EROI Ratios: Implications for Energy Forecasting and Long-Term Prosperity

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Abstract

This paper describes the concept of energy return on energy invested (EROI), and sets out some of the various approaches to calculating EROI ratios that exist, particularly in terms of boundary conditions. The paper presents a range of current estimates of EROI ratios for conventional oil and gas, and shows that these have generally fallen in recent years. EROI values for non-conventional oil and gas, and for a range of other energy sources, are also presented. These show that with the exception of coal and hydroelectricity, most of these other energy sources have lower EROI ratios than conventional oil and gas, and more so if energy storage is needed to compensate for intermittency of supply. The reasons that EROI data should be incorporated into energy forecasts, and the implication in terms of the EROI required to support modern society, are then briefly explored.

Note: This paper is an extract, with permission, from Chapter 9: Charles A.S. Hall, Energy Return on Investment (EROI) and its Implications for Long-term Prosperity, pp 197-224, of Matthias Ruth (ed.) Handbook of Research Methods and Applications in Environmental Studies, 2015; Edward Elgar Publishing Ltd., Cheltenham, UK and Northampton, MA, USA. website: www.e-elgar.com. This text has been slightly expanded and updated. See the original chapter for additional information on concepts and history of net energy, for methodologies and data sources for calculating EROI values, and on the minimum EROI required by society.

1. Introduction

Energy is usually taught as an independent entity; as something that lives unto itself. In truth it is a component of everything around us that moves and most that does not: the skies, seas, land, all geological, meteorological and hydrological processes, all plants, animals and microbes, all ecosystems, including those human-dominated ecosystems called cities and societies; essentially everything. Consequently, energy is associated with, indeed drives, all that society and its economies do.

Many observers from different disciplines who have thought deeply about the long-term relation of humans and wealth production have concluded that the best general way to think about how different societies evolved over time is from the perspective of surplus energy, sometimes called net energy. These have included the chemists Frederick Soddy and William Ostwald, anthropologist Leslie White, archaeologist and historian Joseph Tainter, sociologist Fred Cottrell, historian John Perlin, systems ecologist Howard T. Odum, economist Nicolas Georgescu-Roegan, and energy scientist Vaclav Smil.

But this fundamental fact seems to have escaped the attention of most economists, who seem impervious to energetic reality despite a century of intelligent criticism. The latter includes that from Georgescu-Roegan (1975), Leontief (1982), Hall et al. (2001) and Piketty (2014). Three of these are distinguished economists, and two Nobel Prize laureates. Instead, economists have continued to consider energy as just another commodity, and the drivers of economic production to be solely capital and labour.

Moreover, it is not just energy that is important, but *cheap energy* (Campbell and Laherrère, 1998; Hall and Klitgaard, 2012), and this is only possible when there is a large surplus of net energy; that energy left after the energy cost of getting the primary energy. This applies whether the source energy is food, wood or fossil fuels. A society must have a net energy surplus for there to be division of labour, creation of specialists and the growth of cities; and a substantially greater surplus for there to be widespread wealth, art, culture and other social amenities.

This ratio of energy gained divided by the energy cost of getting it is measured by energy return on investment (EROI). This ratio reflects the basic physical situation, including depletion and the state of present technology. This ratio also largely drives and explains the critically important energy return on monetary investments, which appears to be driven in large part by the underlying EROI value (King and Hall, 2011).

More generally, economic conditions and their fluctuations tend to reflect, directly or indirectly, variations in a society's access to cheap and abundant energy (Cleveland et al., 1984; Tainter, 1988). Today, fossil fuel resources are among the most important global commodities and are essential for the production and distribution of most of the rest. Fossil fuels supply greater than 75 percent of the total energy consumed by societies, (see EIA data, as discussed in Hall et al., 2009). The prosperity and stability of modern society is thus inextricably linked to the production and consumption of energy, especially that of oil (Odum, 1973; Hall et al., 1986; Hall and Klitgaard, 2012; Tverberg, 2012; Lambert et al., 2014).

2. Energy Return on Investment (EROI)

The energy return on investment (EROI) is simply the energy gain from an energy-acquiring process. It is expressed as the ratio of the energy produced divided by the energy (or occasionally monetary or other) investment for that return, where numerator and denominator are in the same units. There are a number of potential benefits that proper EROI analysis can provide:

1. Much like economic cost–benefit analysis, EROI analysis can provide a numerical output that can be compared easily with other similar calculations. For example, the EROI of oil (and hence gasoline) is currently between about 10:1 and 20:1, whereas that for corn-based ethanol is below 2:1, and perhaps below 1:1 (for example, Farrell et al. 2006; Murphy et al. 2011a). From this perspective it is easy to see that substituting ethanol for gasoline would have significant energy, economic and environmental implications, since the same energy investment into gasoline yields at least a fivefold greater energy return (with a correspondingly lower impact per unit delivered to society) than that from ethanol. Thus good EROI analysis can save us from investing large amounts of our remaining fossil fuels into alternative fuels that contribute little or nothing

to our financial or energy well-being, as appears to have been the case with corn-based ethanol, and is likely to be the case with some other energy alternatives currently being considered.

2. The EROI ratio is a useful measure of resource quality. Here quality is defined as the ability of a heat unit to generate economic output (Hall et al., 1986). High EROI resources are considered to be, ceteris paribus, more useful than resources with low EROIs. If an EROI ratio declines over time then more of society's total economic activity goes just to get the energy to run the rest of the economy, and less useful economic work (that is, producing desirable goods and services) is done.

3. Energy return on investment, and especially its rate of change, offers the possibility of looking into the future in a way that markets seem unable to do. Advocates of EROI analysis suggest that in time market prices must approximately reflect comprehensive EROIs, at least if appropriate corrections for quality are made, and energy subsidies are removed (King and Hall, 2011).

4. Using EROI measurements in conjunction with standardised measures of the magnitude of energy resources provides additional insight about the total net energy gains from a potential energy resource. For example, the oil sands of Canada present a vast resource base, roughly 170 billion barrels of recoverable crude oil, yet the EROI of this resource is presently about 4:1 on average at the mine mouth, indicating that only 80 percent of the 170 billion barrels of recoverable oil, or 136 billion net barrels, will be available to society (that is, energy remaining after accounting for the extraction cost (see, for example, Poisson and Hall, 2013); and considerably less after the additional processing and transport costs are accounted for.

5. Time-series datasets of EROI measurements for a particular resource provide insights as to how the quality of a resource base is changing over time. For example, the EROI of US and presumably global oil production generally increased during the first half of the twentieth century and has declined since (see Gagnon et al. 2009; Guilford et al., 2011). The decrease in EROI indicates that the quality of the resource base is also declining, that is, either the investment energy used in extraction has increased without a

commensurate increase in energy output, or the energy gains from extraction have decreased.

Energy return on investment can tell us a great deal about the relative desirability of various possible energy paths into the future, and should be analysed routinely. In addition, it is important to consider the present and future potential magnitude of the fuel, how the EROI is changing over time, and how this might change if the use of a fuel is expanded. Nevertheless, the EROI by itself is not necessarily a sufficient criterion by which policy judgments should be made.

3. Economic cost of energy

To understand EROI more fully we start with the more familiar monetary assessment, and then develop how this relates to the energy behind economic processes. In real economies, energy comes from many sources – from imported and domestic sources of oil, coal and natural gas, as well as hydropower and nuclear, and from a little renewable energy – most of that as firewood but increasingly from wind and photovoltaics. Some of these are cheaper per unit energy delivered than oil and some are considerably more expensive. So let us look at what this real ratio of the cost of energy (from all sources, weighed by their importance) is relative to its benefits. We may think of this as the investment cost necessary to make gross domestic product (GDP):

Monetary return on investment

= GDP / (Dollars to get the energy required for that GDP)
Eqn. 1

By this token the relation of the proportional energy cost in dollars is similar, as we shall see, to the proportional energy cost in joules; in 2007 roughly 9 percent (1 trillion dollars) of the US GDP was spent by final demand for all kinds of energy in the US economy to produce the 12 trillion dollars' worth of total GDP, and hence the monetary return on investment was about 12:1.

Energy return on investment (EROI, or sometimes EROEI with the second E used to refer to the use of energy in the denominator) is similarly the ratio of energy returned to society (i.e. not including the investment energy) from an energy-gathering activity compared to the energy invested in that process. Energy return on investment is calculated from the following simple equation, although the devil is in the details:

EROI = (Energy returned to society) / (Energy required to get that energy) Eqn. 2

Since the numerator and denominator are usually assessed in the same units (an exception is treated later is when quality corrections are made) the ratio so derived is dimensionless, for example, 30:1 which can be expressed as '30 to one'. This implies that a particular process yields 30 joules on an investment of 1 joule (or kcal per kcal, or barrels per barrel). Energy return on investment is usually applied at the mine-mouth, wellhead, farm gate, and so on, that is, at the point that the energy leaves the production facility. We call this more explicitly $EROI_{mm}$. (Note that energy return on investment is not to be confused with conversion efficiency, that is, the efficiency of a process when converting one form of energy to another, such as upgrading petroleum in a refinery, or converting the energy in diesel fuel to electricity.)

4. Types of EROI and the Effect of Boundaries and Data Sources

There are a number of dimensions along which a system boundary may vary. One dimension runs 'parallel' to the energy process chain from extraction ('mine-mouth') to intermediate processing ('refinery gate') to distribution (final demand) and determines the numerator in the EROI ratio, in answer to the question: 'What do we count as energy outputs?' This dimension is depicted with the three system boundaries in Figure 1.

A second 'perpendicular' dimension over which the system boundary may vary is to include a greater variety of direct and indirect energy and material inputs which determine the comprehensiveness of the denominator of the EROI ratio, in answer to the question: 'What do we count as inputs?' Level 1 includes only those 'on site' inputs from the energy chain under investigation, level 2 incorporates energy inputs used off site required to make physical infrastructure (such as steel used on site), levels 3 and 4 incorporate energy embodied in supporting labour and economic services.

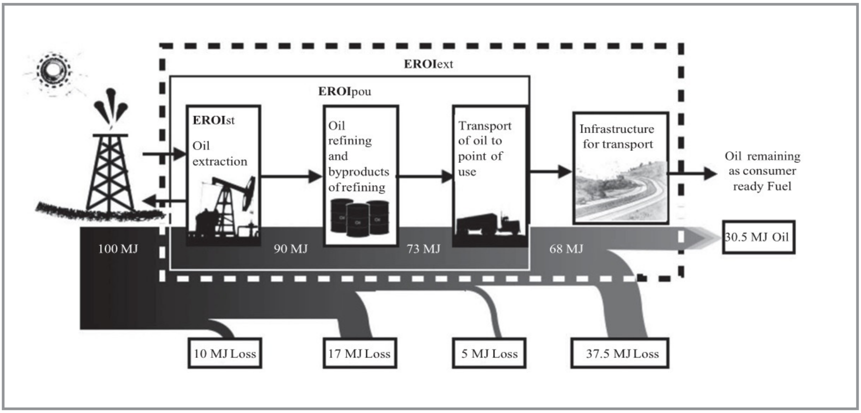

Figure 1. Boundaries of various types of EROI analyses and energy loss associated with the processing of oil as it is transformed from 'oil at the well-head' to consumer ready fuels. Source: Lambert and Lambert (in preparation) based on calculations by Hall et al. (2009).

Much of the recent EROI literature tends to focus on the net or surplus for a given project, industry, nation, fuel, or resource, for example discussions on the 'energy break even' point of EROI for corn based ethanol, that is, whether the EROI is greater or less than 1:1. The apparently different results from this relatively straightforward analysis generated some controversy about the utility of EROI. But, the variation in these findings is mostly the result of the choice of inclusion or exclusion of various direct and indirect energy costs associated with energy production/extraction: that is, the boundaries of the denominator (Hall et al. 2011). The investigator should be explicit in what is included and why.

Any method of calculating EROI must have two, somewhat contradictory, attributes; consistency and flexibility. The methodology must be consistent so that researchers can replicate calculations accurately, yet flexible so that meaningful comparisons can be made across disparate energy extraction or conversion pathways or to accommodate differing objectives or philosophies. Thus we need to ascertain a straightforward and universally accepted approach to EROI even while accommodating different approaches or philosophies.

Hall et al. (2008), and especially Murphy et al. (2011b), gave specific subscripts to EROI in an attempt to standardize the boundaries used at different points in the 'food chain' of energy from well head (and so on) to final consumption and/or by using different degrees of comprehensiveness of inputs. Of greatest concern are the boundaries of the analysis: should co-products (such as hulls left from generating biodiesel from sunflower seeds that can be fed to animals, reducing energy needed to make the animal feed) be included, or should we include the costs of the energy to support a labourer's pay check? Since there are no clear and unambiguous answers to those questions, Murphy et al. advocated a basic EROI approach using simple standardized energy output divided by the direct (that is, on site) plus indirect (that is, energy used to make the steel used on site) to generate a standard EROI, EROIstnd. Thus Murphy et al. also advocate the use of additional EROIs, including new approaches that allow for special consideration of other aspects of that EROI.

$$EROI_{stnd} = \text{(Energy returned to society)} / \text{(Direct and indirect energy required to get that energy)} \quad \text{Eqn. 3}$$

The standard EROI ($EROI_{stnd}$) divides the energy output for a project, region or country at the wellhead, farm gate, and so on by the sum of the direct (that is, on site) and indirect (that is, offsite energy needed to make the products used on site, such as steel, machinery and so on) energy used to generate that output (that is, level 2 above). It does not include, for example, the energy associated with supporting labour, financial services and the like.

This EROI calculation is applied to fuel at the point where it leaves the extraction or production facility (well-head, mine mouth, farm gate, and so on). It is the approach most generally used. Prieto and Hall (2012) see this as a departure point for comprehensiveness of assessing energy costs. This standard but flexible approach allows for the comparison of different fuels even when the analysts do not agree on the rest of the methodology that should be used (Murphy et al. 2011a). Murphy et al. recommend always using $EROI_{stnd}$, and hence enabling comparison, but also using any other approach the authors may wish.

Other classes of EROI sometimes considered are: 'Point of Use'

EROI, 'Extended' EROI, and 'Societal' EROI. See the original chapter from which this paper is drawn for the definitions of these. There are also similar formulae for deriving or expressing net energy used by other authors. Three variants are the 'Fossil Energy Ratio' (FER), often used in the discourse on biofuels, which compares the total energy gains from fossil fuel investment only; 'External Energy Ratio' (EER) which excludes *in situ* energy such as the bitumen used for *in situ* tar sands extraction, and net energy yield ratio (NEYR) which has as the numerator the net energy from the energy production process and all of the inputs necessary to produce that net flow as the denominator (Brandt and Dale, 2011). The absolute energy ratio (AER) also includes in the denominator the energy content of the energy resource, from the natural environment, which is being processed. At this time EROI is most commonly used.

5. Exemplar Results: EROI of Petroleum Oil and Gas

Most industry data is maintained in dollars, not energy, so there are relatively few places where it is possible to undertake energy-based EROI analysis. Fortunately, some countries (the US, Canada, the UK, Norway and China) maintain reasonably good data files and it is possible to use these direct energy inputs, plus make some inferences on the indirect energy used to make equipment. The most useful data are those for which one can derive an EROI time series.

The EROI for petroleum production appears to be declining over time for every place we have data, which is consistent with, and probably causes, the general increase in monetary costs for finding and exploiting oil and gas. Gagnon et al. (2009) were 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 and industry-specific energy intensities. These results indicate that the EROI for publicly traded global oil and gas was approximately 23:1 in 1992, 33:1 in 1999 and 18:1 in 2005 (Figure 2). This 'dome shaped' pattern seems to occur wherever there is a long enough dataset, perhaps as a result of initial technical improvements being trumped in time by depletion.

Their analysis found that EROI had declined by nearly 50 percent in the past decade and a half after an earlier increase. New technology and production methods (initially, seismology, geophysics and enhanced recovery using, for example, water flooding, and later, deep water exploitation and horizontal drilling) are maintaining production but appear insufficient to counter depletion of conventional oil.

There are three independent estimates of EROI time series for oil and gas production for the US. These are plotted along with some important oil-related historical events in Figure 3 (Cleveland et al. 1984; Hall et al. 1986, Guilford et al. 2011).

The data show a general pattern of an increase and then a decline in EROI over time except as impacted by changes in exploration (drilling) intensity. During the mid-1970s to 1980s and late 2000s, the price of oil increased as did exploration intensity, as measured by increased feet drilled and energy used. Energy return on investment values tend to decline both over time (in mature industries) and when there is an increase in the energy used for exploration and drilling when oil prices ae high. However, increased drilling usually was linked to little or no additional oil discoveries; hence EROI values declined. At this time there is insufficient information to determine how the new technologies of horizontal drilling and fracking will affect these patterns.

Two independent EROI estimates for Canadian production of oil exist (Figure 4). Poisson and Hall (2013) found that the EROI of conventional oil and gas has decreased since the mid-1990s from

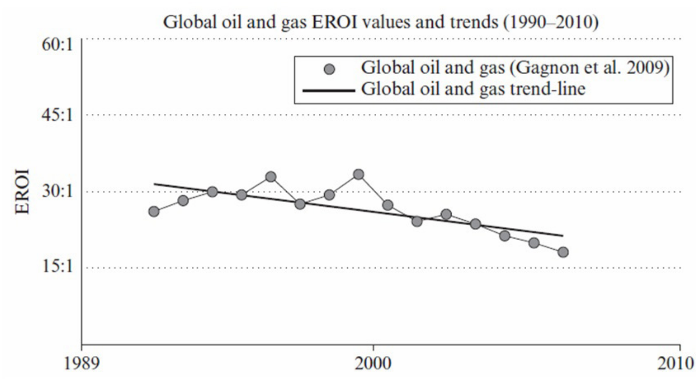

Figure 2. EROI for global publicly traded oil and gas. Source: Gagnon et al. (2009).

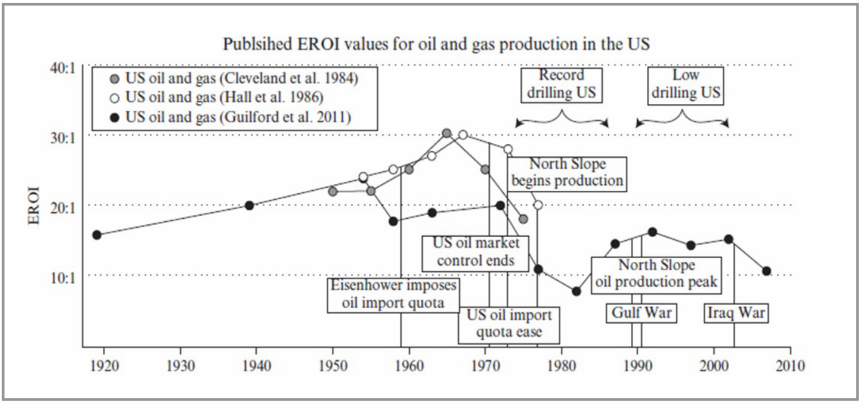

Figure 3. Time series analyses of oil and gas production within the US including several relevant 'oil related' historical events.
Source: Cleveland et al. (1984); Hall et al. (1986); Guilford et al. (2011).

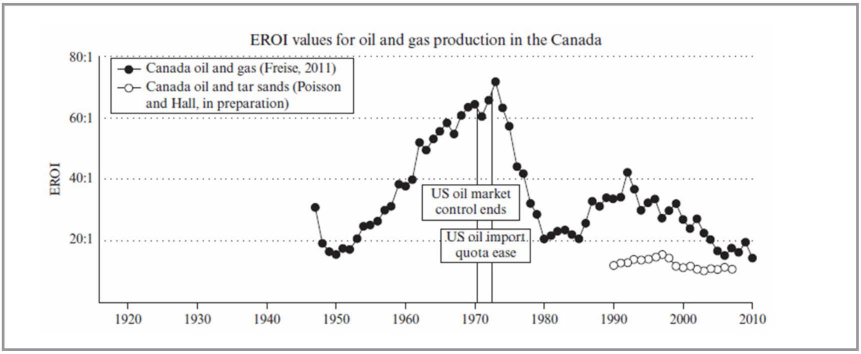

Figure 4. Two independent estimates of EROI for Canadian petroleum production: oil and gas (top line, from Freise 2011) and oil, gas and tar sands combined (bottom line, from Poisson and Hall, 2013). Source: Freise (2011); Poisson and Hall (2013).

roughly 20:1 to 12:1, a 40 percent decline. The EROI of conventional combined oil-gas-tar sands has also decreased during this same period from 14:1 to 7.5:1, a decline of 46 percent (Figure 5) (Poisson and Hall 2013). Poisson and Hall's estimated EROI values for Canadian oil and gas are about half those calculated by Freise and their rate of decline is less. Freise (personal communication) thinks that Poisson and Hall's values are more accurate.

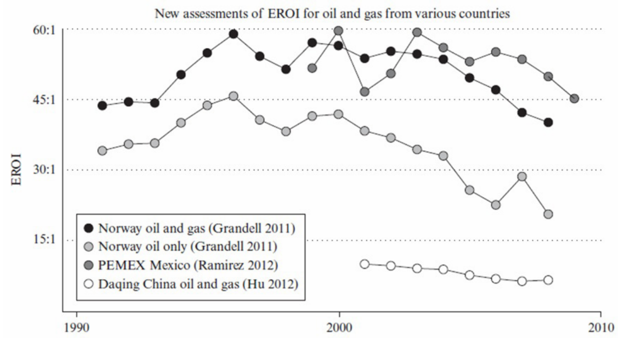

Figure 5. Time series data on EROI for oil and gas for Norway, Mexico and the Daqing oil field in China. Source: based on Hall and Hansen (2012) and Lambert et al. (2013).

Poisson and Hall's estimate of the EROI of tar sands is relatively low, around 4.5 (even though using a conservative, that is, low, estimate of costs at the front end of the life cycle); incorporating tar sands into total oil and gas estimates decreases the EROI of the oil and gas extraction industry as a whole. These estimates would be lower if more elements of the full life cycle (for example, environmental impact) were included in the calculation. On the other hand the energy inputs come from the resource itself, so it is possible.

Norwegian conventional 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 ranged from 44:1 (during the early 1990s) to 59:1 (1996), to approximately 40:1 (during the latter half of the last decade), again showing dome shaped pattern (Figure 5). Norwegian production, and presumably EROI, has continued on a strong downward trend through 2013.

Ramirez's preliminary oil and gas EROI trends for Mexico suggests that this country may have peaked twice in the past decade. The EROI for conventional oil and gas production in Mexico declined from roughly 60:1 in 2000 to 47:1 the following year, but returned to 59:1 by about 2003 (Figure 5). This was followed by a steady decline over the following six years reaching 45:1 by 2009. The collapse of production from the Cantarell field, once the world second largest, appears largely responsible for this decline.

The EROI for the Daqing field, China's largest conventional oil field, has declined continuously from 10:1 in 2001 to 6:1 in 2009 (Figure 5) (Hu et al. 2013).

The data represented in Figure 6 includes analyses for a portion of the US and for all of Canada. Since most published numbers combine data on natural gas with that of oil, it is usually, difficult or impossible to assess the production costs of these fossil fuel resources independently.

Sell et al.'s (2011) trends for EROI of natural gas trends for Pennsylvania (US) has an undulating decline; from roughly 120:1 in 1986 to 67:1 in 2003. This value is probably a high value as some indirect costs were not included. Freise (2011) estimated the EROI of western Canadian natural gas from 1993 to 2009 and found that the EROI of natural gas has been decreasing since 1993 through 2006, from roughly 38:1 to 14:1. This trend shifted in 2006 resulting in a steady increase and an EROI of roughly 20:1 by 2009 (Figure 6) (Freise 2011).

There are two published studies on the EROI of fracked natural gas for the Marcellus formation in Pennsylvania: Aucott and Mellilo (2013) and Hiroaki and Matsushima (2014). Both papers give high values (~60:1) for gas at the well head but much lower (about 12:1) after compression and pipeline shipping, so that the value for both is about 12:1 by the time the consumer gets it (Aucott, personal communication). Both papers also emphasize that these values are from 'sweet spots' and that future values are likely to be lower (Figure 6).

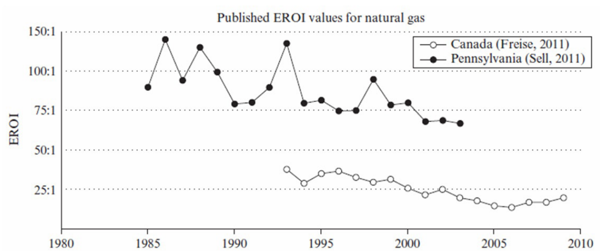

Figure 6. Two published studies on the EROI of dry natural gas (not associated with oil): Sell et al. (2011) examined tight natural gas deposits in western Pennsylvania in the US, and Freise (2011) analysed all convention natural gas wells in western Canada. Source: Freise (2011); Sell et al. (2011).

6. EROI of Other Fuels and Energy Sources

The other important fossil fuel, coal, has a relatively high EROI value and shows no clear trend over time. Coal has a mean EROI of about 46:1 based on 72 studies from 17 publications (Lambert et al. 2013). The energy content of coal has been decreasing even though the total tonnage has continued to increase (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 – at least until recently. The maximum energy (versus tonnage) from US coal seems to have occurred in 1998 (Hall et al. 2009; Murphy and Hall 2010). The only time series EROI analyses for coal production are from the US and China because information on the energy expended to extract coal in other areas of the world appear unavailable. Time series of EROI for coal production for the US and China are given in Figure 7. A great variability in EROI is evident from these figures. This data, however, has significant holes (for example, no data is reported for approximately 30 years, from the mid-1950s to the mid-1980s). Cleveland's work provides additional information for three non-contiguous years that is inconsistent with Balogh et al.'s (2012) findings. Hu et al. (2013) establishes annual data for Chinese coal production for the years 1994 through 2009. These show very little variation in EROI values (Figure 7).

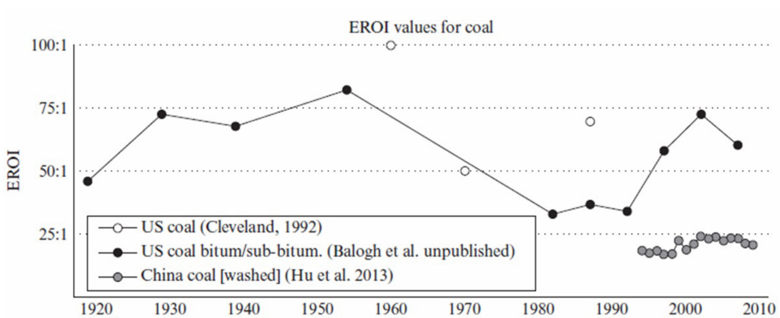

Figure 7. EROI for US and Chinese coal production. Source: derived from Cleveland (1992); Balogh et al. (2012); Hu et al. (2013).

Meta-analysis of EROI values for nuclear energy suggest a mean EROI of about 14:1 (Lambert et al. 2013; see also Lenzen 2008) (Figure 9). Newer analyses need to be made as these values may not adequately reflect current technology or ore grades. Whether to correct the output for its relatively high-quality electricity is an unresolved issue and a quality correction for electricity appears to contribute to those relatively high values given here.

Hydroelectric power generation systems have the highest mean EROI value, 84:1 of electric power generation systems (Lambert et al. 2013). The EROI of hydropower is extremely variable based on the wide variability of dam sites, although the best sites in the developed world were constructed long ago (Hall et al. 1986).

We calculated the mean EROI value for ethanol from various biomass and data sources. The variability is extreme: for example, an EROI of 0.64:1 (Pimental and Patzek 2005) for ethanol produced from cellulose from wood, versus an EROI of 48:1 for ethanol from molasses in India (Von Blottnitz and Curran 2007). These values resulted in a mean EROI value of roughly 5:1 (Lambert et al. 2013). Diesel from biomass seems to be about 2:1 (Hall et al. 2013). We believe that EROI values at or below the 3:1 minimum extended EROI value are minimally useful to society (Hall et al 2008; Murphy et al. 2011b; see Section 9).

Wind power has a relatively high EROI value, with the mean perhaps as high as 18–20:1 (Kubiszewski et al. 2010; Lambert et al. 2013). However these values would presumably be much less if the energy cost of providing energy backups were included, as the wind does not blow all the time. With a wind capacity factor of typically only about 30 percent, systems - depending on load - can need up to twice as much energy from backup generation (or storage) as that generated by the wind.

An examination of the EROI literature on solar photovoltaic (PV) energy generation is effected by inconsistencies and ambiguities in the assumptions and methodologies employed, and in the type of EROI values calculated. These differ from study to study, making comparisons of EROI values between PV and other energy sources difficult and fraught with potential pitfalls unless extreme care is taken to ensure consistency. Nevertheless, we calculated a mean EROI value of roughly 10:1 from 45 publications (Hall et al. 2013).

It should be noted that several recent studies that have broader - but more appropriate, we feel - boundaries give lower EROI values of 2 to 3:1 (Prieto and Hall 2012; Palmer 2013; Weissbach et al. 2013), although these may already be out of date. All solar EROIs would be higher if weighed for the quality of the electricity and lower, probably much lower, if necessary backups for intermittency of the input were included. To this author's knowledge the latter has not been done except by Palmer (2013).

Geothermal electricity production has a mean EROI of approximately 9:1 (Atlason and Unnthorsson 2013, 2014). While geothermal is in principle renewable, good sites are rare and some (for example, geysers in California) are showing signs of depletion of heat. Ground heating of homes has an EROI of roughly 4:1 although the input is electricity and the output lower-quality heat, perhaps resulting in an approximate wash.

7. Summary of EROIs

Energy return on investment values for our most important fuels, liquid and gaseous petroleum and coal, tend to be relatively high.

World oil and gas has a mean EROI of about 20:1. That for publicly traded companies has declined from 30:1 in 1995 to about 18:1 in 2006. The EROI for discovering oil and gas 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. Alternatives to traditional fossil fuels such as tar sands and oil shale deliver a lower EROI, having a mean EROI of 4:1 and 7:1, respectively. It is difficult to establish EROI values for natural gas alone as data on natural gas are usually aggregated in oil and gas statistics. Fracked oil and gas appear to be in the vicinity of conventional US oil and gas, although that may change as the 'sweet spots' are depleted (Figure 8).

A positive aspect of most renewable energies is that the output of these fuels is high-quality electricity. A potential drawback it that the output is far less reliable and predictable. Energy return on investment values for PV and other renewable alternatives are generally computed without converting the electricity generated into its 'primary energy-equivalent' (Kubiszewski et al. 2010) but also without including any of the considerable cost associated with the required energy backups or storage.

Energy return on investment calculations of renewable energy technology appear to reflect some disagreement on the role of technological improvement. Raugei et al. (2012) attribute low EROI values sometimes calculated for PVs 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. Other researchers contend that values derived using this methodology do not represent adequately the 'actual' energy cost to society and the myriad energy costs associated with this delivery process. For example Prieto and Hall (2012; also Palmer 2013) calculated EROI values that incorporate most energy costs, with the assumption that where ever money was spent energy too was spent. They use data from existing installations in Spain, and derived EROI values of roughly 2.4:1, considerably lower than many less comprehensive estimates. (Note also that some recent data suggest that many PV structures are lasting considerably less than the 25 years assumed by Prieto and Hall.) Nearly all renewable energy systems appear to have relatively low EROI values when compared with conventional fossil fuels, especially if needed energy backups are included (Figure 9).

A question remains as to the degree to which total energy costs can be reduced into the future if there is a large programme to reduce the use of most fossil fuels, for - as it stands - most 'renewable' energy systems appear to be still heavily supported by fossil fuels. Nevertheless they may be more efficient at turning fossil fuels into electricity than are thermal power plants, although over much more time (Prieto and Hall, 2012).

8. Use of EROI Data in Energy Forecasting

If humankind is to properly understand its energy future, then EROI data such as those presented here must be incorporated into all energy forecast models, as for example is the case with Campbell's latest oil and gas model (Campbell, 2015).

However, as explained above, due account must be taken of the purpose for which any given EROI ratio is used. For example, if forecasting future energy available from extensive use of retorted

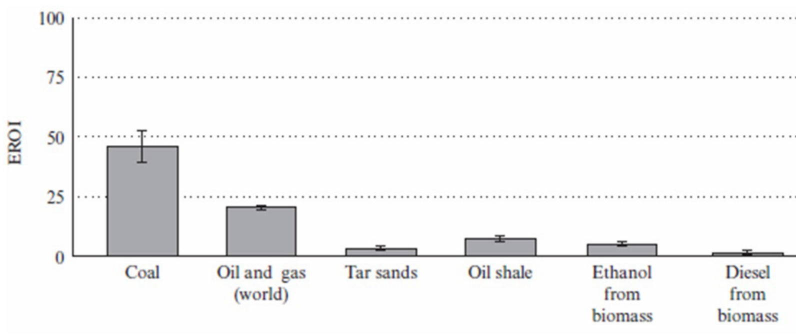

Figure 8. Mean EROI (and standard error bars) values for thermal fuels based on known published values. Source: Values derived using known modern and historical published EROI and energy analysis assessments and values published by Dale (2010).

Note: For this Figure, and Figure 9 below, see Lambert et al. (2013) for a detailed list of references; and see that paper also for discussion, as the values given here should not be taken strictly at face value.

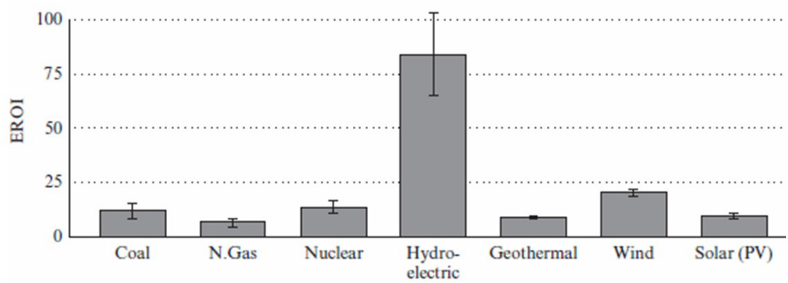

Figure 9. Mean EROI (and standard error) values for known published assessments of electric power generation systems.

kerogen from shale rock, then to understand the net energy available for productive use there may be no need to include in the denominator of the EROI ratio used that thermal energy provided on-site by combustion of the kerogen (although getting that kerogen can be energetically and monetarily expensive). However, if considering the CO_2 implications, then the burning of this kerogen does need to be considered.

To illustrate the importance of EROI ratios in energy modelling, consider the case of modelling the energy produced by photovoltaic (PV) systems.

Quite a number of recent well-respected global energy models have examined humankind's ability to meet all its energy needs from renewable sources, and where in most of these studies significant expansion of PV is often seen as one of the solutions. However, such an analysis faces a significant flaw, at least in the short and medium term. While there is discussion over what is the most likely value of EROI for PV (see above), even if we take a fairly high-end value of the EROI of a fully-installed large-scale PV system, of say, 7:1, then using EROI ratios paints a surprisingly gloomy picture of what might be achieved in the near or medium term.

The owner of a single PV plant having a life of, say, 28 years, at an EROI ratio of 7:1 has a good energy return; 'paying' for the system's embodied energy in the first four years of operation, and getting net energy back for the remaining twenty-four years. But by contrast, for society as a whole, where the rate of installed PV has been growing rapidly, and still needs to do so to meet a major fraction of total global energy, then it is easy to show that globally the embodied energy in building PV during this growth phase has been negative. In other words, to date the over 200 GWp of global installed PV has contributed *no net energy* to society (see, e.g., Dale and Benson, 2013). Admittedly PV, with its fairly modest EROI ratio, and very high growth rate, is a rather extreme example of this principle, but it reinforces the notion that energy modelling without incorporating EROI ratios can be very misleading.

9. What Level of EROI Does Society Need?

Those who focus on EROI and its decline believe that the concept has enormous implications for society (Jones et al. 2004; Hall et al. 2008; Lambert et al. 2013). At the societal level, declining EROI ratios mean that an increasing proportion of energy output must be diverted to attaining the energy needed to run an economy, leaving less discretionary funds available for 'non-essential' purchases which often drive growth and the better things of civilization.

This in turn leads to the critically important question of the level of EROI that society needs from its fuels to support modern life. This is discussed at greater length in the original chapter from which this paper is taken, and is discussed here briefly.

The real question revolves around what EROI is necessary to run society as we know it. Together with Jessica Lambert, this author developed a 'hierarchy of energetic needs', which represents the importance of the quality of energy (in terms of net energy delivered) devoted to the production and maintenance of infrastructure and activities required to support society. We analyse this using EROI (Hall et al. 2009, Hall and Klitgaard 2012).

If, for example, you lived on an island with one oil well as the only source of energy besides the sun, and the EROI for that oil was 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. 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 et al. (2009) examined the EROI required to run a truck. They found that an EROI of at least 3:1 EROI at the well-head was necessary to build and maintain the truck and the roads and bridges required to use one unit of oil in that truck, including depreciation. In a thought experiment Hall and Lambert 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 a great deal of it, and this requires a high EROI (or, theoretically, a massive source of moderate-EROI fuels). Hall et al. 2008 found from both data analysis and a model that as EROI declines so does discretionary income; in their model to essentially zero by 2050.

It is astonishing, given the enormous size of fossil fuel investments, and the many poorly understood issues relating to their costs, including environmental costs, that we do not have a large national budget to assess EROI comprehensively, including the environmental and other externalities. Meanwhile there is a degradation of the needed statistics by governmental agencies, such as the Bureau of Census (Guilford et al. 2011).

Thus society seems to be caught in a dilemma unlike anything experienced in the last few centuries. During that time most problems (such as needs for more agricultural output, worker pay, transport, pensions, schools and social services) were solved by employing both technology and investment to solve the problems. In many senses this approach worked, for many of the problems were indeed resolved - or at least ameliorated, although at each step populations grew so that new potential issues had to be addressed. But in a general sense, all of this was possible only because there was an abundance of cheap (that is, high-EROI), high-quality energy - mostly oil, gas or electricity - which supported the research and the investments that occurred.

We believe that the future is likely to be very different, for while there remains considerable energy in the ground it is unlikely to be exploitable cheaply, or eventually at all, because of its increasingly low EROI. If any resolution to these problems is possible it is probable that it will have to come at least as much from an adjustment of society’s aspirations for increased material affluence, and an increase in willingness to share, as from technology.

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