Chapter 12
A Framework for Energy Alternatives: Net Energy, Liebig's Law and Multi-criteria Analysis

Nathan John Hagens and Kenneth Mulder

Abstract Standard economic analysis does not accurately account for the physical depletion of a resource due to its reliance on fiat currency as a metric. Net energy analysis, particularly Energy Return on Energy Investment, can measure the biophysical properties of a resources progression over time. There has been sporadic and disparate use of net energy statistics over the past several decades. Some analyses are inclusive in treatment of inputs and outputs while others are very narrow, leading to difficulty of accurate comparisons in policy discussions. This chapter attempts to place these analyses in a common framework that includes both energy and non-energy inputs, environmental externalities, and non-energy co-products. We also assess how Liebig's Law of the minimum may require energy analysts to utilize multi-criteria analysis techniques when energy may not be the sole limiting variable.

Keywords Net energy · EROI · EROEI · liebig's law · ethanol · biophysical economics · oil · natural gas

12.1 Introduction

Human energy use, ostensibly the most important driver underpinning modern society, may soon undergo a major transition of both kind and scale. Though numerous energy technologies are touted as alternative supplies to fossil fuels, scientists and policymakers continue to lack a meaningful and systematic framework able to holistically compare disparate energy harvesting technologies. Net energy analysis attempts to base decisions largely on physical principles, thus looking a step ahead

✉ N.J. Hagens
Gund Institute for Ecological Economics, University of Vermont, 617 Main St., Burlington, VT 05405, USA
e-mail: Nathan.Hagens@uvm.edu

K. Mulder
Green Mountain College, Poultney VT, USA

D. Pimentel (ed.), *Biofuels, Solar and Wind as Renewable Energy Systems*,

of political and/or market based signals distorted by fiat monetary data. The importance of net energy has been overlooked, primarily as a result of confusing and conflicting results in energy literature. In this chapter, we (a) provide an introduction to the history, scale and scope of human energy use (b) reiterate the role of net energy analysis in a world of finite resources, (c) establish a two dimensional net energy framework synthesizing existing literature and (d) illustrate (via the example of corn ethanol) why multi-criteria analysis is important when energy is not the only limiting variable.

12.2 Net Energy Analysis

Energy, along with water and air, completes the trifecta of life's most basic needs. Organisms on the planet have a long history of successfully obtaining and using energy, mostly represented as food. Indeed, some have suggested that the harness of maximum power by both organisms and ecosystems from their environments is so ubiquitous it should be considered the Fourth Law of Thermodynamics (Odum 1995). Cheetahs, to use one example, that repeatedly expend more energy chasing a gazelle than they receive from eating it will not incrementally survive to produce offspring. Each iteration of their hunting is a behavior optimized to gain the most energy (calories in) for the least physical effort (calories out), thus freeing up more energy for growth, maintenance, mating and raising offspring. Over evolutionary time, natural selection has optimized the most efficient methods for energy capture, transformation, and consumption. (Lotka 1922) This concept in optimal foraging analysis extrapolates to the human sphere via *net energy analysis*, which seeks to compare the amount of energy delivered to society by a technology to the total energy required to transform that energy to a socially useful form. Biophysical minded analysts prefer net energy analysis to standard economic analysis when assessing energy options because it incorporates a progression of the physical scarcity of an energy resource, and therefore is more immune to the signals given by market imperfections. Most importantly, because goods and services are produced from the conversion of energy into utility, surplus net energy is a measure of the potential to perform useful work for social/economic systems.

12.3 An Introduction to EROI – Energy Return on Investment

Knowing the importance of energy in our lives, how do we compare different energy options? Unfortunately, the word 'renewable' does not automatically connote 'equality' or 'viability' when considering alternatives to fossil fuels. In assessing possible replacements for fossil fuels, each alternative presents special trade-offs between energy quantity, energy quality, and other inputs and impacts such as land, water, labor, and environmental health (Pimentel et al. 2002, Hill et al. 2006). When faced with these choices, energy policymakers in business and government will require a comprehensive and consistent framework for accurately comparing all aspects of an alternative fuel.

Many criteria have historically been used to assess energy production technologies based on both absolute and relative yields and various costs (Hanegraaf et al. 1998). Many assess economic flows (e.g. Bender 1999, Kaylen 2005) while others focus on energy (e.g. Ulgiati 2001, Kallivroussis et al. 2002, Cleveland 2005, Farrell et al. 2006) or emissions (e.g. EPA 2002). With the recent acceptance of global climate change as a problem, energy analyses favoring low greenhouse gas emissions are becoming more frequent (Kim and Dale 2005, Chui et al. 2006). Though not yet widely accepted by market metrics, some other analyses have attempted to include environmental and social inputs as well as energy costs. (e.g. Giampietro et al. 1997, Hanegraaf et al. 1998, Pimental and Patzek 2005, Reijnders 2006).

The objective of an energy technology is to procure energy. A common measure combining the strength/quality of the resource with its procurement costs is the ratio of energy produced to energy consumed for a specific technology/source. This concept has many labels in energy literature including the energy profit ratio (Hall et al. 1986), net energy (Odum 1973), energy gain (Tainter 2003), and energy payback (Keoleian 1998). In this chapter, we focus on Energy Return on Investment (EROI) (Hall et al. 1986, Cleveland 1992, Gingerich and Hendrickson 1993) EROI is a ratio and is equal to 'net energy +1'. Total energy surplus is EROI times the size of the energy investment, minus the investment. We will use the terms energy gain, net energy and EROI interchangeably, throughout this chapter.

12.4 Humans and Energy Gain

Ancestral humans first major energy transformation came from the harnessing of fire, which provided significant changes to daily tribal life by providing light, warmth and eventually the ability to work metals, bake ceramics, and produce tools. (Cleveland 2007). More recently, the energy gain of agriculture further transformed human culture. Though the per unit energy gain of widespread agriculture was actually lower than many hunting and gathering practices, a large amount of previously unused land was brought under cultivation, thus freeing up substantially larger energy surplus for society as a whole. (Smil 1991) This is a first example of how an energy return combines with scale to determine an overall energy gain for society. Much more recently, the development of the steam engine catapulted mankind into the fossil fuel era by leveraging the embodied energy in coal deposits. The high energy gain of coal rippled its way through the economy akin to a deposit in a fractional banking system, and the industrial revolution had its first power source. In the 19th century, modern humans learned to unlock the hydrocarbon bonds in the higher quality fossil fuels of crude oil and natural gas, freeing up orders of magnitude more energy than our evolutionary forbears even dreamed about. The changing size of this subsidy, how to measure it and meaningfully compare it to potential

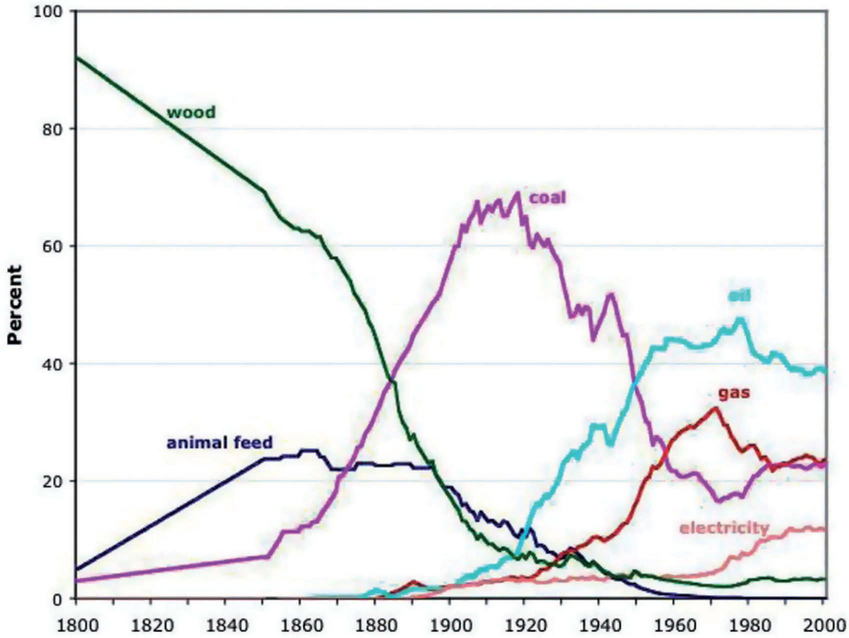

Fig. 12.1 *Composition of US energy by* (Cleveland 2007)

energy substitutes that will be required to power future society is the subject of this chapter (Fig. 12.1).

12.5 Current Energy Gain

The current scale of our energy gain is unprecedented. When coal, oil and natural gas are included, the average American uses 57 barrel of oil equivalents per year (BP 2005). Each barrel of oil contains 6.1178632 × 10ˆ9 Joules of energy. An average man would need to work about 2.5 years to generate this amount of heat work[1]. Multiply it by 57, and the average American uses a fossil fuel subsidy equal to over 150 annual energy slaves. But the quality of oil is also fantastic – liquid at room temperature and highly dense – oil possesses energy quality that human labor cannot.

An important nuance underlying the concept of net energy analysis, is that fossil fuel production is itself cannibalistic, as oil production uses a great deal of natural gas (and some oil) to procure. Coal production, wind turbine creation, solar photovoltaic panels, etc. all require liquid transportation fuels to generate their products

[1] An 'average' worker utilizes 300 calories per hour. At 8 hours per day, 5 days per week and 50 weeks per year this is 600,000 calories per year. (6.1178632 × 10ˆ9 Joule) per barrel / (600,000 Calories × 4,184 joules required work energy per year) = **2.44 years/barrel.**

in a modern economy. In fact, over 90% of world transportation is accomplished using liquid fuels. (Skrebowski 2006).

The scale of remaining recoverable crude oil is a topic under much debate, with many analysts saying we are already past peak production (Deffeyes), and others (IEA, Cambridge Energy Research Associates) saying we will reach a broad plateau by 2030–2040. A large number of analysts believe a peak in oil production will occur sometime in the next decade. However, few if any of these analysts look at how much of future oil and gas production nets down to the societal use phase after the energy costs have been accounted for. Nor is there a distinction made in ‘crude oil’ statistics between actual crude oil, ethanol, coal-to-liquids, etc. all of which not only have disparate energy costs, but different BTU contents as well.

The Hubbert curve of resource extraction is roughly Gaussian in shape, and the energy surplus (or lack thereof) drops down dramatically after its peak (see Hall et al., 1986 for an example on Louisiana). If oil is peaking soon, asking how much is still in the ground is not the most important question. How much can be brought to market at one time? How much energy is left after energy companies use what they require internally to procure the harder to find, deeper, more sulfurous, more environmentally and socially sensitive drilling locations, etc.? These questions ultimately address how much of our remaining fossil resources will be available for non-energy, non-government society.

12.6 An Energy Theory of Value

There is a rich history over many decades of the concept of an energy theory of value, dating back to Howard Scott and the Technocrats who stated that ‘A dollar may be worth – in buying power – so much today and more or less tomorrow, but a unit of heat is the same in 1900, 1929,1933 or 2000’ (Berndt 1983). In the 1970s, Senator Mark Hatfield argued that ‘Energy is the currency around which we should be basing our economic forecasts, not money supply.’ His efforts resulted in the passing of (now defunct) Public Law 93.577 which stipulated that all prospective energy supply technologies considered for commercial application must be assessed and evaluated in terms of their ‘potential for production of net energy’. (Spreng 1988) And in a still broader sense, ecological analysts have long stated that money does not properly account for externalities – ecologist Howard Odum stated ‘Money is inadequate as a measure of value, since much of the valuable work upon which the biosphere depends is done by ecological systems, atmospheric systems, and geologic systems.’

12.7 Why is Net Energy Important?

This ‘work’ Professor Odum alluded to requires an energy surplus. (Odum 1994) In a world where energy is likely to become scarcer, net energy analysis is more forward looking than conventional economic analysis, and as such can be an important tool for policymakers. Net energy is important because we need energy to accomplish work. The surplus energy of a system, or society, is what allows it to continue growth, maintenance, repair and leisure. Energy technologies can be stock or flow based. Stocks are depletable and non-renewable on human time scales. Flow-based resources are renewable, provided the infrastructure that supports them is renewable. There is only so much low entropy energy present in fossil fuel stocks and solar/tidal flows that can be accessed at a meaningfully positive energy return. If society has collectively become dependent on a certain aggregate energy gain system and attempts to replace it with a lower energy gain portfolio, while keeping all other inputs equal, then a larger % of societies resources (labor, capital, land, water, etc) would have to be devoted to energy procurement, leaving less available for hospitals, infrastructure, science, etc.

So in one sense, the Energy Return on Investment is a story of demand, and how a civilization uses their BTU endowments. A doubling in efficiency of use, or a doubling of conservation efforts, are equivalent to a doubling of an energy surplus. *But if efficiency and conservation do not occur, we are left trying to maintain a high gain system from new energy supply as original stocks of resources deplete*. Historian Joseph Tainter has shown, with both examples from the animal kingdom and historical human societies (Rome), that high energy gain systems undergo social upheaval and ultimately collapse if they cannot maintain the energy gain that their infrastructure is built upon (Tainter 2003). The more energy required to harvest, refine and distribute energy to society, (assuming we're at maximum scale), the less will be left over for non-energy sectors. This is especially important in a society that has built its infrastructure around high-energy-return inputs (Smil 1991). Our modern situation, the energy density required for our shopping centers, hospitals, high rises, etc. is orders of magnitude higher than that of biomass and other renewables. (Smil 2006).

12.8 Net Energy and Energy Quality

In a human system, the desirability of a resource derives both from its absolute energy gain as well as from its utility to a unique sociocultural system. (Tainter 2003) Thermal energy quantity is important from a thermodynamic standpoint. However, a human society does not use or value energy based on its heat component alone. Prehistoric man would have viewed a horse as a source of meat, not as an animate converter of cropland or as a riding steed. Similarly, an ancient Yibal tribesman in Saudi Arabia would have little use for the high energy density oil bitumen just under the sands surface, but enormous use for the energy conversion capacity of a healthy horse. Today's shopping centers and hospitals could not be powered by meat calories or horsepower, but require the dense energy concentrated in fossil fuels. Thus, energy quality is a definition dependent on the context of a society.

When Watt was developing his steam engine, the heat value and liquid form of petroleum were of little use, because the new technologies of that day required wood or coal. And, unlike other mammals, humans have evolved to utilize exosomatic energy, and build and expand society around specific inanimate converters, earlier the steam engine and more recently the internal combustion engine. In this fashion, energy 'quality', as defined by an energy sources ability to perform economic or other work valued by society, can and does depart from a straight thermal assessment of the energy. Coal does not make a refrigerator work, and natural gas does not have the density to run a computer printer; these fuels must first be transformed into higher quality energy, at a thermal loss.

When assessing the quality of an alternative energy, the following factors need to be considered: energy power and density, timing, energy quality, environmental and social impacts of energy procurement and use, geographic and spatial scales, volatility, and the potential scale of the resource (energy surplus). We will now briefly discuss this first set of objective energy quality criteria. The majority of the chapter will deal with the penultimate societal energy metric; the scale of the energy surplus, and its EROI.

Energy density refers to the quantity of energy contained per unit mass or volume. The lower energy density of biomass (12–15 MJ/kg) compared to crude oil (42 MJ/kg) means that replacing the latter with the former will require a larger infrastructure (labor, capital, materials, energy) to produce an equivalent quantity of energy. (Cleveland 2007) The energy carrying molecule hydrogen, has very low energy per unit volume, creating many technical hurdles to a 'hydrogen economy', even were cheap abundant hydrogen fuel stocks available.

Due to the enormous amount of geologic energy invested in their formation, fossil fuel deposits are an extraordinarily concentrated source of high-quality energy, commonly extracted with power densities of 100 to 1000 Watts/m^2 for coal or hydrocarbon fields. (Cleveland 2007). This implies that very small land areas are currently used to supply enormous energy flows. In contrast, biomass energy production has densities well below 1 Watt/m^2, while densities of electricity produced by water and wind are commonly below 10 Watt/m^2. In effect, as power dense fossil resources deplete, less power dense energy must be secured from more of the earth's surface to match the gross amount available from the concentrated high-gain sources (Smil 2006).

Bioenergy made from annual crops will also undergo unexpected volatility from periodic droughts or floods, whereas oil production can provide gasoline and its energy services continuously (or at least until a well runs dry). On a shorter time scale, the intermittency (or fraction of time that an energy source is usable to society), is low for wind and solar technologies as neither the sun nor the wind give us energy twenty four hours a day. This is potentially important with modern electricity generation systems that need to combine power generated from multiple sources and locations to supply electricity '24/7.' A derivative concept of intermittency is the dispersion over time of a source. In economics and finance, investors care greatly about the 'shape' of portfolio returns. A portfolio returning 10% consistently is much preferred to an investment that averages 15% but has periodic negative years. In effect, investors preferences are measured by a 'risk adjusted return' which is the mean return divided by the standard deviation. Energy too, has a risk adjusted return, and constantly flowing and storable fossil fuels have built a society that depends on smooth flows of energy services. Going back to ecosystem services to procure energy may have higher standard deviations of energy availability.

All natural resources show distinct geographical gradients. In the case of oil and natural gas more than 60% of known resources are in the Middle East. Just as with stored ancient sunlight, renewable energy from current sunlight (solar, wind, etc.) is geographically diffuse. This implies that significant investments (of dollars and energy) into new infrastructure will be required to concentrate, store and distribute energy over distance in order to procure useful amounts of energy services to human population centers.

Historical human energy transitions occurred when the human population was small, and had technology that was much less powerful than today. Environmental impacts associated with energy occurred locally but did not exhibit the current global impact. But the future of energy and the environment are linked, as there are numerous ecological constraints. Our future energy systems must be designed and deployed with environmental constraints that were absent from the minds of the inventors of the steam engine and internal combustion engines (Cleveland 2007).

12.9 Energy Return on Investment – Towards a Consistent Framework

Though all of the above are important factors in assessing renewable energy technologies, perhaps the most critical metric is the actual size of energy surplus freed up for society. Once an energy output becomes truly scarce – large sums of dollars won't improve its scarcity, and all the dollars in the world wont change (quickly) the demand system and energy infrastructure dependent on its energy gain. High energy gain can arise from using a resource that is of high intrinsic quality but untapped, or from technological development that allows an increase in the net energy of a previously used resource. The energy gain of mining deep coal, for example, increased greatly after Watt's engine was widely used (Wilkinson 1973). Conversely, energy gain can decline from exploiting a resource that can yield only small returns on effort under any technology, or from having depleted the most accessible reserves of a once abundant resource (Tainter 2003).

Energy Return on Investment (EROI) is an oft-confused controversial but important cousin to energy gain. EROI is basically a combined measure of how high of quality/density the original energy source is with the energy cost that the composite of harvesting technologies uses to deliver the energy to the consumptive stage. EROI is strictly a measure of energy and its 'harvesting' costs in energy terms, not the efficiency of its use or it's transformation to another energy vehicle. For example, once coal is procured out of the ground at a particular energy return, the decision, and subsequent efficiency loss to turn it into electricity or Fischer-Tropsch diesel, are both part of the consumption choices of society *after* the primary fuel is obtained.

The efficacy of EROI analysis is limited by one of its basic assumptions—that all forms of energy are fungible with a statistic determined by their thermal content (Cleveland 1992). This ignores the fact that the quality of an energy source can be the key determinant of its usefulness to society. A BTU of electricity is of higher value to society than a BTU of coal, a fact reflected by the price differential between these two energy sources as well as our willingness to convert coal into electricity at a significant energy loss. Some would argue that a technology with a low EROI should be given stronger consideration if the energy outputs have a higher quality than the energy inputs—an argument raised by Farrell et al. (2006) in support of corn ethanol which has the potential to convert coal and corn (low quality) into a liquid fuel (high quality). Cleveland (1992) has proposed a variant of EROI methodology that incorporates energy quality. Quality-adjusted economic analysis can even support sub-unity EROI energy production depending on context.

The EROI concept has been specifically used in only a small percentage of national energy analyses, but is implicit in any study that uses a form of net energy as a criterion. Recently it was used as a synthesizing concept for multiple comparisons of biofuels (Farrell et al. 2006, Hammerschlag 2006). It has been used to examine nuclear energy (Tyner et al. 1988, Kidd 2004), ethanol (Chambers et al. 1979, Pimentel 2003, Hu et al. 2004, Farrell et al. 2006, Hammerschlag 2006), other biofuels (Baines and Peet 1983, Giampietro et al. 1997, Kallivroussis et al. 2002), wood energy (Baltic and Betters 1983, Potter and Betters 1988, Gingerich and Hendrickson 1993), and other alternative energies (Crawford and Treloar 2004, Berglund and Borjesson 2006, Chui et al. 2006). Ongoing analysis continues on the EROI of various fossil fuels (Cleveland 1992, 2005, Hall, 2008).

At first blush, the calculation of EROI as the ratio of energy outputs to inputs seems straightforward. However, the concept has never expanded into common usage (Spreng 1988). Even with a recent resurgence of interest in this topic due to escalating oil prices, there is still not a widely accepted methodology for calculating either the numerator (the energy produced) or the denominator (the energy consumed) in the EROI equation. While attempting to use this important criteria to compare energy technologies, different researchers are using different methods to arrive at widely disparate notional EROI numbers, thereby diluting the policy value of this energy statistic. The ongoing heated debate over the viability of grain ethanol is a relevant example. A recent publication (Farrell et al. 2006) suggests that previous analyses of the EROI of grain ethanol are errant because of outdated data and faulty methodology. The analysis attempted to standardize previous studies and introduce modifications of the EROI methodology including measuring energy produced per unit of *petroleum* energy invested. However, because a standardized well-defined EROI formula does not exist, nor is there wide acceptance on the reasons why net energy analysis is important, the Farrell et al chapter has not ameliorated the polarization of the debate but rather heightened it (Hagens et al., 2006). At the very least, this lack of precision and consensus has negative implications for the utility of EROI analysis, in particular as a tool for decision makers. At the worst, it leaves the methodology open to manipulation by partisans in the debate over a given technology.

Furthermore, emphasis is being placed on whether or how much the energy return of a proposed technology exceeds unity, without addressing the shortfall in energy return of the segment of energy services it is trying to replace. Corn ethanol advocates and proponents spend a huge amount of resources and time honing and refining the corn-ethanol energy balance – whether it's slightly negative or slightly positive seems to be of great policy significance. At 1.5:1, which is at the high end of the latest range, corn ethanol's energy return remains an order of magnitude below the fossil energy it purports to replace (Cleveland 2001). Unless society makes large scale changes on the consumption/efficiency side, it will need to address the variance between its current energy surplus and what can be expected with the combination of lower quality fossil stocks and less energy dense renewable infrastructure in the future. Due to differences in demand, and the geographic dispersion of high energy gain renewables, there may be a variety of answers to this question at the local/regional level and at the national/global level. Since fossil fuels power a global society, global energy gain, a function of EROI times scale for all energy sources, will be of central importance in the coming decades. In the following pages, we review the various usages of EROI in the literature and place them into a consistent schematic framework. This allows comparison of the different methodologies in use by clarifying both their assumptions and their quantitative components. We then synthesize the different methodologies into a two-dimensional classification scheme with terminology for each version of EROI that will hopefully yield consistent and comparable results between studies going forward.

Figure 12.2 is a theoretical aggregate of EROI and scale. D = direct energy costs, C = indirect energy costs, and B = externality costs (converted to energy). The area under the outer curve represents the total gross energy production X = A + B + C + D. A is the leftover 'net energy'. Since the most efficient areas of productions are usually developed first (e.g. best cropland, best wind sites, etc. (Ricardo 1819) the annual energy gain tends to decline while energy costs tend to rise with scale of development. Externalities also tend to increase.

At time T1 in Fig. 12.2, there is no surplus energy (A or B) leftover after direct and indirect energy costs (C and D) have been accounted for, meaning this 'source' X, is now an energy sink. If we also translate environmental externalities into energy terms (B), we then are faced with an energy sink shortly after time T2. In effect, if we include all costs, direct, indirect, and non-energy parsed into energy, the green shaded area A is the amount of net resource available under the entire graph. The graphic also illustrates that the peak energy gain in terms of net benefits to society is reached more quickly than the peak in gross energy.

It is important to note that unless the energy output and input are identical types, energy extraction can still continue at an energy loss – but these joules needs to come from elsewhere in productive society. One can envision a summation of all energy technologies used globally. If we aggregate all the 'A's' (Or A+B's if we ignore environmental externalities) of all planetary energy sources, we have a sum total of energy gain for society which is able to do useful work and create human utility (beyond the sun warming us and the wind drying our laundry, and other fixed natural flows not considered in the global 500 quadrillion BTUs of annual energy

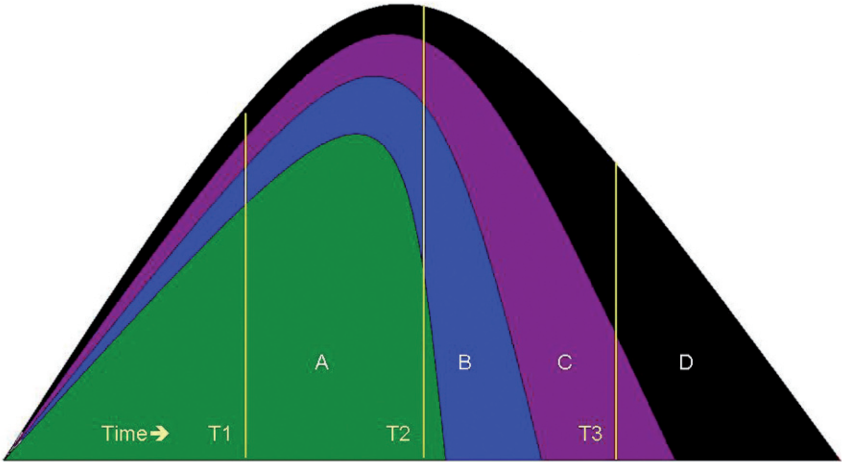

Fig. 12.2 Net energy and EROI as a resource matures over time

use). The surplus energy of a system, or society, is what allows it to continue growth, maintenance, repair and leisure. If our energy sources required equal amounts of energy input in order to obtain an energy output, we would have no surplus energy left for other work (Gilliland 1975). If we had a very small energy surplus, we would only be able to consume at a low level.

EROI has an eventual trade-off with scale – at low scale, EROI can be very high, as the best first principles apply. At higher and higher scale, EROI eventually declines as more resources (energy and other) are needed to harvest the more difficult parts of the original resource. Indeed, analysis of the EROI of US oil and gas exploration shows that we had over 100:1 in the 1930s, when the large oil fields were discovered and put into production. By 1970 the Energy Return on Investment had declined to 30:1 and down to a range of 10–17:1 by 2000. (Cleveland 2001, Hall 2003). Anecdotally, from 2005 to 2006, the finding and production costs of the marginal barrel of oil in the US went from \$15 to \$35 per barrel. (Herold 2007), and offshore in the Gulf of Mexico increased from \$50 to over \$69 per barrel (EIA 2007). Though these are financial increases as opposed to energy, it suggests the high return oil has been found, and increasing amount of dollars (and energy) will be needed to extract the remainder.

12.10 A Framework for Analyzing EROI

Imagine the physical flows of an energy producing technology (T) e.g. a corn ethanol plant. Energy (ED_{in}) and other various inputs ($\{I_k\}$) are taken into the plant and combined or consumed to produce energy output (ED_{out}) as well as possibly other co-products ($\{O_j\}$) i.e. $T(ED_{in}, \{I_k\}) = \{ ED_{out}, O_j\}$. In its narrowest (and least informative) form, EROI (minus 1) is similar to the economic concept of financial

Return on Investment but uses energy as the currency while treating non-energy inputs as negligible. This simple definition yields EROI = ED_{out}/ED_{in}. EROI is rarely used in this simple form (examples being Southwide Energy Committee 1980, Gingerich and Hendrickson 1993), but EROI statistics are frequently published regarding different technologies that ignore the energy costs associated with infrastructure and non-energy inputs (American Wind Energy Association 2006).

12.11 Non-Energy Inputs

EROI rarely conforms to the above simplistic formulation. Depending on the definition of T, the energy inputs, ED_{in} generally do not account for additional and significant energy requirements important to the production process. This energy is embodied in the non-energy direct inputs (Odum 1983), for example the agricultural energy required to grow oilseeds for biodiesel (Hill et al. 2006). Precise calculation of the energy embodied in non-energy inputs is nearly impossible – (e.g. do we include the calories consumed by the farmer for breakfast before he goes to harvest corn? How much energy is the oil field managers expertise worth? etc.). This may be resolved either through an input-output matrix framework or by semi-arbitrarily drawing a boundary beyond which additional, (and presumably negligible), energy inputs are ignored (Spreng 1988). The latter is the accepted approach for Life Cycle Analyses (LCAs – International Standard Organization 1997). A typical EROI formulation applies an appropriate methodology to evaluate the embodied energy costs for the non-energy inputs, which are termed the indirect energy inputs. For a given production process, this should yield a specific set of coefficients, $\{\gamma_k\}$, that give the per-unit indirect energy costs of $\{I_k\}$ (e.g. MJ per tonne soybean). This gives the following version of EROI:

$$EROI = ED_{out}/(ED_{in} + \Sigma\gamma_k I_k). \tag{12.1}$$

Some analyses arbitrarily include the indirect energy costs for certain inputs while excluding the energy cost of others, something that clearly creates difficulty of comparison between studies (Pimentel and Patzek 2005, Farrell et al. 2006). The embodied energy costs of labor in particular are difficult to define but can be a significant component of the energy cost. (Costanza 1980, Hill et al. 2006).

Though energy return analysis obviously treats energy as a critical limiting variable, there are potentially numerous other limiting inputs to a production process. In addition to the direct and indirect energy requirements of an energy technology, important inputs such as land, time, and water, are difficult (some would argue impossible) to accurately reduce into energy equivalent measures. In this chapter we refer to these as *non-energy requirements* so as to distinguish them from *non-energy inputs* (which can be parsed into energy terms). Non-energy requirements can have embodied components as well (Wichelns 2001). For example, the biodiesel conversion process requires labor and water. Similarly, the oilseeds used to produce biodiesel require inputs such as land, labor, and water in addition to direct and indirect energy requirements (Pimentel et al. 1994, Pimentel 2003). The standard assumption underlying past EROI analyses is that all non-energy requirements are held constant and negligible. In a globally connected world of potentially numerous limiting inputs, energy systems analysis will benefit from a relaxing of this assumption.

The direct and indirect non-energy requirements can be handled two different ways. The first method is to identify key, potentially limiting resources and treat them completely separate from energy inputs. This would create a new indicator of efficiency for each resource tracked e.g. EROLI(Land) measured in MJ/ha, or EROWI(Water) measured in MJ/gallon. In particular, for non-energy requirement X, EROXI is given by:

$$\mathrm{ERO}X\mathrm{I} = \mathrm{ED}_{\mathrm{out}}/(\Sigma \pi_{X,\mathrm{k}} \mathrm{I}_{\mathrm{k}}) \tag{12.2}$$

where $\pi_{X,\mathrm{k}}$ gives the direct and indirect per-unit requirements of X into $\mathrm{I_k}$.

While this method increases the complexity, it also has advantages. First, it provides a metric of energy harvesting efficiency that could be included in a broader energy systems analysis. In combination with other technologies that require different array of resource inputs, this type of metric can be informative on the scaling capacity of a renewable energy portfolio. Second, this type of multicriteria approach allows for contextual assessment of a technology. Different geographic and political will be limited in their growth by different resources (Rees 1996), a Liebig's law of the minimum for economic growth (Hardin 1999). Some resources like water may be equally if not more limiting than energy (Barlow 2002). An ideal energy technology would optimize on scarce resource X (high EROXI) thus deemphasizing the return necessary on abundant resource Y (lower EROYI).

Another way to deal with non-energy primary inputs is to convert them into energy equivalents via some set of coefficients ($\{\psi_X\}$) for all non-energy requirements X. A justification for this is that in order for any energy procurement process to be truly sustainable, it must be able to regenerate all resources consumed (Patzek 2004). An approach adopted by Patzek (2004) and Patzek and Pimentel (2005) is to assign energy costs based on a resource's exergy (Ayres and Martinas 1995, Ayres et al. 1998), approximately defined as the ability of a system to perform work and equated with its distance from thermal equilibrium. This can also be viewed as the amount of energy necessary to reconstitute a given level of thermodynamic order.

The above set of coefficients yields the following measure for EROI:

$$EROI = \frac{ED_{out}}{\left(ED_{in} + \sum_k \gamma_k I_k + \sum_X \sum_k \psi_X \pi_{X,k} I_k\right)}. \tag{12.3}$$

Assuming consensus around the validity of the energy equivalents, this measure of EROI provides for complete commensurability by reducing all inputs to a single currency.

12.12 Non-Energy Outputs

Just as consideration of non-energy inputs yields a fuller, and more complex EROI statistic, so too can non-energy outputs be incorporated to provide a more complete indicator of the desirability of a process. Firstly, many technologies yield co-products in addition to a primary energy product. Most studies assume that a credit should be given for these co-products which increases the EROI by reducing the numerator for the process. Mathematically, each co-product O_j is assigned a per-unit energy equivalency coefficient (υ_j) indicative of its value relative to the energy product.

The most straightforward method is to assign co-products an explicit energy value based on their thermal energy content (Pimental and Patzek 2005) or their exergy (Patzek and Pimentel 2005). However, co-products are seldom used for their energy content (bagasse in sugar cane ethanol being an exception). If energy is the limiting variable to be optimized, a full energy credit for dry distiller grains or milk, may be aggressive, and the EROI of a technology giving full allocation to co-products will decline as the co-products scale beyond their practical use (e.g millions of tons of DDGs). Energy values can also be assigned according to the energy that would be required to produce the most energy-efficient replacement (Hill et al. 2006). Economic value and mass are two non-energy metrics that are used to establish relative value, both of which are frequently used in life cycle analyses (International Standard Organization 1997, deBoer 2003).

Once the energy equivalency coefficients have been established, the EROI formulation is modified to the following:

$$EROI = \frac{ED_{out} + \sum \nu_j O_j}{ED_{in} + \sum \gamma_k I_k}. \tag{12.4}$$

For example, when procuring biodiesel from soybeans, the soybean meal is a valuable co-product often used as a source of protein for livestock. An energy credit can be assigned to this co-product based on its actual thermal content (Pimentel and Patzek 2005), its market value (e.g. Mortimer et al. 2003), or its mass (e.g. Sheehan et al. 1998). The fact that calculated EROI can vary by a factor of 2 or more depending on allocation method gives insight that EROI, though much more so than dollars, is not a purely physical concept.

12.13 Non-Market Impacts

We have considered inputs and outputs that are currently recognized by the market system. However, many energy production processes create outputs that have social, ecological, and economic consequences external to the market. As we are all part of a planetary ecosystem, to properly include energy externalities should provide us with more accurate information of the desirability of an energy procuring technology (Hill et al. 2006). Negative externalities can include loss of topsoil erosion, water pollution, loss of animal habitat, and loss of food production capacity (Hanegraaf et al. 1998, Pimentel et al. 2002). Externalities can also be positive such as the creation of jobs and the maintenance of rural communities (Bender 1999).

As with non-energy requirements, these externalities can be incorporated into our framework in one of two ways—as separate indicators in a multicriteria framework or through conversion into energy equivalents. Thus, if topsoil is lost or nitrous oxide is emitted as part of the life cycle of the technology, we can measure EROI (*Topsoil*) or EROI(*Nox*). Studies that include such externalities have been published by the US Department of Energy (1989a, 1989b), Giampietro et al. (1997). Such measures are useful for assessing the scalability of a process within a given context by indicating what resources (e.g. waste sinks) might become limiting under increased production.

Negative externalities also can be assigned energy equivalency coefficients equal to the energy required to prevent or remediate their impacts (Cleveland and Costanza 1984, Pimental and Patzek 2005, Farrell et al. 2006). If we assume a set of externalities $\{E_i\}$ with energy equivalency coefficients $\{\nu_i\}$, then we must add into the denominator of the EROI calculation the term $\sum \nu_i E_i$. Not many studies have attempted this approach, however and pursuing this strategy has the drawback of parsing important non-reducible criteria into one metric.

12.14 A Summary of Methodologies

Table 12.1 lists all of the different formulations of EROI (or net energy analysis) presented above based on the formulation of the denominator. For each, we've cited one or more studies that have employed that specific variation. While all the works surveyed fall within the same methodological framework, as outlined above,

Table 12.1 Exisiting EROI Formulations in the Literature

Cost category	Direct	+ Indirect	+ Allocation
	Cost = ED_{in}	Cost = $(ED_{in} + \sum \gamma_k I_k)$	Numerator = $ED_{out} + \sum \upsilon_j O_j$
Energy	Wood Biomass[a]	Soy/Sunflower Biodiesel[c]	Corn Ethanol[e]
	Wood to Electric[b]	Solar Cells[d]	Soy Biodiesel[f]
	Cost = *X*	Cost = $\sum \pi_{X,k} I_k$	Numerator = $ED_{out} + \sum \upsilon_j O_j$
Primary Input(X)	Hydroelectric, X = Land[b]	Corn Ethanol, X = Various Inputs[c,h]	Soy Biodiesel, X = Various Inputs[f]
	Various Technologies, X = Water[g]	Rapeseed Biodiesel, X = Various Inputs[g]	Rapeseed Biodiesel, X = Water[i]

Table 12.1 (continued)

Cost category	Direct	+ Indirect	+ Allocation
	Cost = *E*	Cost = $\sum \pi_{E,k} I_k$	Numerator = $ED_{out} + \sum \upsilon_j O_j$
Externality (E)	Wind, E = Emissions[j] Various Technologies, E = Soil Loss[g]	Various Technologies, E = Emissions[k] Wind, E = Emissions[l]	Biodiesel, E = Emissions[f] Ethanol, E = GHG[m]
Energy Equivalents	(1) Conversion of externalities into energy: Cost = $ED_{in} + \sum \gamma_k I_k + \sum \nu_i E_i$[e,h] (2) Conversion of primary inputs into energy: Cost = $ED_{in} + \sum \gamma_k I_k + \sum \psi_X \pi_{X,k} I_k$[c,h]		

Citations:
[a] (Gingerich and Hendrickson 1993)
[b] (Pimentel et al. 1994)
[c] (Pimentel and Patzek 2005)
[d] (Pearce and Lau 2002)
[e] (Farrell et al. 2006)
[f] (Sheehan et al. 1998)
[g] (Hanegraaf et al. 1998)
[h] (Patzek 2004)
[i] (DeNocker et al. 1998)
[j] (American Wind Energy Association 2006)
[k] (European Commission 1997)
[l] (Schleisner 2000)
[m] (Mortimer et al. 2003)
(Table and accompanying text adapted from Mulder et al. 2008)

assumptions and terminology vary significantly among studies resulting in conflicting results that make them difficult to compare.

12.15 A Unifying EROI Framework

If net energy analysis is to produce results that are clear, and comparable across studies, and be of practical use to researchers and policy-makers, it will be necessary for the methodology to become uniform and well-specified. Such standards exist in the area of life cycle analyses (International Standard Organization 1997). However, unlike LCA, it is probably not possible or even desirable that EROI be restricted to a single meaning or methodology. The different levels of energy and environmental analysis outlined above are relevant to different problems, contexts, and research objectives. *The problem heretofore has arisen when the same term is used for methodologies with different assumptions and different goals.*

We propose a two-dimensional framework for EROI analyses (with accompanying terminology) that clarifies the major assumptions in an analysis. In the first dimension, we identify three distinct levels of analysis that can be distilled from the above examples. These levels differ in terms of *what* they include in their analysis.

The first level deals with only the direct inputs (energy and non-energy) and direct energy outputs. We term this *Narrow Boundary EROI* as, while it can offer more precise EROI calculations, it is also the most superficial, restricting the analysis to simple inputs and thus missing many critical energy costs (as well as ignoring co-products). The next level, *Intermediate Boundary EROI*, involves incorporating indirect energy and non-energy inputs as well as crediting for co-products. This is the methodology used by Life Cycle Analysis to estimate the EROI of an energy technology. Intermediate Boundary EROI requires two assumptions that must be made clear: (1) What allocation method is used for the co-products (thermal content, price, mass, exergy etc.); and (2) What boundaries are used for determining indirect inputs. Finally, *Wide Boundary EROI* incorporates additional costs (and possibly benefits) for the externalities of the energy technology. Admittedly, this is the most imprecise but also the most relevant of the EROI measures in that it presents the fullest measure of the net energy available to society.

	Basic EROI	**Total EROI**	**Multicriteria EROI**
Narrow Boundary	$\frac{ED_{out}}{ED_{in}}$	$\frac{ED_{out}}{ED_{in} + \sum_k \psi_k I_k}$	$\frac{ED_{out}}{I_k}$
Intermediate Boundary	$\frac{ED_{out}}{\alpha\left(ED_{in} + \sum_k \gamma_k I_k\right)}$	$\frac{ED_{out}}{\alpha\left(ED_{in} + \sum_k \gamma_k I_k + \sum_k \psi_k \pi_{X,k} I_k\right)}$	$\frac{ED_{out}}{\alpha \sum_k \pi_{X,k} I_k}$
Wide Boundary	X	$\frac{ED_{out}}{\alpha\left(ED_{in} + \sum_k \gamma_k I_k + \sum_k \psi_k \pi_{X,k} I_k + \sum_i \nu_i E_i\right)}$	$\frac{ED_{out}}{\alpha \sum_k \pi_{E,k} I_k}$

Fig. 12.3 Methodological framework for net energy analysis. The side axis determines *what* to include (direct inputs, indirect inputs, and/or externalities). The top axis dictates *how* to include non-energy requirements (ignore, convert to energy equivalents, or treat as separate inputs.) Note that since basic EROI ignores non-energy inputs, it does not have a wide boundary form that accounts for externalities. (Table and accompanying text adapted from Mulder et al. 2008)

Once it has been determined what can (and should) be included in the analysis, the second dimension in our framework dictates *how* to include these inputs. We delineate three choices for handling of the non-energy requirements and externalities. They can be ignored, yielding *Basic EROI*, or converted to energy equivalents, yielding '*Total EROI*', or handled as separate components yielding '*Multi-criteria EROI*'.

Our framework is presented in Fig. 12.3. Note that while the grid is 3×3, it yields only 8 meaningful formulations. The different levels of analyses are nested hierarchically. The computation of a wider boundary EROI for an energy production process should easily yield all other forms of EROI found below it. That is to say, the necessary data will have been compiled and it is merely a decision of which components to include in the calculation. Similarly, a Total EROI calculation will use the same data set as a Multi-criteria EROI with the addition of energy equivalency coefficients. This means that more comprehensive studies should yield results at least partially comparable with less comprehensive studies as seen in a meta-study of ethanol by Farrell et al. (2006).

12.16 Liebig's Law, Multi-Criteria Analysis, and Energy from Biofuels

Though it is becoming apparent that energy will be a limiting variable for society going forward, it is easy to envision other equally limiting variables as the planetary population increases its demand on ecosystems. Water, land, and carbon sinks are only three examples of inputs and impacts of renewable energy production that could limit the potential of a technology (Giampietro et al. 1997, Hagens et al. 2006, Hill et al. 2006). These should be included explicitly in a net energy analysis or else their cost in terms of energy should be estimated.

Liebig's Law of the minimum states that the production of a good or resource is limited by its least available input. In layman's terms something is only as good as its weakest link. This form of ecological stoichiometry will loom large in the procurement of energy alternatives to fossil fuels. Water, land, soil, greenhouse gas emissions, and specific fossil inputs themselves will potentially limit scaling of alternative energy.

Though EROI is generally measured as the ratio of the gross energy return to the amount of energy invested, it has been argued this can give a false indicator of the desirability of a process due to the increasing cost of non-energy requirements as EROI approaches 1. Following Giampietro et al. (1997), let $\omega = \text{EROI}/(\text{EROI} - 1)$ be the ratio of gross to net energy produced. ω equals the amount of energy production required to yield 1 MJ of net energy. From an energy perspective, all costs have been covered. However, for non-energy requirements the perspective and the implications, change.

Let EROXI be the energy return for 1 unit of non-energy requirement X. Then 1/EROXI is the number of units of X required for 1 MJ gross energy production. From the above, it is easily seen that ω/EROXI units of X are required, or more generally, the net energy yielded per unit of X is equal to EROXI/ω. Since ω increases non-linearly (approaching infinity) as EROI approaches 1, a relatively small change in EROI can produce a large decrease in the 'net EROI' for non-energy requirements. For energy production processes with significant non-energy requirements such as biofuels, this suggests a low EROI can imply strong limitations on their ability to be scaled up (Giampietro et al. 1997, Hill et al. 2006).

If we assume the Intermediate Boundary EROI for non-cellulosic ethanol from corn is in the neighborhood of 1.34 (Farrell et al. 2006), this implies net energy of .34 for every 1 unit of energy input. The corn-based ethanol Energy Return on Land Invested (EROLI) = 11,633 MJ/ha gross energy production (equivalent to 3475 l per hectare). However, the net energy per unit of land is only 2,908 MJ/ha. At 2004 levels of gasoline consumption for the United States, this is equivalent to consuming the net energy production of 42 ha of cropland per second. If the EROI of ethanol is reduced to 1.2, a decrease of only 10%, the net return on land decreases by 33% while the amount of land required to achieve this same net yield increases by 50%. Conversely, an oil well requires equipment access, roads, etc. but pulls its bounty out of a comparatively small land area. This contrast has significant implications for the potential scale of biofuel production (Giampietro et al. 1997). In effect, due to significant power density differentials, replacing energy-dense liquid fuels from crude oil with less power dense biomass fuels will utilize 1,000- to 10,000-fold increases in land area relative to our existing energy infrastructure (Cleveland 2007).

Though land is one limiting factor, water may be another. In a forthcoming paper, we use Multicriteria EROI analysis to define and quantify the EROWI (Energy Return on Water Invested) for various energy production technologies. Since water and energy may both be limiting, we care about the 'Net EROWI', which is a combined measure of EROI and EROWI for each technology. With the exception of wind and solar which use water only in indirect inputs, the 'Net EROWI' of biofuels are one to two orders of magnitude lower than conventional fossil fuels. We also determined that approximately 2/3 of the world population (by country) will have limitations on bioenergy production by 2025, due to other demands for water (Mulder et al. *In press*).

Nitrogen, a byproduct of natural gas via ammonia, is essential to a plant's ability to develop proteins and enzymes in order to mature. The importance of nitrogen fertilizers to U.S. agriculture, particularly corn and wheat, is evidenced by its accelerated use over the last 50 years. From 1960 to 2005, annual use of chemical nitrogen fertilizers in U.S. agriculture increased from 2.7 million nutrient tons to 12.3 million nutrient tons (Huang 2007). This increase is considered to be one of the main factors behind increased U.S. crop yields and the high quality of U.S. agricultural products (Huang 2007). Furthermore, biofuels, especially the ethanols, require large amounts of natural gas for pesticides, seedstock and primary electricity to concentrate the ethanol. In areas that have natural gas fired electricity plants (as opposed to coal), fully 84% of the energy inputs into corn ethanol are from natural gas (the nitrogen, a portion of the pesticides, and the electricity). (Shapouri 2002). Ethanol proponents, other than optimizing 'dollars' (making money), are presuming that 'domestically produced vehicle fuel' is the sole item in short supply. Were the math on corn ethanol somehow scalable to 30% of our national gasoline consumption, in addition to land and water, we would use *more than the entire yearly amount of natural gas currently used for home heating* as an input.

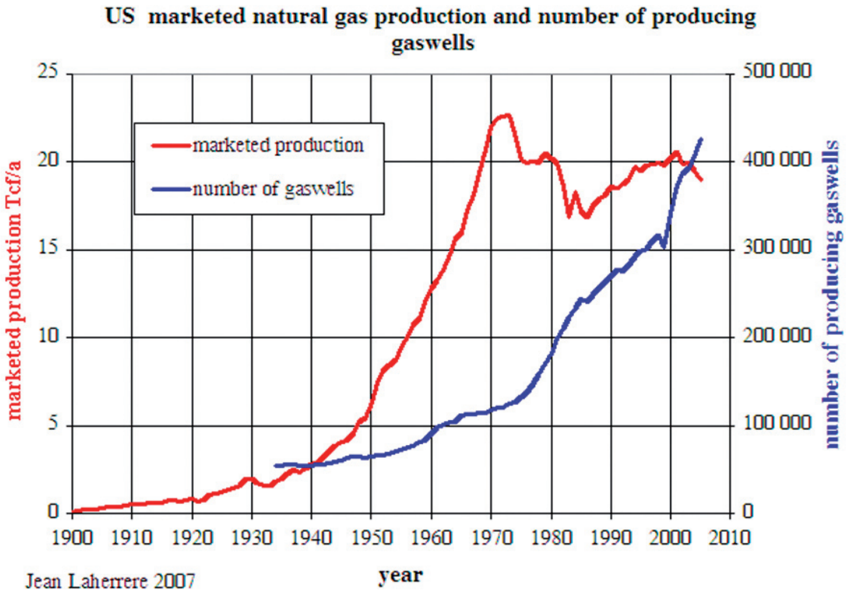

Fig. 12.4 Natural gas production vs. # of natural gas wells (Source Laherrere 2007)

Though many biofuel studies imply that fertilizer, and therefore natural gas, are more abundant and cheaper than petroleum, we are actually on a ‘natural gas treadmill’ in North America and low prices are being kept down only by 2 consecutive mild winters and summers with no hurricanes. In 1995 the average new gas well in North America took 10 years to deplete. A new gas well in 2007 takes under 10 months. More and more drilling of new gas wells is necessary just to stay at constant levels of production. As can be seen in Fig. 12.4, US production peaked in 1973 followed by another peak in 2001. The second peak required 370% more wells to produce the same amount of gas. Furthermore, the energy/$ effort on Canadian natural gas production implies a decline in EROI from 40:1 to 15:1 from 2000 to 2006, with an extrapolated energy break even year circa 2014. (CAPP 2007, methodology Hall and Lavine 1979). The falling EROI makes it impossible for natural gas production to maintain both low costs and current levels of production. When US oil peaked in 1970, we made up our oil demand shortfall by imports. Natural gas can also be imported (as LNG), but it must first be liquefied at a high dollar and energy cost. It requires over 30% of its BTU content to be transported overseas – another energy loss. In this sense, studies that show energy use on petroleum invested are perhaps overlooking natural gas as a limiting input.

So corn ethanol, and other biofuels requiring both natural gas for fertilizers and pesticides, as well as for electricity to steam the ethanol solution, are essentially turning 3 scarce resources: water, land, and natural gas, into liquid fuels, at an energy gain an order of magnitude lower than what societal infrastructure is currently adapted to. What will the strategy and metrics to measure it become when natural gas too, is recognized as limiting input?

12.17 Conclusion

At some point in the near future, those reading this chapter will witness a forced change from the fossil fuel mix that has powered society smoothly for decades. In a perfect world, all information about externalities and an accurate balance sheet of the size and quality of our resources would be available to decision-makers. In reality however, accurate information about the reliability of upcoming resource flows is opaque beyond a few months. Only 6% of the worlds (stated) oil reserves are owned by public companies subject to SEC requirements, leaving the NOCs and private companies each individually knowing only their own share of the oil pie. It is unlikely the market will respond in time once critical limiting variables to society become apparent. Unfortunately, this cannot be empirically proven until after the fact. To have a framework in hand that anticipates such problems is a first but important step.

New energy technologies require enormous capital investments and significant lead time as well as well-defined research and planning. Aggregating decisions surrounding alternative energy technologies and infrastructure will be both difficult and time sensitive. As a growing population attempts to replace this era of easy energy with alternatives, net energy analysis will reassert its importance in academic and policy discussions. Alongside ecological economics, it is one of the few methods we can use to attempt to measure our 'real' wealth and its costs. As such, it will be advantageous to adhere to a framework that is consistent among users and attempts to evaluate correctly the complex inputs and outputs in energy analysis in ways that are meaningful. Accounting for the subtle and intricate details in net energy analysis is difficult. However, in a growing world constrained by both energy and increasingly by environmental concerns, adherence to a common framework will be essential for policy-makers to accurately assess alternatives and speak a common language.

Perhaps the biggest misconception of net energy analysis, particularly in its most popular usage referring to corn ethanol, is the comparison on whether or not something is energy positive – this myopic focus on the absolute, ignores the much larger question of relative comparisons – what happens to society when we switch to a lower energy gain system? While net energy analysis outcomes will not guide our path towards sustainable energy with the precision of a surgical tool, they are quite effective as a blunt instrument, helping us to discard energy dead-ends that would be wasteful uses of our remaining high quality fossil sources and perhaps equally as important, our time. Ultimately when faced with resource depletion and a transition of stock-based to flow-based resources, EROI will function best as an allocation device, marrying our demand structure with our supply structure, thus guiding our high quality energy capital into the best long term energy investments. Finally, analysts and policymakers may use net energy analysis not only to compare the merits of proposed new energy technologies, but also as a roadmap for possible limitations on demand, if global energy systems analysis points to declines in net energy not adequately offset by conservation, technology or efficiency. A framework like the one presented above, may also be useful for analyses involving limiting inputs in addition to energy.

References

American Wind Energy Association. 2006. Comparative air emissions of wind and other fuels. Retrieved on Jan 27 2007 from http://www.awea.org/pubs/factsheets.html.

Ayres, R., L. Ayres, and K. Martinas. 1998. Exergy, waste accounting, and life-cycle analysis. Energy 23:355–363.

Ayres, R., and K. Martinas. 1995. Waste potential entropy: The ultimate ecotoxic? Economie Appliquees 48:95–120.

Baines, J., and M. Peet. 1983. Assessing alternative liquid fuels using net energy criteria. Energy 8:963–972.

Baltic, T., and D. Betters. 1983. Net energy analysis of a fuelwood energy system. Resources and Energy 5:45–64.

Bender, M. 1999. Economic feasibility review for community-scale farmer cooperatives for biodiesel. Bioresource Technology 70:81–87.

Berglund, M., and P. Borjesson. 2006. Assessment of energy performance in the life-cycle of biogas production. Biomass & Bioenergy 30:254–266.

Barlow, M., Clarke T. 2002. "Blue Gold: The Battle Against Corporate Theft of the World's Water" Stoddart, Toronto.

Berndt, E. 1983. From technocracy to net energy analysis: Engineers, economists, and recurring energy theories of value. Pages 337–366 in A. Scott, editor. Progress in Natural Resource Economics. Clarendon, Oxford.

British Petroleum. 2005. Quantifying Energy: BP Statistical Review of World Energy 2005.

Canadian Assoc of Petroleum Producers (CAPP). "Wells and Meters Drilled in Canada 1981–2006", 2007.

Chambers, R., R. Herendeen, J. Joyce, and P. Penner. 1979. Gasohol: Does it or doesn't it produce positive net energy. Science 206:789–795.

Chui, F., A. Elkamel, and M. Fowler. 2006. An integrated decision support framework for the assessment and analysis of hydrogen production pathways. Energy & Fuels 20:346–352.

Cleveland, C. 1992. Energy quality and energy surplus in the extraction of fossil fuels in the U.S. Ecological Economics 6:139–162.

Cleveland, C. 2001. "Net Energy from Oil and Gas Extraction in the United States, 1954-1997". Energy, 30: 769-782.

Cleveland, C. 2005. Net energy from the extraction of oil and gas in the United States. Energy 30:769–782.

Cleveland, C. 2007 "Net Energy Analysis", Retrieved 3/16/2007 from http://www.eoearth.org/article/Net_energy_analysis

Cleveland, C. 2007 "Energy Transitions Past and Future", The Encyclopedia of Earth, Retrieved 7/29/2007 from http://www.eoearth.org/article/Energy_transitionspastandfuture

Cleveland, C., and R. Costanza. 1984. Net Energy Analysis of Geopressured Gas-Resources in the United States Gulf Coast Region. Energy 9:35–51.

Cleveland, C., R. Costanza, C. Hall, and R. Kaufmann. 1984. Energy and the United States Economy – A Biophysical Perpsective. Science 225:890–897.

Costanza, R. 1980. Embodied energy and economic valuation. Science 210:1219–1224.

Crawford, R., and G. Treloar. 2004. Net energy analysis of solar and conventional domestic hot water systems in Melbourne, Australia. Solar Energy 76:159–163.

deBoer, I. 2003. Environmental impact assessment of conventional and organic milk production. Livestock Production Science 80:69–77.

DeNocker, L., C. Spirinckx, and R. Torfs. 1998. Comparison of LCA and external-cost analysis for biodiesel and diesel. in Proceedings of the 2nd International Conference LCA in Agriculture, Agro-industry and Forestry. VITO, Brussels.

Energy Information Agency. 2007. "Performance Profiles of Major Energy Producers 2006", December 2007

EPA. 2002. A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions. EPA420-P-02-001, US Environmental Protection Agency.

European Commission. 1997. ExternE, Externalities of Energy, Methodology Report, Vol. 1. European Communities.
Farrell, A., R. Plevin, B. Turner, A. Jones, M. O'Hare, and D. Kammen. 2006. Ethanol can contribute to energy and environmental goals. Science 311:506–508.
Giampietro, M., S. Ulgiati, and D. Pimental. 1997. Feasibility of Large-Scale Biofuel Production. Bioscience 47:587–600.
Gilliland, M. 1975. Energy analysis and public policy. Science 189:1051–1056.
Gingerich, J., and O. Hendrickson. 1993. The theory of energy return on investment – A case-study of whole tree chipping for biomass in Prince Edward Island. Forestry Chronicle 69:300–306.
Hagens, N., R. Costanza, and K. Mulder. 2006. Energy Returns on Ethanol Production. Science 312:1746.
Hall, C. A. S., and M. Lavine. 1979. "Efficiency of Energy Delivery Systems:1. An Economic and Energy Analysis", Environmental Management, vol 3, no 6, pp 493–504.
Hall, C. A. S., C. J. Cleveland, and R. Kaufmann. 1986. Energy and resource quality: The ecology of the economic process. Wiley, New York.
Hall, C., Tharakan, P. Hallock, J. Cleveland, C. and Jefferson, M. 2003. "Hydrocarbons and the Evolution of Human Culture", Nature 426:318–322, 20 November 2003.
Hammerschlag, R. 2006. Ethanol's energy return on investment: A survey of the literature 1990 – Present. Environmental Science & Technology 40:1744–1750.
Hanegraaf, M. C., E. E. Biewinga, and G. Van der Bijl. 1998. Assessing the ecological and economic sustainability of energy crops. Biomass & Bioenergy 15:345–355.
Hardin, G. J. 1999. The ostrich factor: Our population Myopia. Oxford University Press, New York.
Herold and Co. Upstream Performance Summary 2007.
Hill, J., E. Nelson, D. Tilman, S. Polasky, and D. Tiffany. 2006. Environmental, economic, and eneretic costs and benefits of biodiesel and ethanol biofuels. Proceedings of the National Academy of Sciences 103:11206–11210.
Hu, Z., F. Fang, D. Ben, G. Pu, and C. Wang. 2004. Net energy, CO2 emission, and life-cycle cost assessment of cassava-based ethanol as an alternative automotive fuel in China. Applied Energy 78:247–256.
Huang, W. 2007. Impact of Rising Natural Gas Prices on U.S. Ammonia Supply, US Department of Agriculture, August 2007
International Standard Organization. 1997. Environmental Management – Life Cycle Assessment – Principles and Framework. ISO, Geneva.
Kallivroussis, L., A. Natsis, and G. Papadakis. 2002. The energy balance of sunflower production for biodiesel in Greece. Biosystems Engineering 81:347–354.
Kaylen, M. 2005. An economic analysis of using alternative fuels in a mass burn boiler. Bioresource Technology 96:1943–1949.
Keoleian, G. 1998. Application of Life Cycle Energy Analysis to Photovoltaic Design. Progress in Voltaics 5.
Kidd, S. 2004. nuclear: Is there any net energy addition? Nuclear Engineering International 49:12–13.
Kim, S., and B. Dale. 2005. Environmental aspects of ethanol derived from no-tilled corn grain: Nonrenewable energy consumption and greenhouse gas emissions. Biomass & Bioenergy 28:475–489.
Laherrere, J. 2007, "North American natural gas discovery & production", August 2007, ASPO France, pg 15.http://aspofrance.viabloga.com/files/JL_NAmNG07.pdf
Lotka, A., 1922. "Contributions to the Energetics of Evolution", Biology. 8:147-151.
Mortimer, N. D., M. A. Elsayed, and R. Matthews. 2003. Carbon and Energy Balances for a Range of Biofuel Options. Resources Research Unit, Sheffield Hallam University, Sheffield, England.
Mulder, K., and Hagens N. 2008."Energy Return on Investment – Towards a Consistent Framework", AMBIO Vol. 37, no 2, pp. 74–79 March 2008.
Odum, H. T. 1973. Energy, Ecology, and Economics. Ambio 2:220–227.
Odum, H. T. 1983. Systems ecology: An introduction. Wiley, New York.

Odum, H.T. 1994. “Ecological and General Systems: An Introduction to Systems Ecology”, University Press of Colorado, Revised Edition of Systems Ecology, 1983, Wiley.
Odum, H. T. 1995. ‘Self-Organization and Maximum Empower’, in C.A.S.Hall (ed.) Maximum Power: The Ideas and Applications of H.T.Odum, Colorado University Press, Colorado.
Patzek, T. 2004. Thermodynamics of the corn-ethanol biofuel cycle. Critical Reviews in Plant Sciences 23:519–567.
Patzek, T., and D. Pimentel. 2005. Thermodynamics of energy production from biomass. Critical Reviews in Plant Sciences 24:327–364.
Pearce, J., and A. Lau. 2002. Net energy analysis for sustainable energy production from silicon based solar cells. in Proceedings of Solar 2002, Reno, Nevada.
Pimentel, D., and T. W. Patzek. 2005. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. Natural Resources Research 14:65–76.
Pimentel, D. 2003. Ethanol Fuels: Energy Balance, Economics, and Environmental Impacts are Negative. Natural Resources Research 12:127–134.
Pimentel, D., M. Herz, M. Glickstein, M. Zimmerman, R. Allen, K. Becker, J. Evans, B. Hussain, R. Sarsfeld, A. Grosfeld, and T. Seidel. 2002. Renewable energy: Current and potential issues. Bioscience 52:1111–1120.
Pimentel, D., and T. W. Patzek. 2005. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. Natural Resources Research 14:65–76.
Pimentel, D., G. Rodrigues, T. Wang, R. Abrams, K. Goldberg, H. Staeker, E. Ma, L. Brueckner, L. Trovato, C. Chow, U. Govindarajulu, and S. Boerke. 1994. Renewable energy – economic and environmental issues. Bioscience 44:536–547.
Potter, L., and D. Betters. 1988. A net energy simulation model – Applications for domestic wood energy systems. Forest Products Journal 38:23–25.
Rees, W. 1996. Revisiting carrying capacity: Area-based indicators of sustainability. Population and Environment 17:195–215.
Reijnders, L. 2006. Conditions for the sustainability of biomass based fuel use. Energy Policy 34:863–876.
Ricardo, D. 1819. On the principles of political economy, and taxation, 1st American edition. J. Milligan, Georgetown, D.C.
Schleisner, L. 2000. Life cycle assessment of a wind farm and related externalities. Renewable Energy 20:279–288.
Shapouri H., J. Duffield and M. Wang, “The Energy Balance of Corn Ethanol – An Update”, USDA 2002.
Sheehan, J., V. Camobreco, J. Duffield, M. Graboski, and H. Shapouri. 1998. An Overview of Biodiesel and Petroleum Diesel Life Cycles. NREL/TP-580-24772, National Renewable Energy Laboratory, Golden, CO.
Skrebowski, Chris, Oil Depletion Analysis Center (ODAC Newsletter May 2006).
Smil, V. 1991. General Energetics: Energy in the Biosphere and Civilization. John Wiley, New York.
Smil, V. 2006. “21st Century Energy - Some Sobering Thoughts.” OECD Observer 258/59: 22–23, December 2006
Southwide Energy Committee. 1980. Petroleum product consumption and efficiency in systems used for energy wood harvesting. American Pulpwood Association, No. 80-A-10.
Spreng, D. T. 1988. Net-energy analysis and the energy requirements of energy systems. Praeger, New York.
Tainter, J. A. 2003. Resource transitions and energy gain: Contexts of organization. Conservation and Ecology 7.
Tyner, G., R. Costanza, and R. Fowler. 1988. The net energy yield of nuclear power. Energy 13:73–81.
Ulgiati, S. 2001. A Comprehensive Energy and Economic Assessment of Biofuels: When Green is not Enough. Critical Reviews in Plant Sciences 20:71–106.
US Department of Energy. 1989a. Energy Systems Emissions and Material Requirements. Prepared by the Meridian Corporation, Washington, DC.

US Department of Energy. 1989b. Environmental Emissions from Energy Technology Systems: The Total Fuel Cycle. R L San Martin, Deputy Assistant Secretary for Renewable Energy, Washington D.C.

Wichelns, D. 2001. The role of 'virtual water' in efforts to achieve food security and other national goals, with an example from Egypt. Agricultural Water Management 49:131–151.

Wilkinson, R. G. 1973. "Poverty and progress: an ecological model of economic development". Methuen, London, UK.