


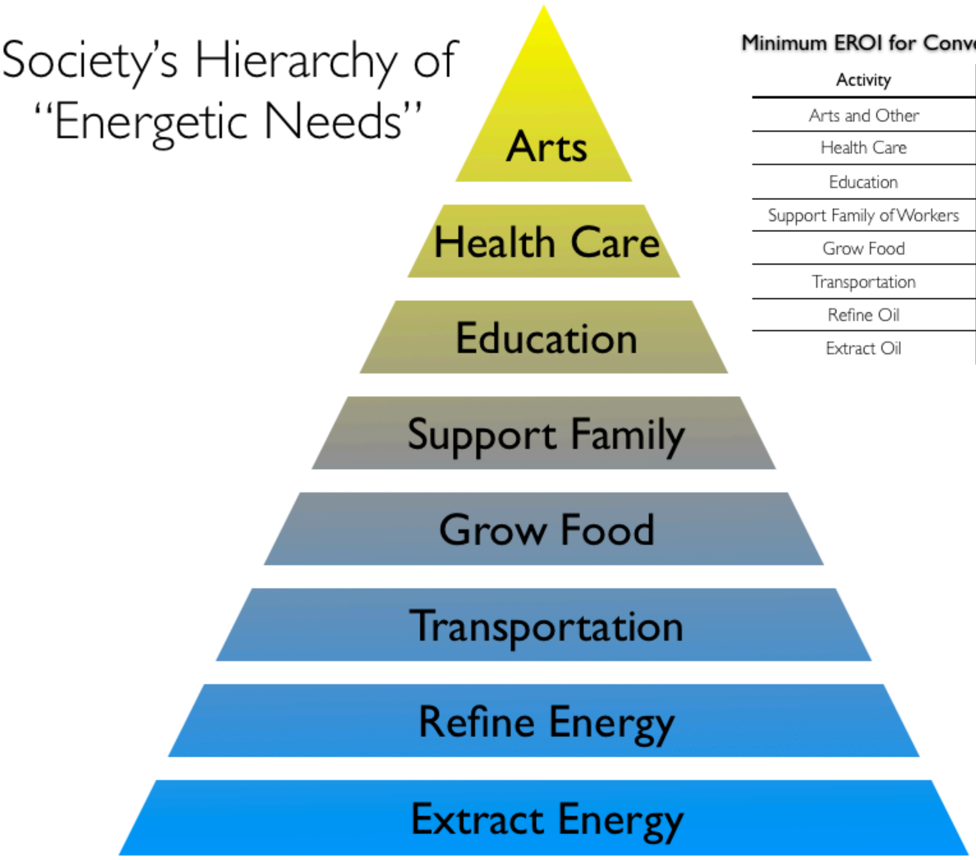
Figure 4c: A timeline (not drawn to scale) of influential works in the fields of energy science, EROI, biophysical economics and net energy published in the 1990s and 2000s.

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 [6]. This has resulted in a flurry of new EROI-related papers (See MDPI Sustainability 2011 [11]; these papers will soon be published as a separate book).

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 [51]. Very productive metal mines and an aggressive foreign policy backed by high quality weapons made Sweden the most powerful country in Northern Europe from 1560 until 1720. Enormous amounts of enegy 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 [6] 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." [6]

They conclude that if both direct and indirect energy are included, the EROI is reduced to approximately 4:1 [6]. 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 [51].



Minimum EROI for Conventional Sweet Crude Oil

Activity	Minimum EROI Required
Arts and Other	14 : 1
Health Care	12 : 1
Education	9 or 10 : 1
Support Family of Workers	7 or 8 : 1
Grow Food	5 : 1
Transportation	3 : 1
Refine Oil	1.2 : 1
Extract Oil	1.1 : 1

Figure 5: "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 (figure adapted from Lambert and Lambert, in preparation [3]).

Hierarchy of Energetic Needs

Certain thresholds of surplus energy must be met in order for a society to exist and flourish. The above hierarchy of "energetic needs" is somewhat akin to Maslow's "pyramid of (human) needs". It represents the importance of the quality of energy devoted to the production and maintenance of infrastructure required to support society. We analyze this using EROI analysis. 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. If it were 1.2:1 you could both extract it and refine it (Appendix B). At a 1.3:1 EROI it could also be distributed to where it is useful but, once again, all you could do is look at it. Hall and Klitgaard examined the EROI required to run a truck [6]. They found that an EROI of at least 3:1 EROI at the wellhead was necessary to build and maintain the truck and the roads and bridges required to use one unit, including depreciation (Appendix C) [6]. In a thought experiment Hall and Klitgaard found 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 of the oil field worker, the refinery worker, the truck driver and the farmer, it would require the support of the families and an EROI of approximately 7 or 8:1. If the children of these families were to be educated an EROI value in the region of 9 or 10:1 would be required. If the families and workers receive health care and higher education then an EROI value of perhaps 12:1 at the wellhead is required. An EROI value of at least 14:1 is needed provide the performing arts and other social amenities to these families and workers. In other words to have a modern civilization, one needs not simply surplus energy but lots of it, and that requires either a high EROI or a massive source of moderate EROI fuels.

Language and information for Hierarchy of Energetic Needs is adapted from: Hall, C. Introduction to Special Issue on New Studies in EROI (Energy Return on Investment) Sustainability 2011, 3. [11]

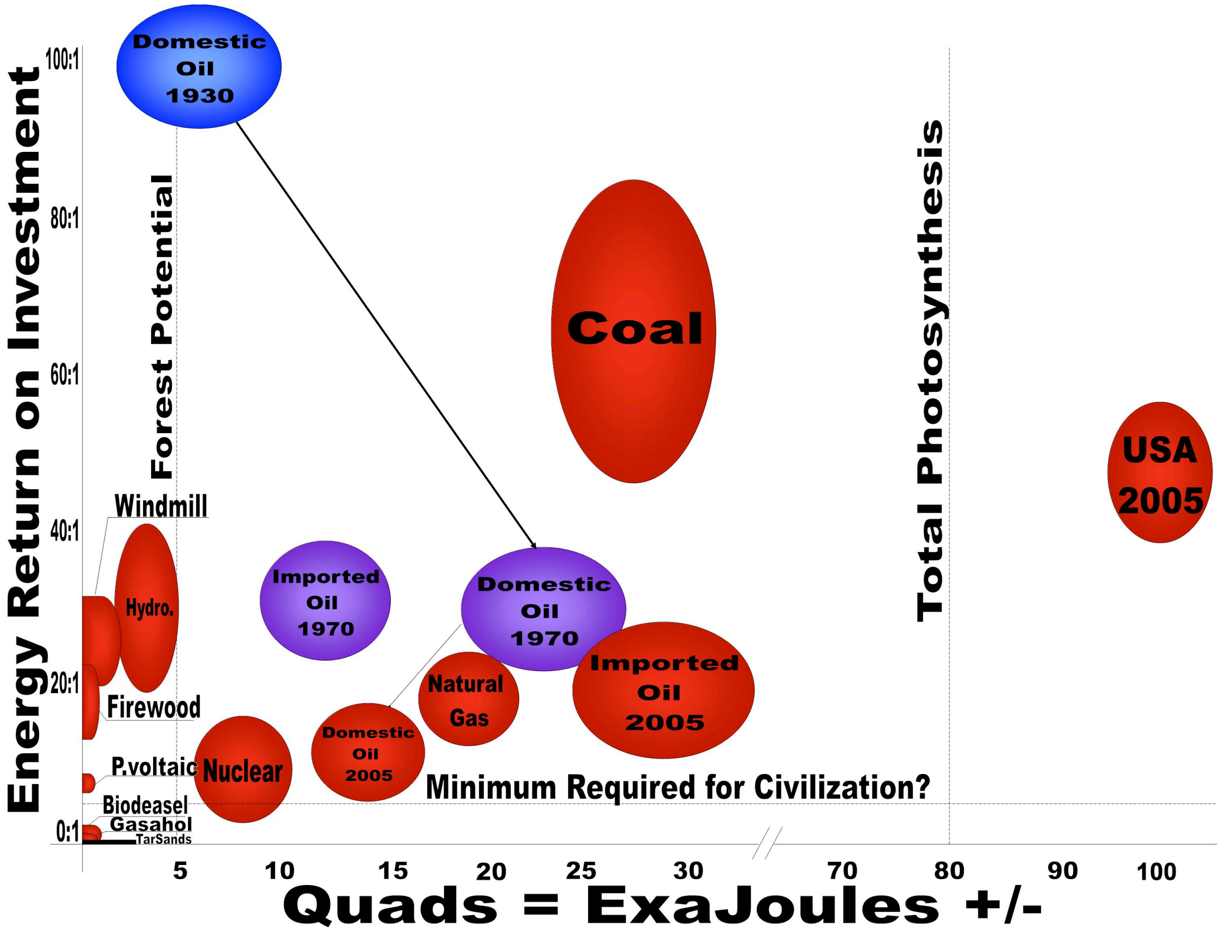


Figure 6: "Balloon graph" representing quality (vertical axis) and quantity (horizontal axis) of various fuels used by the United States' economy at various times (blue represents the 1930s, purple presents the 1970s and red represents 2005). Arrows connect fuels from various times (i.e., finding domestic oil 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) [68, 69].

Oil and Gas

Image: "Two Oils Of Alberta" by Rosemary Ratcliff

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 [72]. The global EROI for the production of oil and gas has declined from 30:1 in the 1995 to about 18:1 in 2006 [80]. It is difficult to establishing EROI values for natural gas alone as these values are usually aggregated in oil and gas statistics [70, 71].

Language adapted from: Hall, C. and Klitgaard, K. Energy and the Wealth of Nations: Understanding the Biophysical Economy. Springer, 2011. [6]

Coal

Image: "Coals" by dan

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 [6]. 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 from US coal seems to have occurred in 1998 [4, 71].

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 [12, 71]

Nuclear

Image: ""Power Station Cooling Towers" by xedos4

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 or ore grades [6].

Language adapted from: Hall, C. and Klitgaard, K. Energy and the Wealth of Nations: Understanding the Biophysical Economy. Springer, 2011. [6]

Renewables

Image: "Solar And Wind Energy" by dan

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 [73-76]. Wind power has a high EROI value (perhaps 18:1) [77] while photovoltaic (solar electric) power remains relatively low, perhaps only 7:1 or less [70]. A positive aspect of most renewables is that the output of these fuels is high quality electricity. A potential draw back it that the output is far less predictable.

Language adapted from: Hall, C. and Klitgaard, K. Energy and the Wealth of Nations: Understanding the Biophysical Economy. Springer, 2011. [6]

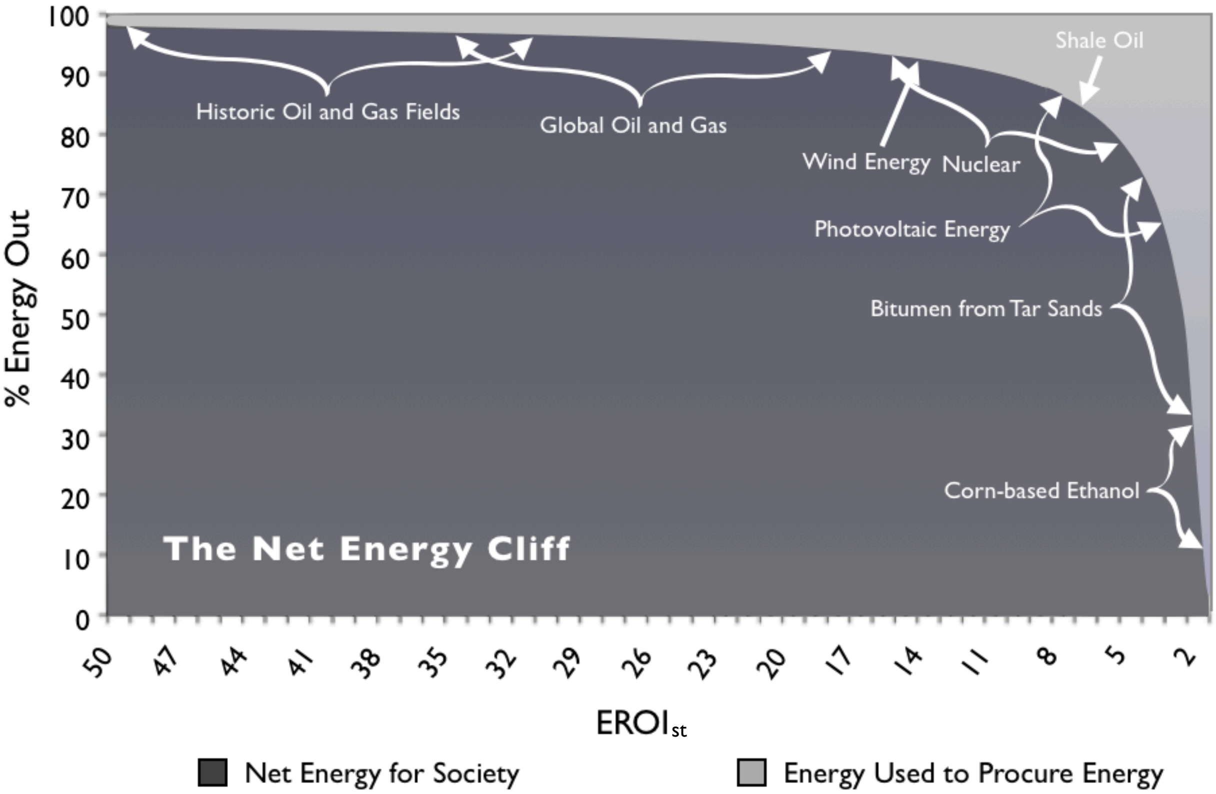


Figure 7: The "Net Energy Cliff" (figure adapted from Lambert and Lambert, in preparation [3] and Murphy et al. 2010 [71]) As EROI approaches 1:1 the ratio of the energy gained (dark gray) to the energy used (light gray) from various energy sources decreases exponentially [71]. High EROI fuels allow a greater proportion of that fuel's energy to be delivered to society (e.g. a fuel with an EROI of 100:1 (horizontal axis) will delivers 99% of the useful energy (vertical axis) from that fuel to society [71]. Conversely, lower EROI fuel delivers substantially less useful energy to society (e.g. a fuel with an EROI of 2:1 will deliver 50% 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 [71] (concept courtesy of Euan Mearns).

Importance of EROI

"The utility of a fuel depends upon not only its quality but also how much of it there is that is, its quantity." - Murphy et. al, 2010 [71]

For example, wind power may have a moderately high EROI, especially at very favorable locations. Nevertheless, the total quantity of electricity that is produced and delivered is typically small in comparison with energetic needs. This is slightly less true for some low population mountainous or coastal regions where wind power is prolific (e.g. Denmark). But, even there, fossil fuels remain dominant in the region's total energy profile, and current technology demands very expensive and energy-intensive backup systems [6].

Other non-traditional energy sources such as biodiesel and photovoltaics tend to have relatively low EROIs when compared to those of traditional fossil fuels (e.g. coal). To date, these alternative fuels claim an insubstantial portion of the total energy consumed by the majority of nations [6]. The total magnitude of alternative energy produced remains so very small that it is not likely to be a significant contributor to total global energy production for many years or even decades. Murphy et al., 2010 report that just prior to the financial collapse of 2008 [71], the annual global *increase* of each conventional fossil fuel (oil, gas, and coal) was greater than the total annual *production* of all non-conventional, solar-based (i.e., wind turbines and photovoltaics) energy [71]. What this means is that energy derived from non-conventional, solar-based, energy sources is not displacing fossil fuel use. Instead, it is merely contributing to the annual global energy growth.

The efficiency of energy production is quantifiable using Energy Return on Investment (EROI). Figure 7 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 [71].

The oil, gas and coal that dominate use today probably had EROI values greater than 30:1 to 100:1 in the past [72]. Therefore, we did not need to be concerned with their EROIs and the potential 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 deposits are depleted. Society has employed Ricardo's "best first principle" [6]. 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 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. In terms of EROI, wind power might be a viable energy source but we must consider the cost of backup systems. Synthetic fuels produced from tar sands appear to be economically viable but have high environmental impact [24, 86]. Additionally temperate latitude corn-based ethanol has insufficient EROI to be considered a viable source of energy. 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 energy production. The former, CCS, is perceived as a potential method of reducing carbon emission. The latter is a method of storing and transferring energy. 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." As EROI declines over time, the surplus wealth that is used to perform valuable but non-essential activities in a society (e.g. health care, higher education, the arts, etc.) declines [6, 11]. This appears to be impacting society now. Given this, we believe that declining EROI will play an increasingly important role in our future economy and quality of life [68].

Current EROI Debate

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. A number of contributors to the corn-derived ethanol debate believe that the EROI of corn-based ethanol is less than 1:1 [73-76]. Others (summarized in Farrell et al. 2006) suggest that there is an energy surplus of 1.2 to 1.6:1 units of energy [75]. The variation in these findings is typically a result of the choice of direct and indirect costs associated with energy production/ extraction included within the EROI calculations: i.e. the boundaries of the numerator [78]. 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) [6].

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 [6]. If such non-conventional or alternative energy resources use high quality energy inputs (e.g. convention oil and gas) for their production, then decreased oil and gas

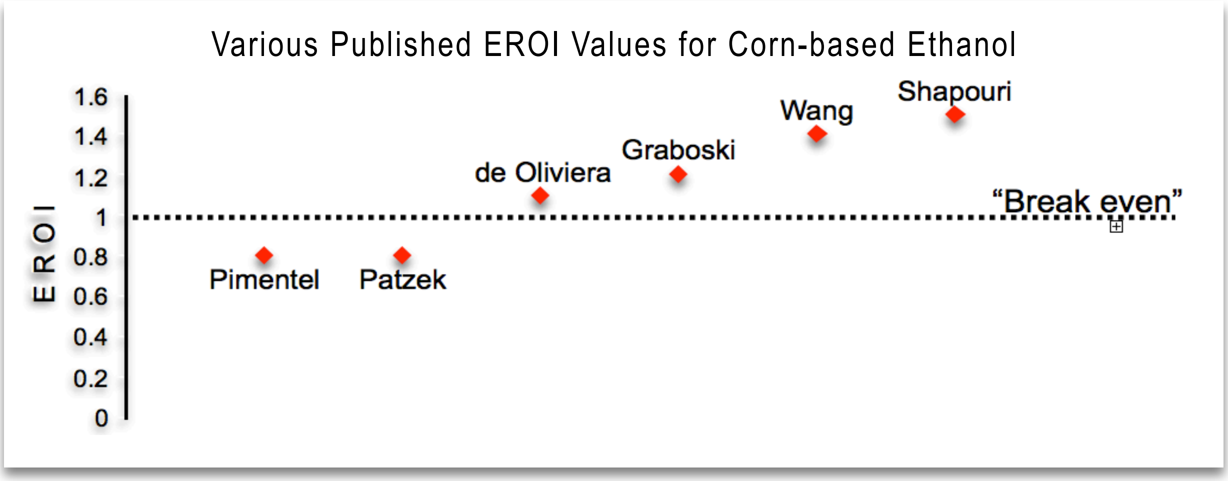


Figure 8: Various values published on the EROI of corn-based ethanol for what are purportedly the same fuel production processes. According to Murphy and Hall [71] at least three different methods of net energy analysis have been utilized in the corn-based ethanol energy literature, resulting in three disparate EROI calculations that are "mutually incommensurable." Pimentel and Patzek [73] and Patzek [74] have published EROI figures for ethanol from corn with a less then 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. [75] and Hammerschlag [76], 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 production process results in a net gain or loss in energy from corn [78]. All of these values are much too low to contribute significant net energy to society [6].

availability could increase the cost of the alternative fuel since high quality (high EROI) energy is used to produce low quality (low EROI) energy. This could reduce its viability and negate possible prospective advantages.

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 [70]. 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.

Review of Methods

EROI values for similar fuels often have large variations leading to large differences within the published data for each EROI assessment. To reduce these differences Murphy et al. 2010 derived a standard EROI calculation method [12]. While recognizing the uncertainties involved in and inherent to all EROI calculations, Murphy et al. 2010 proposed that these differences can be largely reduced when assessed using similar boundaries [12]. The generation of EROI values is best developed using 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") (Appendix E). 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. However, boundaries and variables differ between nations and may result in conflicting or inconsistent data.

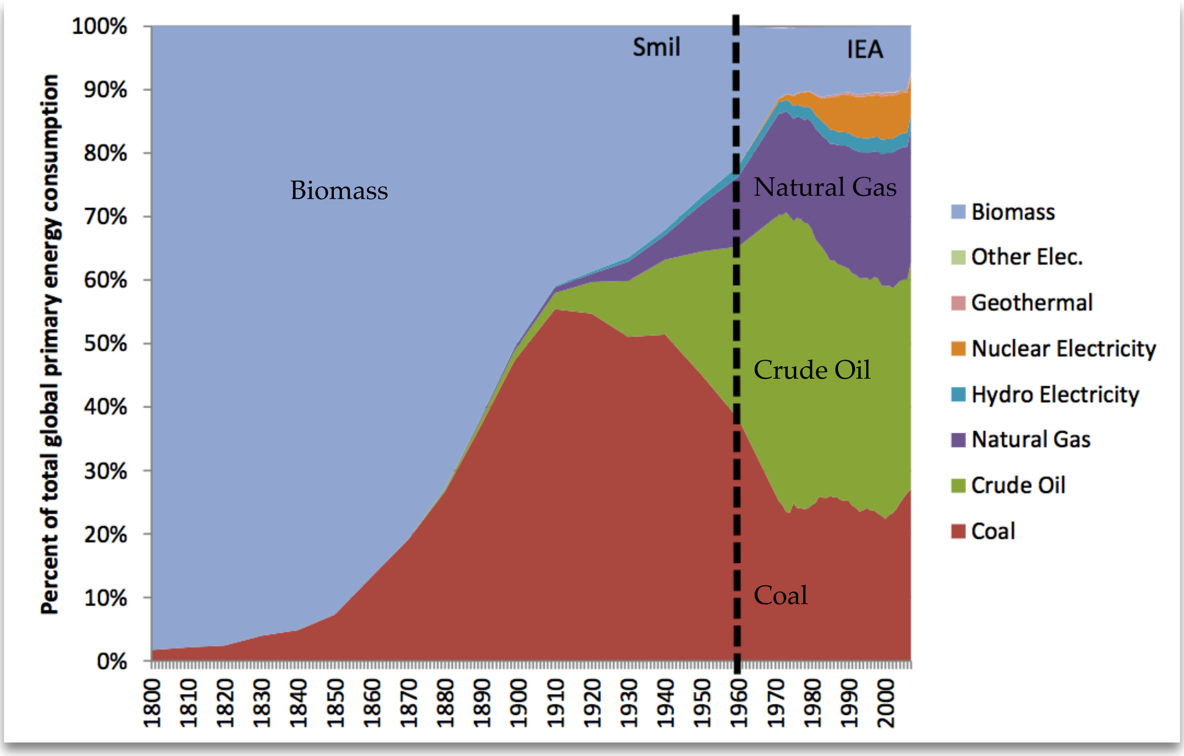


Figure 9: Percent of total global primary energy consumption by fuel type (1800-2007). In 1800, biomass energy was by far the dominant global primary energy source (>95%). By 1900, 100 years into the industrial and fossil fuels revolution, 50% of expanding global primary energy consumption was coal. Today, the three non-renewable fossil fuels coal, oil and gas represent 80% of global primary energy consumption. (Data between 1800-1970 from Smil [86]; and between 1971-2007 from IEA [87]).

Values of EROI by Fuel Type

Existing published and unpublished EROI values has been summarized in Hall et al. 1986 [24], Heinberg, 2010 [79], Gupta and Hall, 2011 [70], and within a special issue of Sustainability [11]. New EROI values have been derived for oil and coal in China and Canada. Typically EROI values are calculated by country and by energy source. Here, we organized existing EROI values by year, fuel type, and individual study. This information, presented in Table 2, summarizes our existing knowledge of EROIs for various energy sources by EROI value, geographic region, and time. A short description on our methodology for each respective fuel follows. A more detailed, technical and discipline specific methodology is available upon request and will be included in future publications.

Coal

We aggregated multiple energy output and cost datasets from the US and China. These represent two large coal producing nations that employ varying coal production technology.

Oil and Gas

Oil and gas EROI values are typically aggregated together. The reason is that since both are 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. Gagnon 2009 estimated global oil and gas EROI from 1992 to 2006 [80]. We also used time series data for oil and gas production in the US going back to 1919 from several sources [2, 24, 72] as well as time series EROI data for Norway [81], Mexico [82], Canada [83, 84] and China [85]. We averaged these EROI values, which all had the same recent decreasing trends, to estimate a new global EROI for oil and gas over the entire period (1920-2010).

Nuclear

Life cycle EROI values for nuclear power, reported in the literature, vary greatly (from 1:1 to 90:1), and like all things nuclear, have been a matter of controversy. In 2006, the Australian government commissioned a comprehensive study to clarify the matter. The results were published in Lenzen (2008) who used mean values with data covering 45-years of activity and arrived at the conservative estimate of roughly 5:1 for a full life cycle analysis (from uranium extraction and processing, to waste treatment and decommissioning) [88]. Most of this data is 30-40 years old and may not reflect current technology or ore grade.

Results and Discussion

EROI for our most important fuels, liquid and gaseous petroleum, tends to be relatively high (from 10:1 to 30:1 depending on location), but is consistently declining. The other important fuel, coal, is high for the US (with an EROI of about 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) but with little recent information. The EROI of hydropower is extremely variable although the best sites in the developed world were constructed long ago [24]. Other renewable fuels tend to have low EROIs (except wind turbines) and probably would be lower if the required backups were included (all fuels are summarized in table 2). The most critically important area for EROI research appears to be liquid and gaseous petroleum. Higher exploitation rate tends to be as important as resource depletion to decreasing EROI. The many trends of declining EROIs suggest that depletion and increased exploitation rates are trumping new technological developments.

Our research summarizes EROI estimates of the three major fossil fuels, coal, oil and natural gas and derives generalized national, regional and/or global EROI values for each fuel respectfully. 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.

There are four major challenges in calculating the EROI of various fuels at the national, regional and global scale. First is the lack of data on fuel used during the extraction process. Data on on-site non-traded (e.g. coal from the mine used to power the mine) fuel is not readily available. Often energy cost calculations must be derived from financial data. This requires converting currency into megajoules (MJ). Methods for accomplishing this conversion are less accurate but sensitivity analyses can be completed to address these uncertainties.

Second is the issue of variation in scale. Are studies at the regional level comparable to those at the national level and how do those size up when presented next to “international” studies that include a small subset of representative countries? Differing variables and boundaries often vary with the scale of investigation making it difficult to compare data between diverse analyses.

Third, energy analysts are not in agreement on what indirect costs should and should not be included in an EROI assessment. One very contentious indirect cost is the inclusion or exclusion of the cost of human labor [12]. This can result in varying and potentially controversial assessments especially when assessing fuels where small differences may determine whether that fuel is perceived as a viable energy option (e.g. corn-based ethanol).

A fourth issue is that the quality or utility of these various fuels is represented differentially within different data sets. Primary energy consumption values on the global level published by the International Energy Agency (IEA), US Energy Information Agency (EIA) [207], BP [206], Smil (2011) [86], and Laherrère (unpublished) tend to be basically similar. They occasionally vary, however, in their method of addressing “primary energy” conversion.

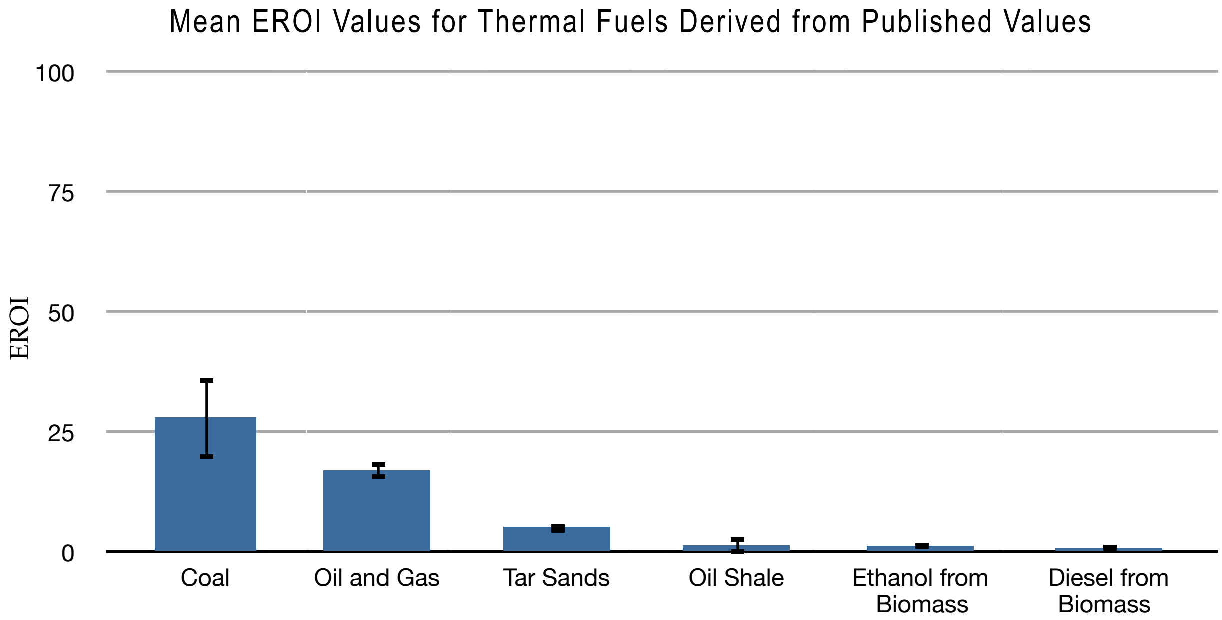


Figure 10: Mean EROI (and standard error) values for thermal fuels based on known published values. Coal has a mean EROI of about 28:1 (n of 62 from 16 publications) [24, 89-104, 197]. World oil and gas has a mean EROI of about 17:1 (n of 22 from 3 publications) [2, 24, 72, 92, 104, 197]. Alternatives to traditional fossil fuels such as tar sands [24, 86, 105, 106] and oil shale [24, 97, 55, 107, 108, 197] deliver a lower EROI, having a mean EROI of 5:1 (n of 4 from 4 publications) and 1.4:1 (n of 14 from 14 publication) respectively. The mean EROI value for ethanol (1.3:1 with an n of 75 from 31 publications) [24, 73, 102, 104, 109-133, 197] and diesel from biomass (0.9:1 with an n of 28 from 16 publications) [73, 104, 112, 122, 134-143, 151, 197] deliver low EROI values that are typically at or below the 3:1 minimum extended EROI value required for a fuel to be minimally useful to society.

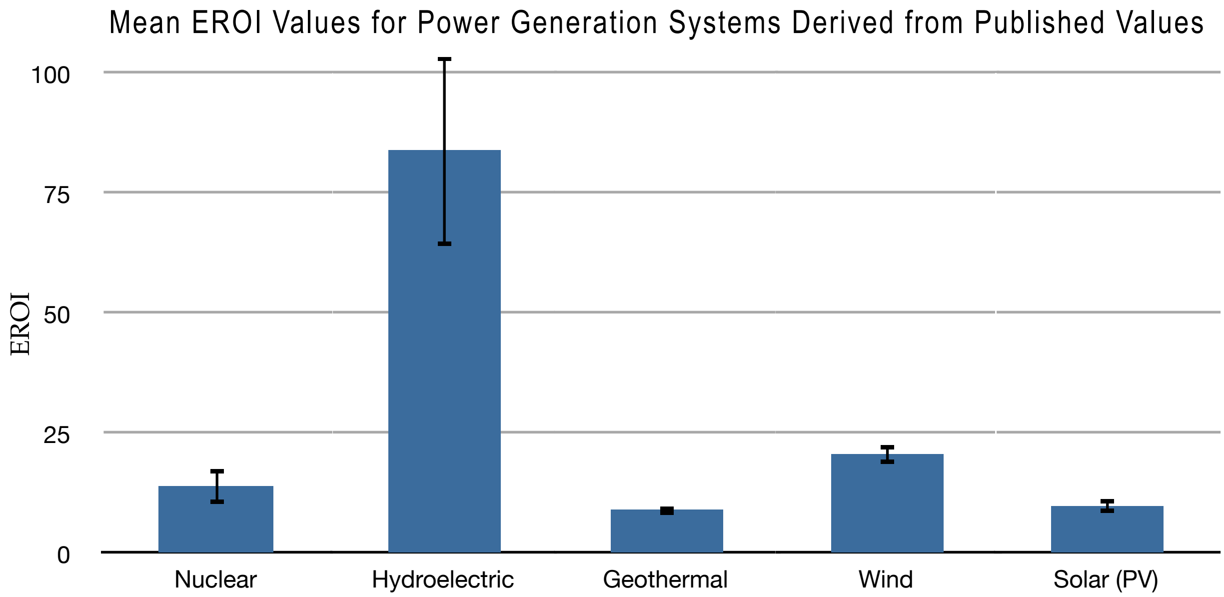


Figure 11: Mean EROI (and standard error) values for known published assessments of power generation systems. Nuclear power has a mean EROI of about 14:1 (n of 33 from 15 publications) [24, 55, 88, 102, 104, 106, 144, 145, 150, 155-160, 197]. Hydroelectric power generation systems have the highest mean EROI value, 84:1 (n of 17 from 12 publications), of electric power generation systems [24, 55, 102, 104, 106, 144-148, 197]. Geothermal electricity production has a mean EROI of approximately 9:1 (n of 30 from 11 publications) [18, 24, 104, 107, 161-163, 197]. Wind power has a mean EROI of about 20:1 (n of 26 from 18 publications) [102, 104, 144, 145, 147, 148, 164-171, 197]. Solar (photovoltaic) power generation has a mean EROI of roughly 10:1 (n of 79 from 45 publications) [24, 55, 104, 106, 144, 145, 147, 148, 153, 154, 167, 168, 150, 170, 172-197].

Note: Values derived using known modern and historical published EROI and energy analysis assessments and values published by Michael Dale [197].

Table 2: Published EROI values for various fuel sources and regions. Table adapted from Murphy et al. 2010 [12].

Resource	Year	Country	Magnitude (EJ/yr)	EROI (X:1)*	Reference
Fossil fuels (Oil and Gas)					
Oil and gas production	1999	Global	200	35	80
Oil and gas production	2006	Global	-	18	80
Oil and gas (Domestic)	1970	US	28	30	2, 24
Discoveries	1970	US		8	2, 24
Production	1970	US	10	20	2, 24
Oil and gas (Domestic)	2007	US	-	11	72
Oil and gas (Imported)	2007	US	28	12	6, 72
Oil and gas production	1970	Canada	-	65	83
Oil and gas production	2010	Canada	-	15	83
Oil, gas & tar sand production	2010	Canada	-	11	84
Oil and gas production	2008	Norway	-	40	81
Oil production	2008	Norway	-	21	81
Oil and gas production	2009	Mexico	-	45	82
Oil and gas production	2009	China	-	6	85
Fossil fuels (Other)					
Natural Gas	2005	US	30	10	152
Natural Gas	1993	Canada	-	38	83
Natural Gas	2000	Canada	-	26	83
Natural Gas	2009	Canada	-	20	83
Coal (mine-mouth)	1950	US	n/a	80	20, 48
Coal (mine-mouth)	2000	US	5	80	20, 48
Coal (mine-mouth)	2007	US	-	60	98
Coal (mine-mouth)	1995	China	-	18	198
Coal (mine-mouth)	2009	China	-	21	198
Other non-renewables					
Nuclear	n/a	US	9	5 to 15	20, 88
Renewables**					
Hydropower	n/a	n/a	-	>100	24
Wind turbine	n/a	n/a	-	18	77
Geothermal	n/a	n/a	-	n/a	70
Wave energy	n/a	n/a	-	n/a	70
Solar collectors**					
Flat plate	n/a	n/a	-	1.9	24
Concentrating collector	n/a	n/a	-	1.6	24
Photovoltaic	n/a	n/a	-	6 to 12	192
Passive solar	n/a	n/a	n/a	n/a	24
Biomass					
Ethanol (sugarcane)	n/a	n/a	-	0.8 to 10	151
Corn-based ethanol	n/a	US	<1	0.8 to 1.6	75, 75
Biodiesel	n/a	US	<1	1.3	73

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

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

For example, EIA data includes the heat generated by nuclear power in its energy output assessments. Various researchers, government agencies and industry organizations present data from a variety of sources using various assessments (e.g. national (EIA), global (IEA) and industrial (BP). Laherrère addressed this issue at the 2011 ASPO conference. He also noted that IEA data is presented as the direct electricity generated for nuclear and hydropower, while EIA data includes waste heat produced by nuclear fission.

There is a broadly consistent pattern to our results, as indicated by the similar temporal patterns of different studies and by the fact that regions developed for oil and gas for a longer period (e.g. US, China or anywhere over time) have lower EROIs, while newer developments (e.g. Norway) have higher values. If and as the Murphy et al. protocol is more universally followed we expect even greater consistency in results. We next examine broad patterns of EROI overtime.

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 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 [6].

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 in 1970 meant an increased reliance on OPEC oil. The increase in oil price reflected the increased energy required to purchase this fuel. The price of other economic activities increased at similar rates [6]. Most natural gas was flared during this period. The oil shocks of the 1970s ended this long period of increased oil use.

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 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 [6]. 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 our economy as it had been in the 1970s, and much of the discretionary spending disappeared [68]. Speculation in real estate was no longer desirable or possible as consumers tightened their belts because of higher energy costs [6].

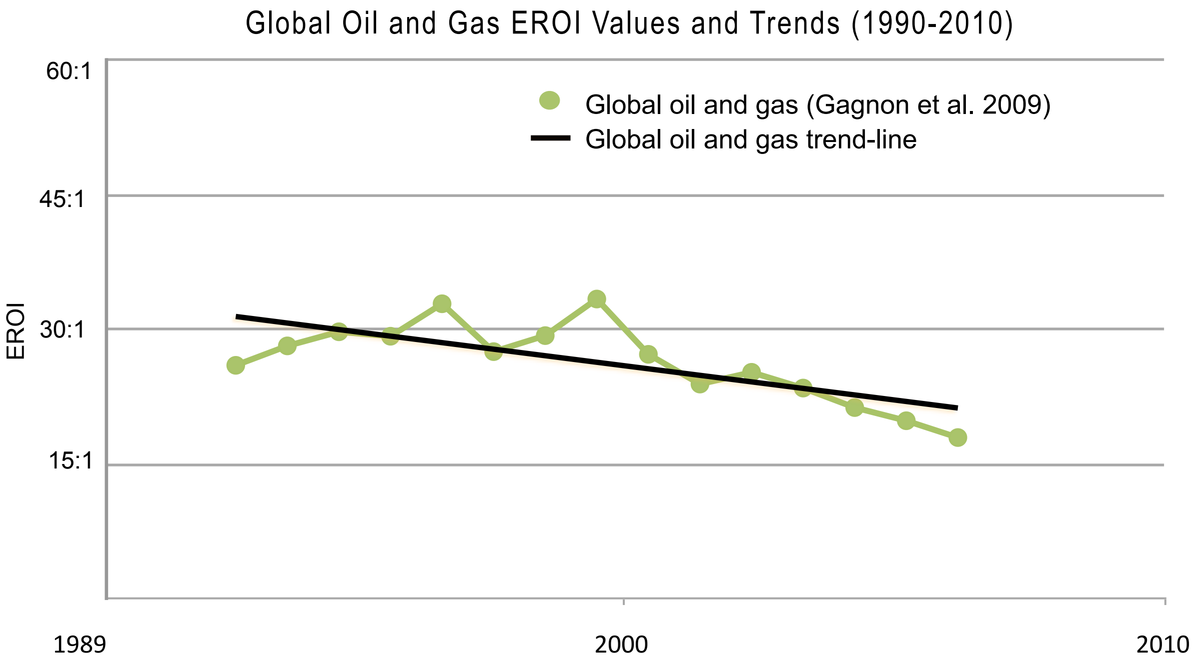


Figure 12: Gagnon et al, 2009, estimated the EROI for global publicly traded oil and gas. Their analysis found that EROI had declined by nearly 50% in the last decade and a half [71, 80]. New technology and production methods (deep water and horizontal drilling) are maintaining production but appear insufficient to counter depletion of conventional oil and gas.

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, who's records tend not to be public. However, Gagnon et al. [80] was able to generate an approximate global EROI for private 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 [6]. 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 [149]. 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 continues to be reasonably high, it is possible that the EROI of oil and gas will continue to decline over the coming decades [80]. 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. The EROI at which a company cannot make a monetary profit is probably approximately 5:1 [6].

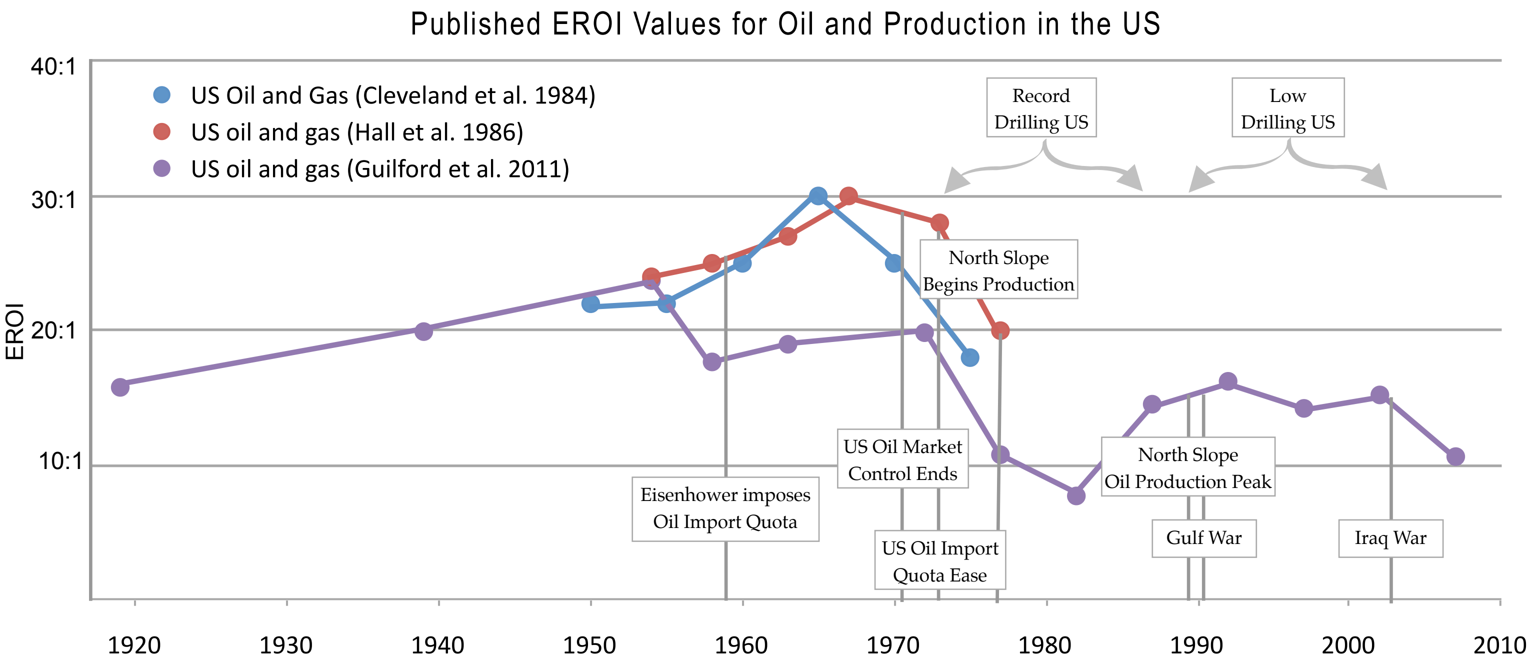


Figure 13: Three independent estimates of EROI time series for oil and gas production for the United States plotted along with some important oil-related historical events [2, 24, 72]. There is a general pattern of decline in EROI over time except as impacted by changes in exploration (drilling) intensity. 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.

United States Oil and Gas

After the oil shocks of the 1970s, oil prices surged, stimulating both an increase in drilling activity and the exploitation of more marginal resources (those with higher production costs) [72]. EROI is related to effort (energy input). Increased drilling activity caused a sharp decline in EROI between the early 1970s and mid 1980s. After 1985 international oil and gas prices fell, then remained stable until 2000 and drilling effort declined until 2005. Important gains in production occurred in non-OPEC countries such as the UK, Norway, Mexico, and China. Recovery was not observed in the US where oil production declined in the continental US since its peak in 1970 although with a very small recovery since 2008. Since the late-1990s prices and drilling rates increased again, and EROI dropped as it had in the 1970s. Since 2008 producers have shifted increasingly to nonconventional oil and gas resources (tar sands, shale oil and gas) which have increased production.

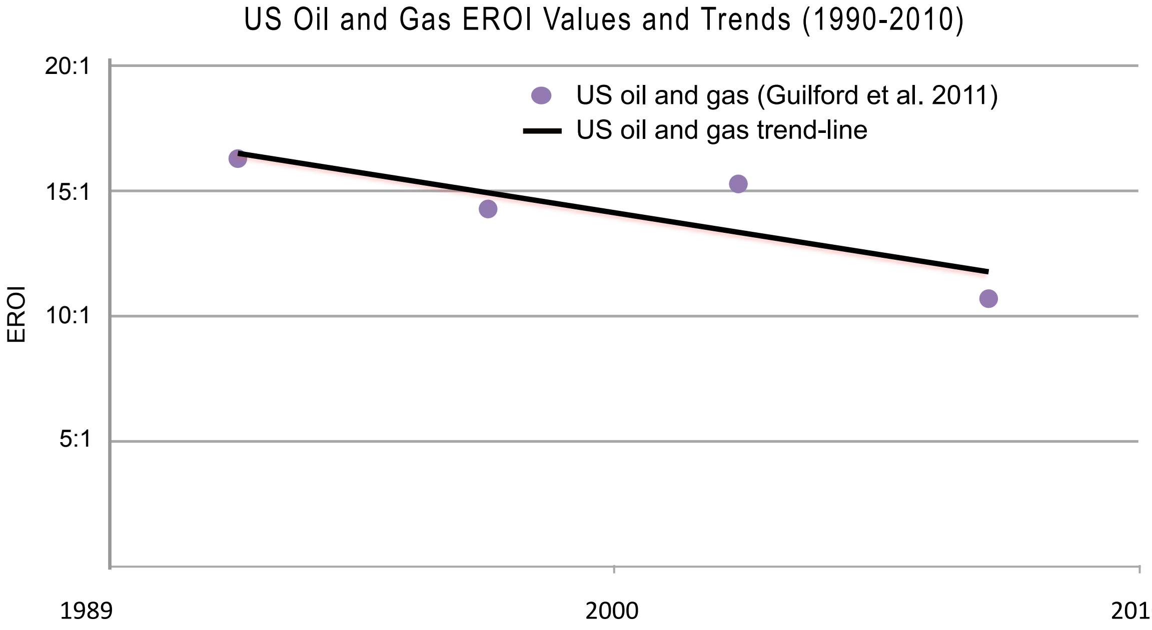


Figure 14: US oil and gas values published by Guilford et al. 2011 from 1992 to 2007 [72].

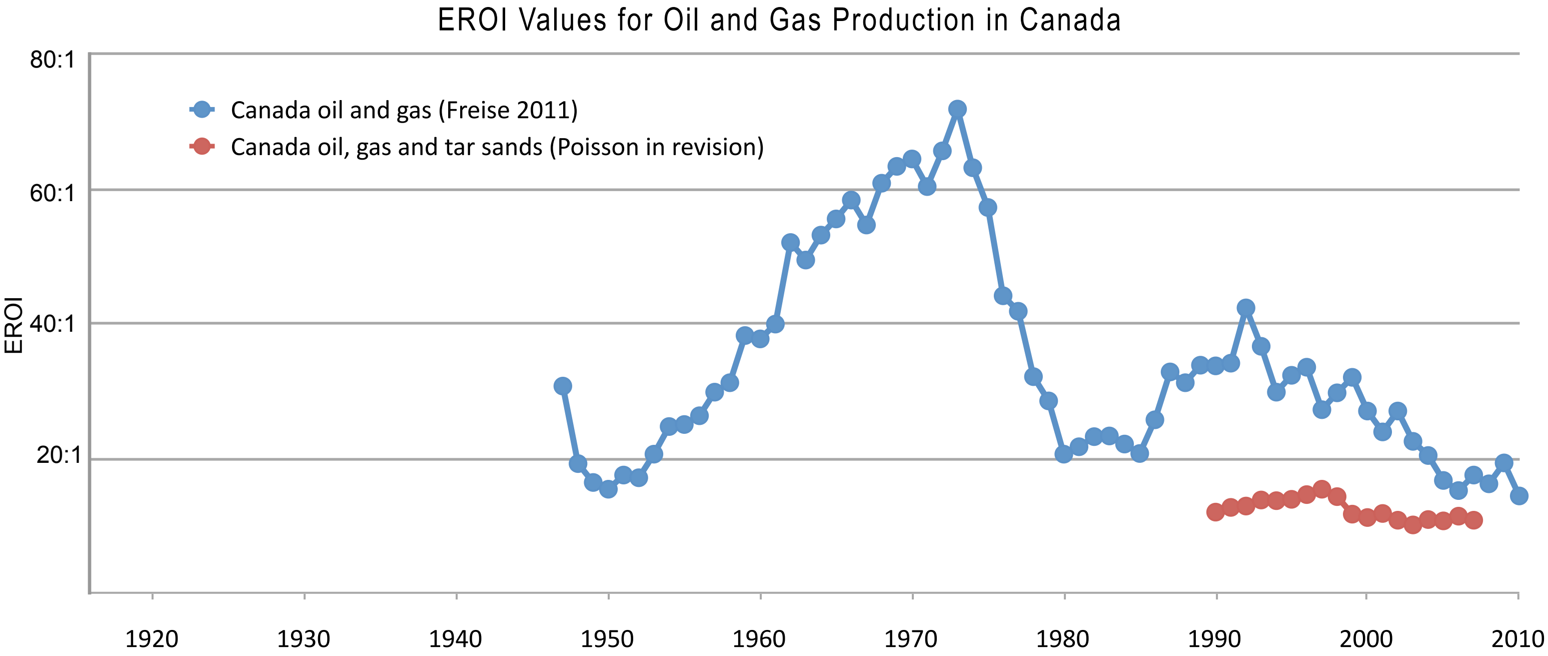


Figure 15: Two independent EROI estimates for Canadian petroleum production: oil and gas (blue line, from Freise, 2011) [83] and oil, gas and tar sands combined (red line, from Poisson et al.) [84].

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 [83]. 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 [83]. Poisson, 2012, 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's estimated EROI values for Canadian oil and gas were about half those calculated by Freise, and their rate of decline is somewhat less rapid [84]. Poisson's 2012 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.

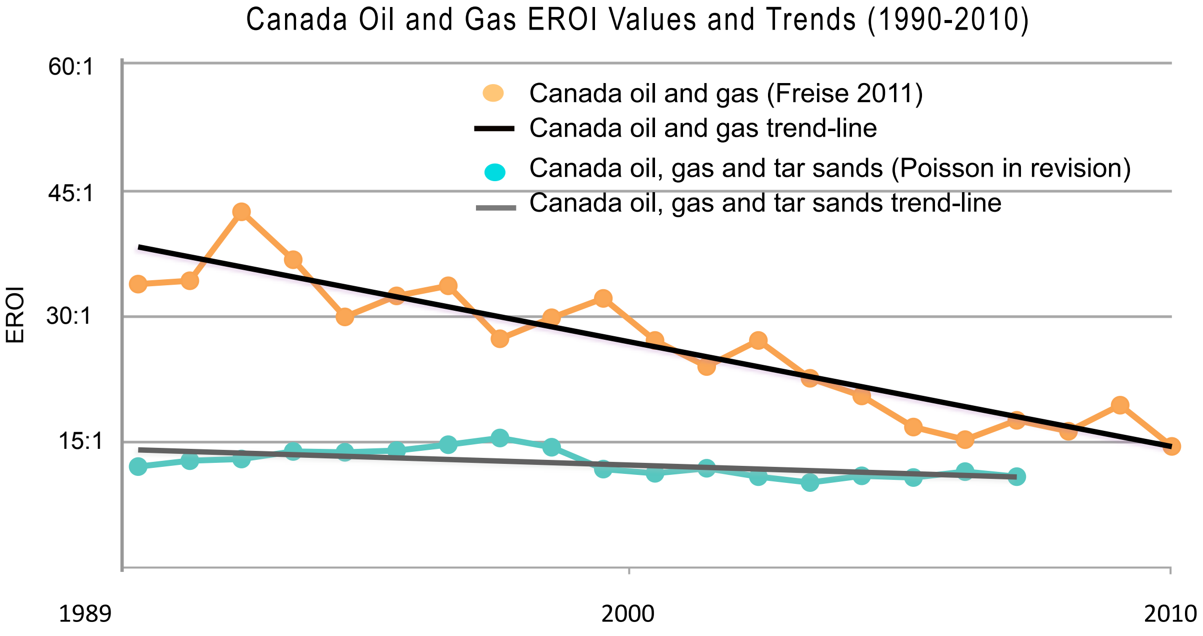


Figure 16: Canada oil and gas and oil, gas and tar sand values by Freise [83] and Poisson [84].

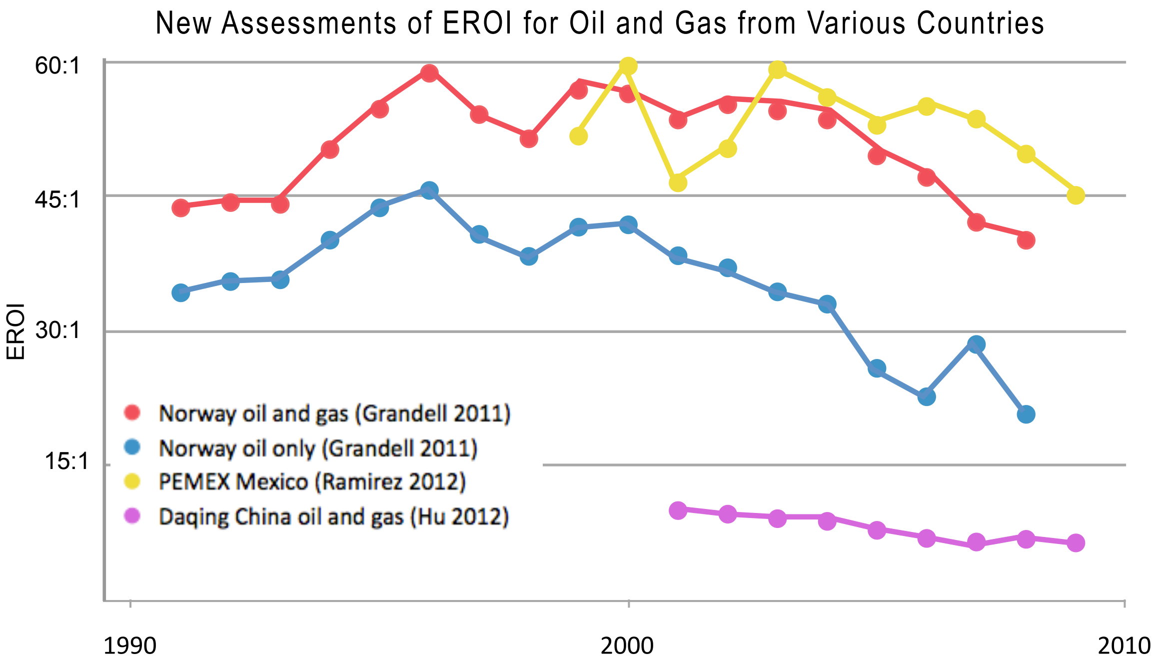


Figure 17: Time series data on EROI for oil and gas based on several papers published in the 2011 special issue of the journal Sustainability [81, 85], and works in progress [82].

Norwegian Oil and Gas

Norwegian oil and gas fields are relatively new and remain profitable both financially and with regard to energy production [81]. 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) [81]. The recent declining trend, is described by Grandell et al. 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. expects the EROI of Norwegian oil and gas production "to deteriorate further as the fields become older" [81].

Mexican Oil and Gas

Ramirez's oil and gas trends for Mexico are in preparation and require further analysis [82]. 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 region can make up for the loss in production of Canterell.

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 form the rest of the world. Recently, China has increased its oil exploitation efforts tremendously, both inside and outside of China. Even so, Yan et al. suggests that China appears to be approaching its own peak in oil production [85].

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 oil extracted from a few sweet spots. These are already being depleted. 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.

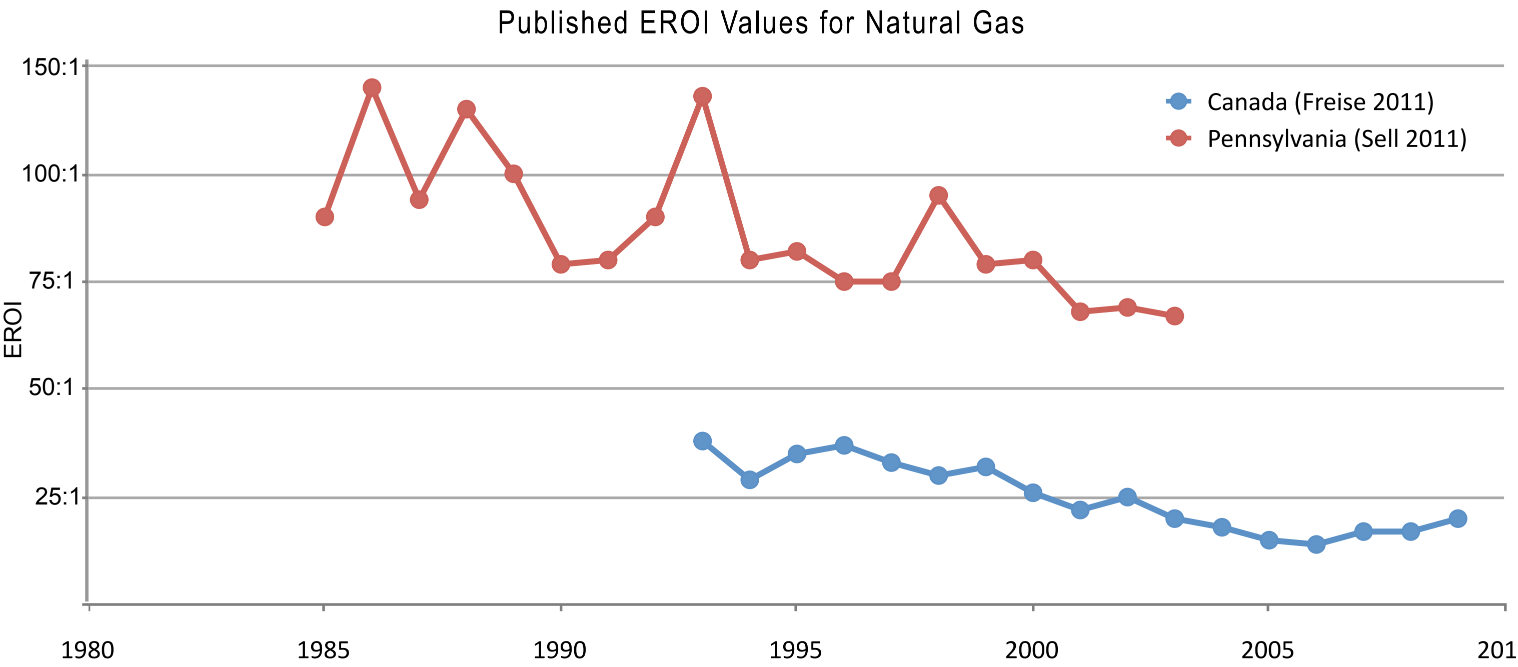


Figure 18: There are two published studies on the EROI of dry natural gas (not associated with oil): Sell et al. 2011 [152] examined tight natural gas deposits in the Appalachian Mountains in the US, and Freise 2011 [83] performed an analysis of all convention natural gas wells in western Canada.

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) 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.

Dry Natural Gas

The data represented in the graph above includes information from a portion of the US and Canada. Most data combines data on natural gas with that of oil, making it difficult or impossible to assess the production costs of these fossil fuel resources independently. 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, somewhat smaller peak [152]. New technologies such as horizontal drilling and hydrofracturing, are currently keeping the total production levels of non-conventional and conventional natural gas production at the same or similar rates achieved by conventional natural gas alone. Given the numerous shifting environmental variables and social issues surrounding horizontal drilling and "fracking", it is difficult to predict the future of natural gas [6].

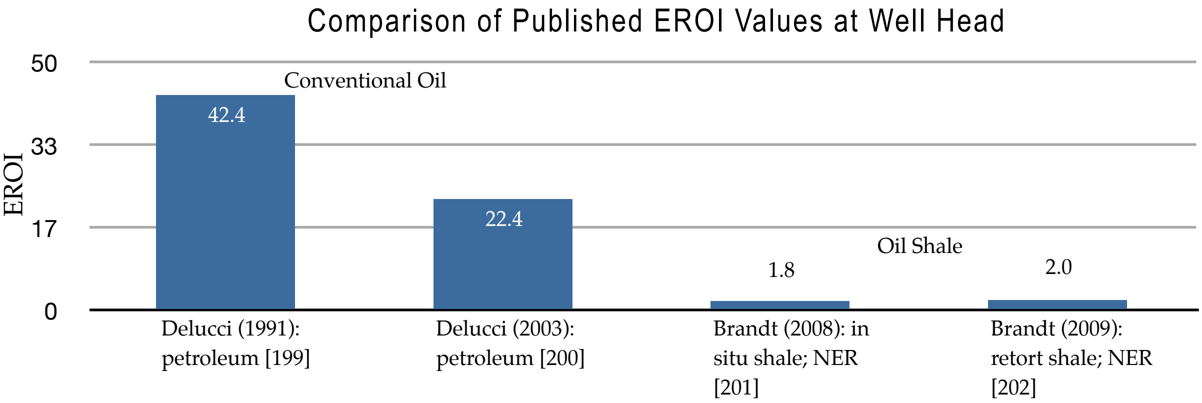


Figure 19: A comparison of estimates of the energy return on investment (EROI) for conventional oil and oil shale published by Cleveland and O'Connor 2011 [203].

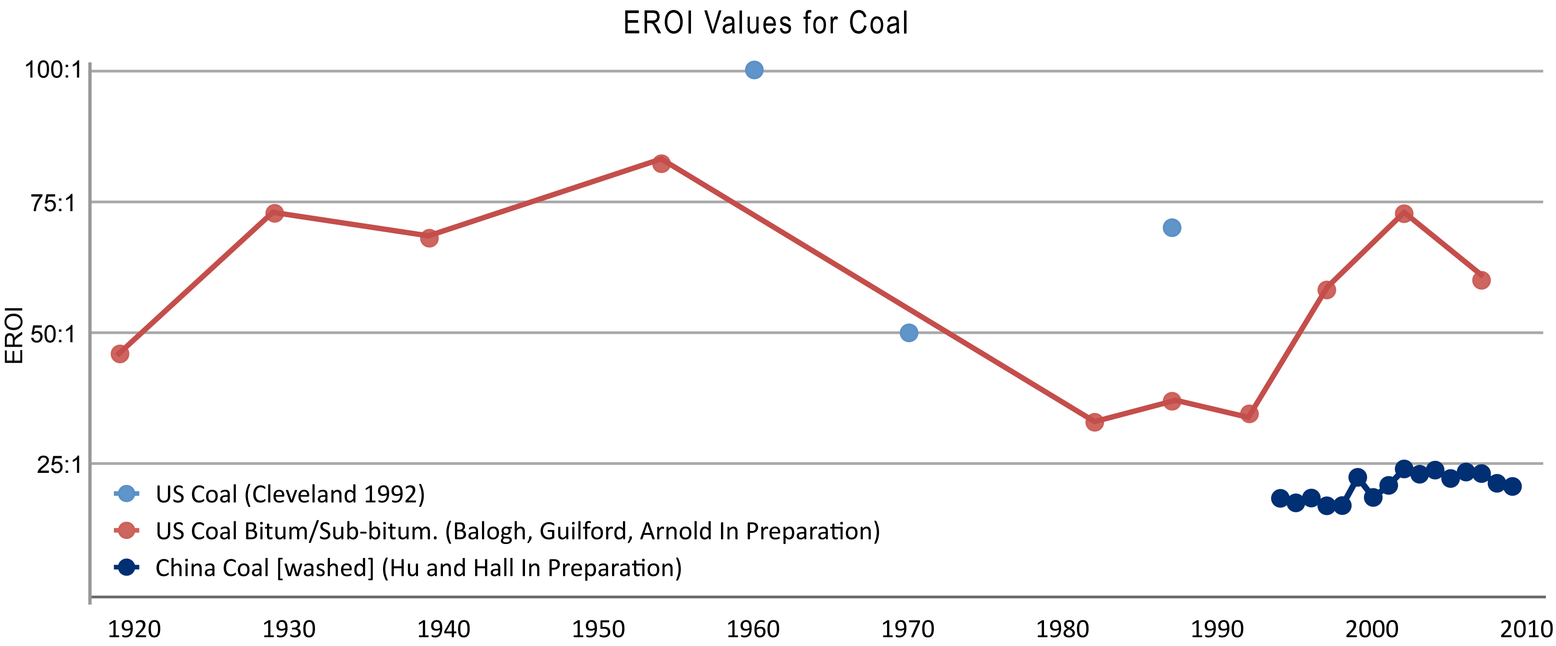


Figure 20: EROI of US and Chinese coal production [198] derived from various sources (e.g. Hall, Cleveland and Kaufmann, 1986 [24]; and as indicated Cleveland, 1992 [50]).

Coal

Much of the discussion about "peak coal" (e.g., Patzek and Croft [208]) involves changing mining technology and capacity, 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. Nations with abundant untapped coal resources (i.e. the US and Russia) are likely to be less affected. Our data, presented in the figure above, represents coal production from the US and China. 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. US coal production in 2009 was 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 [50]. This pattern reflects a shift in the quality 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 combination of anthracite and high quality bituminous coal, coal with higher 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 extraction method, from underground to surface mining (area, contour, auger, and mountain top mining techniques) resulted in less energy required to mine and beneficiate the coal. The energy content of the coal extracted, however, has decreased. The coal currently mined is lower quality bituminous and sub-bituminous coal, coal with much lower BTUs/ton [6]. It is possible that the EROI values for coal for the US are high because official estimates of the cost of production appear to be incomplete.

Wind

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

1. Are not sufficiently "energy dense",
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.

In addition, replacing traditional nonrenewable energy requires the use of energy-intensive technology for their construction and maintenance. Thus it would appear that a shift from nonrenewable to renewable energy sources will result in declines in both the quantity and EROI values of the principle energies required for economic activity.

Although wind energy is currently one of the world's fastest 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 initial capital costs per unit output as well as the backup systems required for the time when there is insufficient wind blowing? Thus, the input for an EROI analysis is the mostly "up-front" capital costs. This is in sharp contrast to the less well known "return" over the lifespan of the system. Therefore, a variable referred to as "energy pay back time" is 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. Thus, the boundaries utilized to define the energy pay back time are incorporated into EROI calculations.

In a recent wind meta-analysis, Cleveland and Kubiszewski [77] 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: l for all operational studies. 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 [204]. Studies employing input–output analysis were found to have an average EROI value of 12:1 while those utilizing less comprehensive process analysis had an average EROI value of 24:1. 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 [77]. Examination of concrete input and output data from operational wind turbines appears to offer the best opportunity to calculate wind EROI values accurately.

Cleveland and Kubiszewski 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 more wind energy and operating at higher efficiency;
3. Large turbines are taller enabling them to take advantage of increased wind speeds occurring farther above the ground [77].

So, despite their larger initial capital investment, large turbines appear to compensate for this with proportionally greater energy outputs. Other factors influencing wind EROI values include energy storage, grid connection dynamics and variations in construction and maintenance costs associated with turbine location. For example, off-shore turbines, while located in wet salty areas with more reliable energy generating winds, require replacement. Turbines located in remote mountainous areas require long distance grid connections that result in energy loss and reduced usable energy values [77].

Solar (PV)

An examination of the EROI literature on solar (photovoltaic) energy generation systems shows inconsistencies in the assumptions and methodologies employed and the EROI values calculated for this renewable energy. 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 frought with potential pitfalls. PV and other renewable alternative EROI values are often computed without converting the electricity generated into its "primary energy-equivalent" [192].

Additionally, PV EROI calculations appear to reflect some disagreement on the role of technological improvement. Raugei et al. attribute low 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 [154]. 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 experimental field data. Other researchers contend that values derived using this methodology do not represent adequately the "actual" energy cost to society and the myriad energy sinks associated with this delivery process. For example Prieto and Hall (in press) calculate EROI values that incorporate these energy costs using data from existing installations [196]. Their EROI values tend to be considerably lower.

Proponents of operational installation EROI assessments believe that, in order to portray PV technology accurately, it is necessary to make note of the fact that this is a technology that is still developing even while it is constructed using, and therefore subsidized by, high EROI fossil fuels. These researchers also believe that the focus of EROI assessments must be on net energy produced from existing installations and variables associated with PV modules once they have entered the infrastructure rather than extrapolating into future. Also of concern to these researchers is that PV technology is not a base load technology meaning that future large scale deployment of PV technology, beyond 20 percent of the grid capacity, will likely require the construction of large, energy intensive, storage infrastructure which, if included within EROI assessments, would likely reduce PV EROI values considerably

Raugei et al. 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). The $EROI_{el}$ of coal-fired electricity systems ($EROI_{el}$ of approximately 12–24), however, is approximately double that of PV [154]. These figures do not, however, take into account the much higher life-cycle greenhouse gas emissions that thermal electricity production, and coal-fired systems in particular produce [154]. The energy intensive carbon capture and storage (CCS) required to reduce these emissions to levels equivalent with that of PV electricity production would reduce the final coal $EROI_{el}$ value considerably.

Kubiszewski et al. [192] calculated EROI values using data from 13 analyses of 51 PV systems. These values resulted in an average PV EROI of 6.56:1. Prieto and Hall [30] 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 [196] or three times this if expressed in electricity.)

Conclusions

In conclusion, the world's most important fuels, oil and gas, have declining EROI values. As oil and gas provide roughly 60-65 percent of the world's energy this will likely have enormous economic consequences for many national economies. Coal, although abundant, is very unevenly distributed, has large environmental impacts and has an EROI that depends greatly on the region mined.

While EROI analyses generate numerical assessments using quantitative data that include many production factors, they do not include other important data such as climate change, air quality, health benefits, and other environmental qualities that are considered "externalities" to these analyses. These could, with difficulty, be workded into more comprehensive EROIs in the future.

Most alternative renewable energy sources appear, at this time, to have a considerably lower EROI values than any of the non-renewable fossil fuels. But wind and photovoltaic energy are touted as having environmental benefits which may be substantial. These benefits may in fact have larger initial carbon footprints than originally suggested. Factors such as the oil, natural gas and coal employed in the creation, transport and implementation of wind turbine and PV panels may not be adequately represented in some cost-benefit analysis nor have the energy costs pertaining to intermittency. On the positive side, the fact that their output is high quality electricity needs to be considered as well.

Perhaps most importantly, resource quality, as measured by high EROI, provided the fuel required for economic growth and activity. Our future prosperity will almost certainly depend on our ability to adjust to lower or negative growth of our principle fuels even while EROI values are likely to decline. This will require a more biophysically-based approach to our understanding of economics.

A future of declining energy availability need not be an undesirable future for many reasons including the enormous inefficiency with which we use energy in our economy. 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.

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Appendix A: Example of Calculations for the Minimum $EROI_{ext}$ of Crude Oil

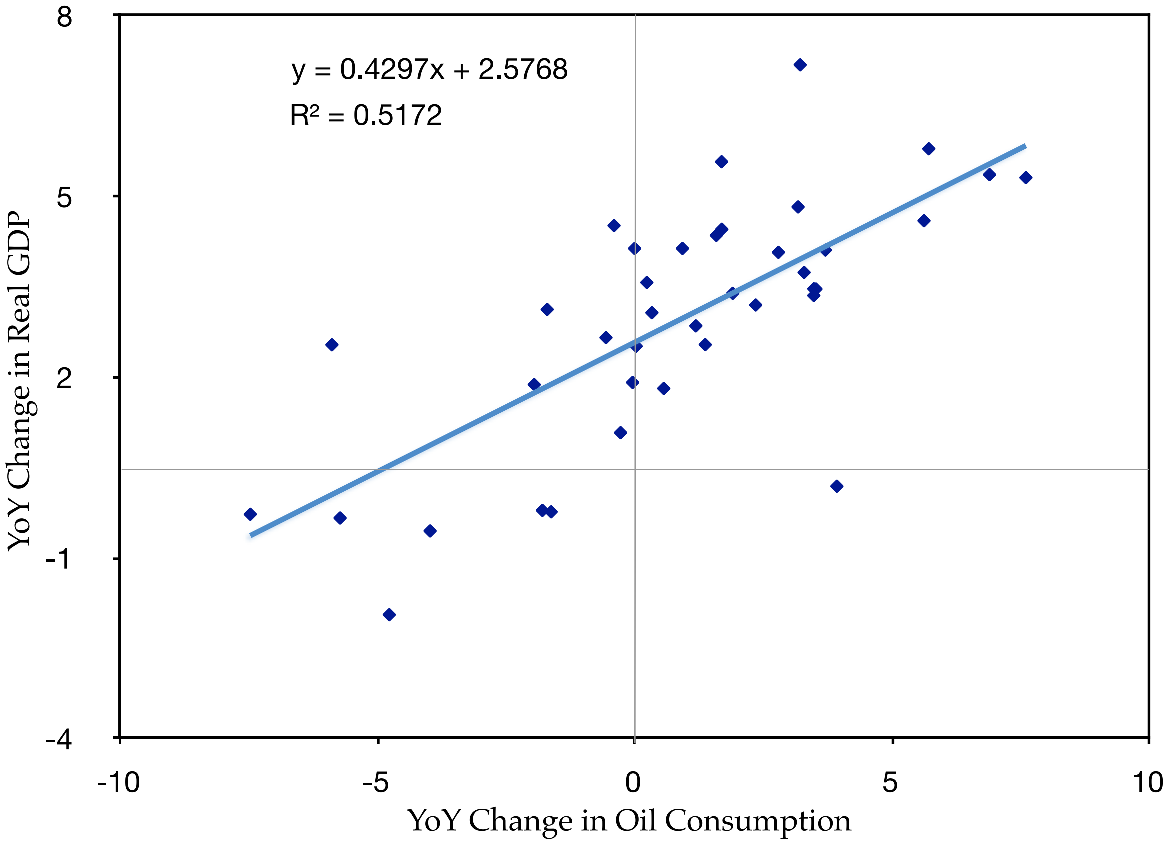


Figure A1: Correlation of YoY changes in oil consumption with YoY changes in the real GDP, for the United States from 1970 through 2010. Oil consumption data from the BP Statistical Review of 2011 [206] and real GDP data from the St. Louis Federal Reserve [9]. Figure and title adapted from Murphy and Hall, 2010 [12].

The energy that flows into an economy and all of its subsequent forms are subject to the laws of thermodynamics. The first law, that energy cannot be created nor destroyed, intimates a hypothetical ceiling on the supply of goods and services that an economy can produce. This suggests that the production of these goods is restricted by the energy available to produced these goods and services. The second law, that energy is degraded during work so that the original stock is capable of doing less work [71], implies that once an energy resource is used it is degraded and consequently is no long able to do the same amount of work. The significance of this is that economic growth requires that we increase energy supply and/or the efficiency with which we use this energy. This is evidenced by a general correlation between the growth trends of global energy consumption (for all major energy source) and GDP (figure A1) [12].

The above year-on-year (YoY) growth rates of oil consumption and real GDP for the US elucidates the relationship between economic growth and oil consumption (figure 2). Four out of the five periods of recessions experienced during this period, about half of the total variations, can be explained by oil consumption [71]. Studies of these recessions by Murphy and Hall and others reveal what appears to be a "common mechanism." During periods of recession, oil prices are apt to be high and consumption tends to be low. Alternately, periods of expansion seem to be accompanied by low oil prices and high energy consumption.

Language, information, and table for Example of Calculations for the Minimum EROIext of Crude Oil is adapted from: Murphy, D.; Hall, C. Energy return on investment, peak oil, and the end of economic growth. *Ann. N.Y. Acad. Sci.* **2011**, 1219 (2011), 52–72. [71]

Appendix B: Example of Calculations for the Minimum EROI_{pou} of Crude Oil

E.g. Refining Losses and Costs:

100 MJ Crude Oil Energy Input
- 10 MJ of Energy Lost in Refining
- 17 MJ of Energy Become Other Products

73 MJ Consumer Ready Fuel

(100 MJ / 73 MJ) = 1.37 MJ
1.37 MJ Input Required for 1 MJ of Output

Oil refineries use approximately 10 percent of the initial energy of oil, in the refining process (to produce fuel in a form that can be used by consumers e.g. gasoline, kerosene), and to generate other intermediary petroleum products (e.g. for use in the production of plastics.) These intermediate petroleum products account for approximately 17 percent of the material in a barrel of crude oil. So for every 100 barrels of crude oil coming into a refinery only approximately 73 barrels leaves as consumer ready fuel. This means that oil resources that have an EROI of 1.1 MJ returned per MJ invested at the wellhead cannot provide an energy profit to society because at least 1.37 MJ (1/0.73) of fuel is required to deliver that one MJ to society.

E.g. Transport Losses and Costs:

Assumptions/Givens:
600 mi = Average distance traveled
0.136 ton/bbl = Average weight of Oil
3.58 MJ/ton-mile = Energy Used in Transport
6.2 GJ/bbl = Energy per barrel of oil

600 miles Traveled
x 0.136 ton/bbl
x 3.58 MJ/ton-mile

292 MJ/bbl Energy Spent on Transportation

(292 MJ / 6,200 MJ) = 4.7%
1.05 MJ Input Required for 1 MJ of Output

Oil weighs roughly 0.136 tons per barrel. Transportation by truck uses about 3.58 MJ per ton-mile. Transportation by fuel pipeline requires 0.52 MJ per ton-mile. We assume that the average distance that oil moves from port or oil field to market is approximately 600 miles. Thus, a barrel of oil, with about 6.2 GJ of contained chemical energy, requires, on average, about 600 miles of travel x 0.136 tons per barrel x 3.58 MJ per ton mile = 292 MJ per barrel to be spent on transport, or about 5% of the total energy content of a barrel of oil to move it to where it is used. If the oil is moved by pipeline, this percentage becomes about 1 percent although trucks are used at the "end point." We assume that these delivery costs, necessary to get the energy to the consumer, would decrease EROI by a conservative 5 percent. In other words, fuels must have an EROI of at least 1.05: 1 to account for delivery of that fuel.

Corresponding Minimum EROI_{pou}

100 MJ Crude Oil Energy Input
- 10 MJ of Energy Lost in Refining
- 17 MJ of Energy Become Other Products
- 5 MJ Transportation Cost

68 MJ Consumer Ready Fuel

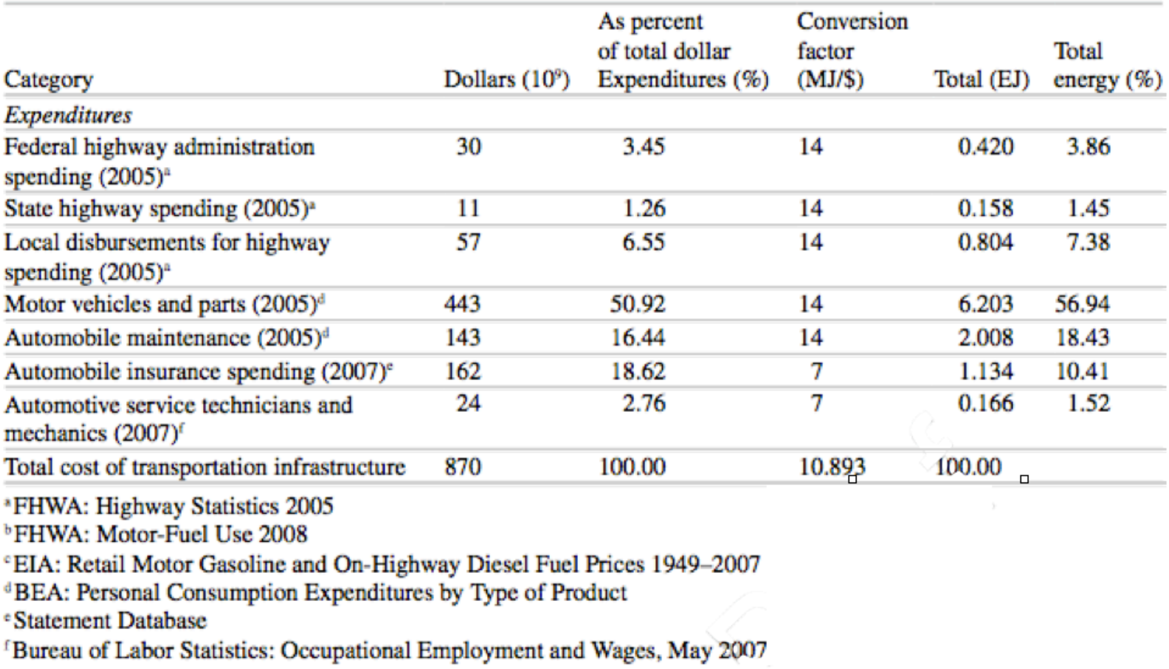
(100 MJ / 68 MJ) = 1.47 MJ
1.47 MJ Input Required for 1 MJ of Output

Thus we find that EROI_{pou} for oil is about 32 percent (17 percent non-fuel loss plus 10 percent to run the refinery plus approximately 5 percent transportation loss) indicating that, at least for oil, one needs a minimum EROI, at the mine mouth, of approximately 1.5 (i.e. 1.0/0.68) in order to get that energy to the point of final use in a usable form.

Language and information for Example of Calculations for the Minimum EROIpou of Crude Oil is adapted from: Hall, C.; Klitgaard, K. Energy and the Wealth of Nations: Understanding the Biophysical Economy; Springer Publishing Company: New York, USA, 2011. [6]

Appendix C: Example of Calculations for the Minimum EROI_{ext} of Crude Oil

Table 1: Estimates of energy and dollar expenditures within the total US transportation Sector



Category	Dollars (10^9)	As percent of total dollar Expenditures (%)	Conversion factor (MJ/$)	Total (EJ)	Total energy (%)
Expenditures					
Federal highway administration spending (2005)[a]	30	3.45	14	0.420	3.86
State highway spending (2005)[a]	11	1.26	14	0.158	1.45
Local disbursements for highway spending (2005)[a]	57	6.55	14	0.804	7.38
Motor vehicles and parts (2005)[d]	443	50.92	14	6.203	56.94
Automobile maintenance (2005)[d]	143	16.44	14	2.008	18.43
Automobile insurance spending (2007)[e]	162	18.62	7	1.134	10.41
Automotive service technicians and mechanics (2007)[f]	24	2.76	7	0.166	1.52
Total cost of transportation infrastructure	870	100.00	10.893	100.00	

[a] FHWA: Highway Statistics 2005

[b] FHWA: Motor-Fuel Use 2008

[c] EIA: Retail Motor Gasoline and On-Highway Diesel Fuel Prices 1949–2007

[d] BEA: Personal Consumption Expenditures by Type of Product

[e] Statement Database

[f] Bureau of Labor Statistics: Occupational Employment and Wages, May 2007

E.g. Refining/Transport/Infrastructure

100 MJ Crude Oil Energy Input
- 32 MJ of Energy Lost in Refining/Transport
- 37.5 MJ of Energy Cost of Infrastructure

30.5 MJ Consumer Ready Fuel

(100 MJ / 30.5 MJ) = 3.3 MJ
3.3 MJ Input Required for 1MJ of Output

We next combine the energy costs of getting the fuel to the consumer in a usable form with the energy cost of the infrastructure necessary to use the fuel. This results in a total cost of approximately 70 percent of the original energy to be able to use it in a truck. Thus, the EROI_{mm} necessary to provide consumer's transportation fuel from crude oil is approximately 3.3 to 1 (1/0.305). In other words, in order to deliver the transportation services associated with one barrel of fuel to the consumer requires more than three barrels produced at the wellhead (this ratio is probably similar for other types of fuels.) Thus, the minimum EROI_{mm} required for a consumer to drive a vehicle would be at least 3:1. To extrapolate further, if we were to replace worn out workers as well as the worn out truck then a much higher EROI_{mm} would be required to support households, health care, education and so on. When various factors of society are added to this list, it becomes clear that fuels with a very positive, not bare positive, EROI values are necessary for economic stability and growth of a modern civilization.

Language, information, and table for Example of Calculations for the Minimum EROIext of Crude Oil is adapted from: Hall, C.; Klitgaard, K. Energy and the Wealth of Nations: Understanding the Biophysical Economy; Springer Publishing Company: New York, USA, 2011. [6]

Appendix D: The Role of Energy Quality and its Effect on Price and GDP

EROI analysis do not include the context in which a fuel is used (e.g. Is it used in transportation or in manufacturing efforts), the state of technology, or other socio-political, economic and environmental factors [58]. This is reflected in different price per energy values for various fuels.

For example, the energy density and utility of oil tends to be greater than that of coal and the price per energy value is typically far higher for oil than for coal. This suggests that from the point of view of the consumer, a MJ of coal is not perfectly substitutable for a MJ of oil. In this example, oil is assigned greater financial value because of its versatility, its ability to be converted into various forms of fuel (e.g. gasoline, kerosene), its ready transport ability and its value to society as a high quality energy carrier. Berndt concludes that the variability of market price per energy (heat) content among fuels reflects a multitude of other attributes not represented in energy content analysis.

E/GDP ratios, can be improved by accounting for energy quality [13, 52]. Kaufmann's econometric analyses of international comparisons of E/GDP demonstrate the importance of including energy quality within such analyses. When energy use is corrected for energy quality (energy use is corrected for with its relative price) then there is a strong connection between energy use and GDP. Analyses of United States, Japan, the UK and France demonstrated that energy quality explains much of the variation in the E/GDP ratio [52]. Declines in the E/GDP ratio are associated with the general shift from coal to oil, gas, and primary electricity. Also important are fuel prices, the structure of economies, and household purchases of energy.

Appendix E: The Use of Currency in EROI Assessments

While it may be desirable to measure energy use directly, this is often not possible because governments and businesses, in their concern for the bottom line, typically focus on economic information rather than energy use in physical units. Monetary expense, however, is generally closely related to energy use (except for the initial purchase of energy), as shown in a number of papers from the Energy Research Group at the University of Illinois (205). This group examined, in great detail, the energy costs of various economic activities and the "interdependency" of sectors of the US economy (how much each sector purchased from other sectors) sometimes referred to as a "Leontief input-output (I-O) analysis." The similarity in energy use per dollar is especially the case for "final demand", that is for the goods and services purchased as actual products rather than intermediate materials. Final demand items, such as a house or an automobile or even an oil well, will include energy-intensive-per-dollar raw materials such as cement and steel, as well as less energy-intensive business services.

Thus when undertaking an EROI analysis (in this case direct and indirect costs) one is usually presented with direct energy use, in physical units, for entire industry sectors such as oil and gas or coal, and financial estimates for equipment purchases. The direct energy used is typically roughly half of the dollars spent for a project [71]. The energy associated with producing indirect inputs is rarely provided in energy units. It is usually calculated by multiplying the money spent for an input multiplied by the energy used per dollar of economic production. Dividing the energy used per economic output for a given industry provides an explicit estimate for energy intensity or economic cost.

A minimum estimate for energy projects is the national mean energy used per dollar of economic production. This is derived by dividing a nation's or region's energy use by that entities' GDP. This was, for example, about 8.3MJ/dollar for the US in 2005 [12]. Energy use per dollar tends to decrease over time due to inflation and in some cases increasing efficiency. This is considered a minimal value because energy projects tend to use a greater proportion of heavy industry (vs. e.g. business services) for the production of the goods and services required for the indirect costs. Sometimes an estimate for "engineering products" can be used; an example is the 14 MJ/dollar figure that which was derived for the US in 2005 by two independent sources [12, 71]. An estimate for all direct and indirect energy used per dollar by oil and gas services (i.e. supplying oil field equipment) derived from actual physical data available for the US and for the UK, was 20 MJ/dollar in 2005 [80]. We feel confident that although we do not have as good energy-intensity factors for specific items as we had in the 1970s from the University of Illinois' work, we do have a best estimate (14 MJ/dollar) and a range of possible values (8.3 to 20 MJ per 2005 dollar) that can be used for any energy assessment [6].

Since the direct values, which usually constitute about half of the expenditures, are often well known, or at least derived from nominally explicit and accurate national data, and the indirect values have a possible range of a factor of 2.4 (8.3 to 20), one can estimate the uncertainty with having to use monetary values. We show this with an example: assume a energy development project of one million dollars. The direct energy dollar cost is half of that amount, or $500,000, with a direct energy cost of say 10,000 GJ as derived from national statistics for energy projects. The indirect costs of $500,000 would have a best guess energy intensity of $500,000 times 14 MJ/$, or 7000 GJ. The uncertainty for energy intensity would range from 8.3 to 20 MJ per dollar spent, or 4,150 to 10,000 GJ for the indirect energy used by the project. The total uncertainty would be 18,000 with a range from 14,150 to 20,000 MJ, for an uncertainty of 3,000 to 17,000MJ or plus 18 and minus 16 percent. Given other uncertainties, for example in the specificity or applicability of the Federal direct estimates, we might assume that total uncertainty are plus and minus one quarter to one third. While we would like to have a more concrete figures based on an up to date I-O analysis such studies are not currently available. We used another approach in Prieto and Hall (in press) where we used both a very aggregated (total dollar use) and a detailed assessment for the EROI of photovoltaic energy and came up with virtually the same figures [196].