Article

Kenneth Mulder and Nathan John Hagens

Energy Return on Investment: Toward a Consistent Framework

Numerous technologies have been proposed as partial solutions to our declining fossil energy stocks. There is a significant need for consistent metrics to compare the desirability of different technologies. The ratio of energy produced to energy consumed by an energy production technology—known as the energy return on investment (EROI)—is an important first indicator of the potential benefits to society. However, EROI analysis lacks a consistent framework and has therefore yielded apparently conflicting results. In this article, we establish a theoretical framework for EROI analysis that encompasses the various methodologies extant in the literature. We establish variations of EROI analysis in two different dimensions based on the costs they include and their handling of nonenergy resources. We close by showing the implications of the different measures of EROI upon estimating the desirability of a technology as well as for estimating its ultimate net energy capacity.

INTRODUCTION

Energy is the lifeblood of modern civilization. The complex globalization of human commerce is made possible by enormous amounts of fossil fuels. Natural gas and crude oil, in particular, are ubiquitous in their global roles of providing food and facilitating transportation (1). When coal is included, fossil fuels make up 87.7% of global primary energy use (2). Joint limitations in the size of remaining fossil stocks and the ability of the atmosphere to absorb their emissions have created a global sense of urgency in replacing them as humanity's primary energy source. History suggests that societies unable to match increases in size and complexity with increases in energy have eventually collapsed (3).

In assessing possible replacements for oil and natural gas, each alternative will present unique trade-offs between energy quantity, energy quality, and other inputs and impacts such as land, water, labor, and environmental health (4). When faced with these choices, policymakers, corporations, and end-users require a comprehensive and consistent framework for accurately comparing all aspects of an alternative fuel.

Several criteria were used in the past to assess energy production technologies based on their absolute and relative yields and assorted costs (5). Some assess strictly economic flows (e.g., 6) whereas others focus solely on energy flows (e.g., 7, 8, 9) or emissions (e.g., 10). Low greenhouse gas emissions in particular are a frequent measure of the desirability of an alternative technology (11). Other assessments rely on a broad range of costs in terms of energy as well as environmental and social inputs (e.g., 5, 12, 13).

Because the goal of an alternative energy technology is to produce energy, one of the most ubiquitous measures of process efficiency is the ratio of energy produced to energy consumed for a given technology. This concept is encapsulated by numerous labels and formulations in energy parlance and literature, such as energy profit ratio, net energy (14), energy gain (3), and energy payback (15). In this article we focus on an equivalent concept—the energy return on energy investment (EROI) (16, 17). Although this concept is used explicitly in only a minority of net energy analyses, it is implicit in any study that uses net energy as a criterion and has been used recently as a synthesizing concept for multiple analyses of biofuels (7, 18). It has been used to examine nuclear energy (19, 20), ethanol (7, 18, 21), other biofuels (12, 22), wood energy (17), and other alternative energies (23, 24). It has also been used to assess the energy efficiency of various fossil fuels (8, 16).

The current EROI formulation is related to optimal foraging analysis in ecology and the notion of "yield per effort," and the concept is rooted in the technocratic notion of energy as the ultimate currency (see 25 for an historic overview). An early coherent expression of the concept was given by Odum (14). In the United States, it was given the legislative imprimatur by the Federal Non-nuclear Energy Research and Development Act of 1974, which mandated net energy analysis resulting in a flurry of net energy studies. Gilliland (26) recommended EROI as the more appropriate form of net energy analysis, and Cleveland et al. (27) demonstrated its significance to economic growth. However, low energy prices, a booming stock market, and relatively smooth international energy markets resulted in net energy analysis being given little attention during the past 20 years. Recent energy shortages and price volatility have rekindled interest.

On the surface, the calculation of EROI as the ratio of energy outputs to inputs seems relatively straightforward. However, the concept has proven difficult to operationalize (28). There still does not exist a consistently applied methodology for calculating either the numerator (the energy produced) or the denominator (the energy consumed) in the EROI equation. As a result, numerous comparisons are being made in the literature for the EROI of a given technology or between different technologies when in reality different researchers are using different methods.

The ongoing, and often vitriolic, debate about the energy return of ethanol production is a relevant example. A recent publication (7) suggests that previous analyses of the EROI of grain ethanol are errant because of outdated data and faulty methodology. They attempt to standardize several studies and introduce modifications of the EROI methodology, including measuring energy produced per unit of petroleum energy used. However, because the overall methodology for calculating EROI is not standardized and the concept is not precisely defined, the paper has not ameliorated the polarization of the debate, but rather heightened it (see response letters in 29). 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 regarding a given technology.

In this article, we review the various usages of EROI in the literature and place them into a consistent schematic framework. This enables comparison of the different methodologies in use by making clear 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 would yield

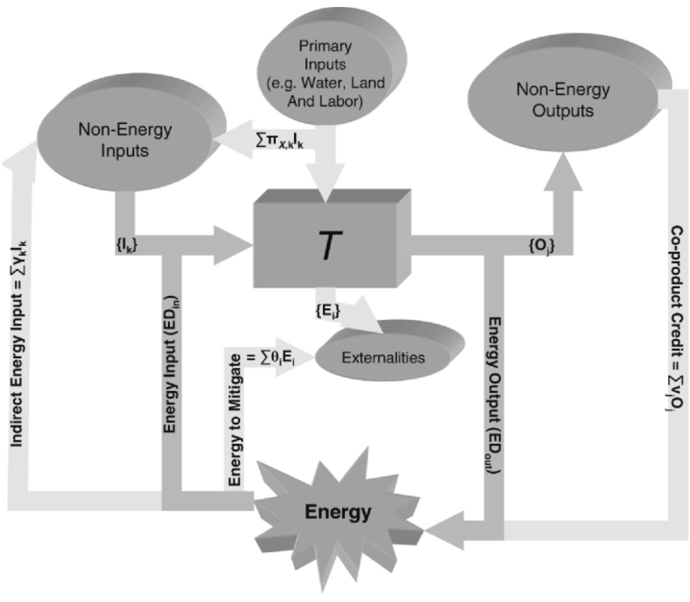

Figure 1. Direct (darker arrows) and indirect (lighter arrows) inputs and outputs for technology, T. All primary inputs (energy and nonenergy) can enter T directly or embodied in other inputs (e.g., the energy and materials required to build production infrastructure). Energy costs can also be assessed as required to mitigate environmental externalities that result from the production process. On the output side, nonenergy coproducts can be given an energy credit based on several potential allocation methods.

consistent and comparable results between studies. Finally, we present some remaining theoretical issues that impact the interpretation and importance of EROI as an indicator.

FRAMEWORK FOR ANALYZING EROI

Figure 1 presents the physical flows of an energy producing technology (T), such as a biodiesel production plant. Energy (ED_{in}) and other various inputs ($\{I_k\}$) are taken into the plant and combined or consumed to produce energy in one or more forms (ED_{out}) as well as possibly other coproducts ($\{O_j\}$), i.e. $T(ED_{in}, \{I_k\}) = \{ED_{out}, O_j\}$. In its simplest and least informative form, EROI is the analog of the economic concept of financial return on investment using energy as the currency and assuming nonenergy inputs to be negligible. This narrowest definition yields $EROI = ED_{out}/ ED_{in}$.

Although EROI is used rarely in such a simple form (examples being 17, 30), statistics regarding different technologies are commonly reported that ignore the energy costs associated with infrastructure and nonenergy inputs (31). Note that it is important that T be defined clearly. For example, biodiesel production can be defined as taking either vegetable oil or oilseeds as an input with concomitant adjustments in energy inputs and coproducts.

Nonenergy Inputs

The reason EROI seldom conforms to the above simplistic formulation is that, depending on the definition of T, ED_{in} generally fails to account for additional and significant energy requirements essential to the production process (Fig. 2, lighter arrows). This energy is embodied in the nonenergy direct inputs (32), for example, the agricultural energy required to grow oilseeds for biodiesel (4). Precise calculation of the energy embodied in nonenergy inputs can lead to infinite regress. This may be resolved either through an input–output matrix framework or by semiarbitrarily drawing a boundary beyond which additional (and presumably negligible) energy inputs are ignored (28). The latter is the accepted approach for life cycle analyses (LCAs) (33).

The most common form of EROI applies an appropriate methodology to assess the embodied energy costs of the nonenergy inputs, which are termed the indirect energy inputs. For a given production process, this should yield a well defined set of coefficients, $\{\gamma_k\}$, that give the per-unit indirect energy costs of $\{I_k\}$ (e.g., MJ t^{-1} soybean). This yields the following version of EROI:

$$EROI = ED_{out}/(ED_{in} + \Sigma\gamma_k I_k) \qquad \text{Eq. 1}$$

The study of Brazilian ethanol by Macedo et al. (34) is an excellent demonstration of this, with energy inputs divided into levels based on whether they are direct or indirect. Some studies somewhat arbitrarily include the indirect energy costs for some inputs and exclude the energy cost of others, something that clearly creates incommensurabilities between studies (7, 35). The embodied energy costs of labor in particular are difficult to define but can be significant (4, 36).

In addition to the energy requirements, both direct and indirect, of T, there are other costs that are irreducible to energy terms in the sense that they are not normally the output of a production process with energy as an input. Examples include land, surface and ground water, and time. These inputs are difficult (some would argue impossible) to accurately reduce to energy equivalent measures. We shall refer to these as nonenergy resources so as to distinguish them from nonenergy inputs. Nonenergy resources can have direct as well as indirect components (37). 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 (21, 38).

Such direct and indirect nonenergy resources can be handled in one of two ways. The most straightforward method is to identify key, potentially limiting resources and treat them as disjoint from energy inputs. This yields a new indicator of efficiency for each resource tracked, e.g. $EROI_{land}$ measured in MJ ha^{-1}. In particular, for nonenergy resource X, $EROI_X$ is given by

$$EROI_X = ED_{out}/(\Sigma\pi_{X,k} I_k) \qquad \text{Eq. 2}$$

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

Although this perhaps increases the complexity, this method has at least two distinct advantages. First, it yields a measure of production efficiency that can be used in a systems framework to examine the scalability of a technology, especially in conjunction with other technologies that may require a different array of resources. It bears resemblance to the concept of total factor productivity, which gives a fuller and more accurate picture of productivity than does labor productivity alone. Second, a multicriteria approach enables contextual assessment of a technology. Different countries will be limited in their growth by different resources (39), a Liebig's law of the minimum for economic growth (40). Some resources (e.g., water) may be more limiting than energy (41). An ideal energy technology would have a lower $EROI_X$ for abundant resource X and higher $EROI_Y$ for scarce resource Y.

Another way to deal with nonenergy primary inputs is to convert them into energy equivalents via some set of coefficients ($\{\psi_X\}$) for all nonenergy resources X. One justification for this is that in order for any process to be truly sustainable, it must be able to regenerate all resources consumed (42). An approach adopted by Patzek (42) and Patzek and Pimentel (43) is to assign energy costs based on the exergy of a resource (44, 45), approximately defined as the ability of a system to do work and equated with its distance from thermal equilibrium. Resources such as iron ore and top soil, through their structure, contain a certain amount of negative entropy that gives them an inherent ability to do work. This can also be thought of as the amount of energy required to reconstitute a given level of order.

Given such a set of coefficients yields the following measure for EROI:

$$EROI = \frac{ED_{out}}{ED_{in} + \sum_k \gamma_k I_k + \sum_X \sum_k \psi_X \pi_{X,k} I_k} \quad \text{Eq. 3}$$

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

Nonenergy Outputs

Just as consideration of the nonenergy inputs yields a fuller and more complex EROI, so too can the nonenergy outputs be incorporated to provide a more complete indicator of the desirability of a process (Fig. 1). To begin, many technologies yield coproducts in addition to the primary energy product. It is assumed in most studies that a credit should be given for these coproducts, which is added to the numerator and thereby increases the EROI for the process. To do this, each coproduct O_j must be assigned a per-unit energy equivalency coefficient (υ_j) that indicates its value relative to the energy product.

The most straightforward method is to assign coproducts an explicit energy value based on their thermal energy content (13) or their exergy (43). However, coproducts are seldom used for their energy content (bagasse in sugar cane ethanol being an exception). Energy values can also be assigned according to the energy required to produce the most energy-efficient replacement (4), a methodology equivalent to expanding the boundaries of the technology (46, 47). Nonenergy metrics that can establish relative value include economic value and mass, both of which are frequently used in LCAs (33, 46).

Once the energy equivalency coefficients are established, the EROI formulation is modified as follows:

$$EROI = \frac{ED_{out} + \sum \upsilon_j O_j}{ED_{in} + \sum \gamma_k I_k} \quad \text{Eq. 4}$$

For example, for biodiesel from oilseeds, oilseed meal is a valuable coproduct most commonly used as a source of protein for livestock. An energy credit can be assigned to this coproduct based on its actual thermal content (35), its market value (e.g., 48), or its mass (e.g., 49). The calculated EROI can vary by a factor of two or more depending on allocation method.

Note that all coproduct credit assignments will also work for determining the energy return from nonenergy resources because they only affect the numerator.

Externalities

The analysis so far has considered only inputs and outputs that are currently recognized by the market. However, many energy production processes create outputs that have social, ecological, and economic consequences that are external to the market (Fig. 1). A full assessment of the desirability of an economic endeavor should include such impacts because they ultimately affect the net benefit to society (4). Negative externalities can include soil erosion, ground and water pollution, loss of habitat, and loss of food production capacity (5, 50). Externalities also can be positive, such as the creation of jobs and the maintenance of rural communities (51).

As with the handling of nonenergy resources, such externalities can be incorporated into the analysis 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 (52), Giampietro, Ulgiati and Pimental (12), and Hanegraaf, Biewinga and Van der Bijl (5). Again, such measures are useful for assessing the scalability of a process within a given context by indicating what resources (e.g., waste sinks) might be strained under increased production.

Negative externalities also can be assigned per-unit energy equivalency coefficients equal to the energy required to prevent or mitigate their impacts (7, 13, 53). 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.

Note that the calculation of the externalities produced may or may not include "embodied" externalities, those that result indirectly from the production of the inputs. Whereas in general the same boundaries should be used across the analysis, sufficient data may not exist to estimate externalities beyond the boundary of the direct impacts.

Summary of Methodologies

Table 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 cite one or more studies that have employed that variation. Whereas all of the works surveyed fall within the same methodological framework, as outlined above, it is clear that assumptions and terminology vary significantly among studies, resulting in conflicting results and essential incommensurability.

A WELL-SPECIFIED FRAMEWORK FOR EROI ANALYSIS

In order for EROI analysis to yield results that are clear, commensurable, and of ultimate use to researchers and policymakers, it is essential that the methodology become uniform and well specified. Such standardization has been successfully accomplished with LCAs (33). However, unlike with LCAs, it is probably not desirable or possible that EROI be restricted to a single meaning and methodology. The different levels of analysis outlined above are germane to different problems, contexts, and investigators. The problem arises when the same term is used for methodologies with different assumptions and ultimately different goals.

We propose a two-dimensional framework for EROI analyses with attached terminology that makes clear the major assumptions being used. Along the first dimension, we identify three distinct levels of analysis that can be distilled from the above examples (Fig. 2). These levels differ in terms of what they include in their analysis. The first level deals with only the direct inputs (energy and nonenergy) and direct energy outputs. We term this first order EROI, because although it is the most precise form of EROI it is also the most superficial, missing many critical energy inputs as well as ignoring coproducts. The next level, second order EROI, incorporates indirect energy and nonenergy inputs as well as credits for coproducts. This is the methodology used by LCA to estimate the EROI of an energy technology. Note that second order EROI requires two assumptions that must be made clear: *i)* What allocation method is used for the coproducts (thermal content, price, mass, exergy, etc.); and *ii)* What boundaries are used for determining indirect inputs. To qualify as second order EROI, we suggest that the boundaries should be drawn such that ignored indirect

Table 1. EROI formulations in the literature.

Cost Category	Direct	+ Indirect	+ Allocation
Energy	Cost = ED_{in}	Cost = $(ED_{in} + \sum \gamma_k I_k)$	Numerator = $ED_{out} + \sum \upsilon_j O_j$
	Wood biomass (17) Wood to electric (38)	Soy/Sunflower biodiesel (13) Solar cells (57)	Corn ethanol (7) Soy biodiesel (49)
Primary Input (X)	Cost = X	Cost = $\sum \pi_{X,k} I_k$	Numerator = $ED_{out} + \sum \upsilon_j O_j$
	Hydroelectric, X = Land (38) Various technologies, X = Water (5)	Corn ethanol, X = Various inputs (13, 42) Rapeseed biodiesel, X = Various inputs (5)	Soy biodiesel, X = Various inputs (49) Rapeseed biodiesel, X = Water (58)
Externality (E)	Cost = E	Cost = $\sum \pi_{E,k} I_k$	Numerator = $ED_{out} + \sum \upsilon_j O_j$
	Wind, E = Emissions (31) Various technologies, E = Soil loss (5)	Various technologies, E = Emissions (59) Wind, E = Emissions (60)	Biodiesel, E = Emissions (49) Ethanol, E = GHG (48)
Energy Equivalents	1) Conversion of externalities into energy: Cost = $ED_{in} + \sum \gamma_k I_k + \sum \upsilon_i E_i$ (7, 42) 2) Conversion of primary inputs into energy: Cost = $ED_{in} + \sum \gamma_k I_k + \sum \psi_X \pi_{X,k} I_k$ (13, 42)		

energy inputs are expected to be <1% of the total energy invested to avoid being incommensurable with other studies. Finally, third order EROI incorporates additional costs (and possibly benefits) for the externalities of the energy technology. Admittedly, this is the most imprecise but also the most accurate of the EROI measures (Fig. 3) in that it presents the fullest measure of the net energy available to society.

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 distinguish three choices for handling nonenergy resources and externalities. They can be ignored, yielding simple EROI (no modifier on this axis), they can be converted to energy equivalents, yielding "total EROI," or they can be handled as separate components yielding "multicriteria EROI."

Our framework is presented in Figure 3. Note that while the grid is 3 × 3, it yields only eight meaningful formulations. We would argue that the issues of scalability and sustainability require us to focus on third order forms of EROI. Energy is not the only production factor that is or will be limited. Water, land, and carbon sinks are only three examples of inputs and impacts of renewable energy production that can limit the potential of a technology (4, 12, 54). They should be included explicitly or else their cost in terms of energy should be estimated.

Finally, note that the different levels of analyses are nested hierarchically. The computation of a higher order EROI for an energy production process should readily yield all other forms of EROI found below it. That is to say, the necessary data were 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 multicriteria 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 metastudy of ethanol by Farrell et al. (7).

	EROI	Total EROI	Multicriteria EROI
1st Order	$\frac{ED_{out}}{ED_{in}}$	$\frac{ED_{out}}{ED_{in} + \sum_k \psi_k I_k}$	$\frac{ED_{out}}{I_k}$
2nd Order	$\frac{ED_{out} + \sum_j \nu_j O_j}{\left(ED_{in} + \sum_k \gamma_k I_k\right)}$	$\frac{ED_{out} + \sum_j \nu_j O_j}{\left(ED_{in} + \sum_k \gamma_k I_k + \sum_k \psi_k \pi_{X,k} I_k\right)}$	$\frac{ED_{out} + \sum_j \nu_j O_j}{\sum_k \pi_{X,k} I_k}$
3rd Order	X	$\frac{ED_{out} + \sum_j \nu_j O_j}{\left(ED_{in} + \sum_k \gamma_k I_k + \sum_k \psi_k \pi_{X,k} I_k + \sum_i \upsilon_i E_i\right)}$	$\frac{ED_{out} + \sum_j \nu_j O_j}{\sum_k \pi_{E,k} I_k}$

Figure 2. Framework of EROI methodologies. The side axis determines what to include (direct inputs, indirect inputs, and/or externalities). The top axis dictates how to include nonenergy resources (ignore, convert to energy equivalents, or treat as irreducible.) Note that because simple EROI ignores nonenergy inputs, it does not have a third order form that accounts for externalities.

OTHER CONSIDERATIONS

EROI, Nonenergy Resources, and Scale

EROI is generally measured as the ratio of the gross energy return to the amount of energy invested. However, it has been argued that this can give a false indicator of the desirability of a process because of the increasing cost of nonenergy resources as EROI approaches one (12).

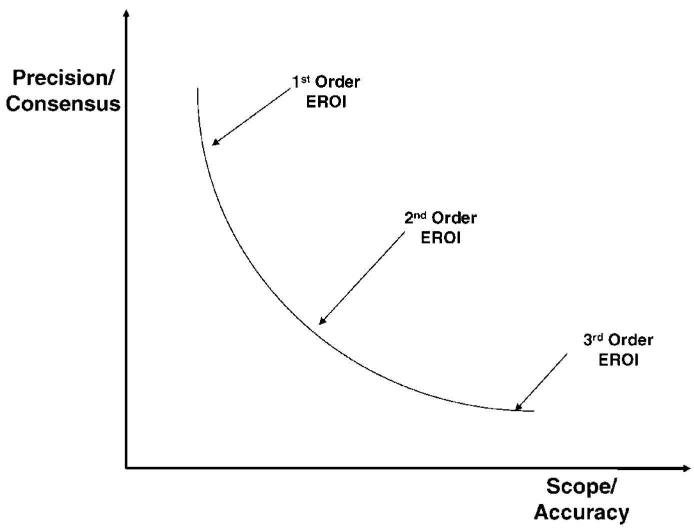

Figure 3. Relationship between EROI scope and detail and level of precision and general acceptance. As EROI measures become more comprehensive in scope and thereby more accurate, their precision decreases as does the level of consensus around their values.

Box 1.
Net energy return to land for corn ethanol

The second order EROI for noncellulosic ethanol from corn is estimated to be 1.34 (7), which implies that $\omega \approx 4$. The ethanol $EROI_{land}$ = 11 633 MJ ha^{-1} gross energy production (equivalent to 3475 l ha^{-1}). However, the net energy per unit of land is only 2908 MJ ha^{-1}. At 2004 levels of gasoline consumption for the United States, this is equivalent to consuming the net energy production of 42 hectares of cropland per second. If the second order EROI of ethanol is reduced to 1.2, a decrease of only 10%, the net return on land decreases by 33% whereas the amount of land required to achieve the same net yield increases 50%. This has significant implications for the potential scale of production (12).

Following Giampietro et al. (12), let ω = EROI/(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, this is not worrisome because all costs have been covered. However, the perspective changes regarding nonenergy resources.

Let $EROI_X$ be the energy return for one unit of nonenergy resource X. Then $1/ EROI_X$ is the number of units of X required for 1 – MJ gross energy production. From the above, it is easily seen that $\omega/EROI_X$ units of X are required, or more generally, the net energy yielded per unit of X is equal to $EROI_X/\omega$. Because ω increases nonlinearly (approaching infinity) as EROI approaches one, a relatively small change in EROI can produce a large decrease in the net EROI for nonenergy resources. For energy production processes with significant nonenergy resources such as biofuels, this suggests a low EROI can imply strong limitations on their ability to be scaled up (4, 12, and Box 1).

EROI and Energy Quality

The efficacy of EROI analysis is limited by one of its basic assumptions—that all forms of energy are fungible with a value determined by their thermal content (16). This ignores the fact that the quality of an energy source is a 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 Farrel et al. (7) in support of corn ethanol, which has the potential to convert coal (low quality) into a liquid fuel (high quality). Cleveland (16) has proposed a variant of EROI methodology that incorporates energy quality. Quality-adjusted economic analysis can even support subunity EROI energy production depending on context.

However, the study of prior civilizations suggests that low energy gain for society as a whole will have negative implications (3). The more energy required to harvest, refine, and distribute energy to society, the less that will be left for nonenergy sectors such as health care, transportation, and basic industry. This is especially important in a society that has built its infrastructure around high-energy-return inputs (55). With regard to future energy scarcity, net energy analysis is more forward-looking than conventional cost-benefit analysis and as such is an important tool for policymakers.

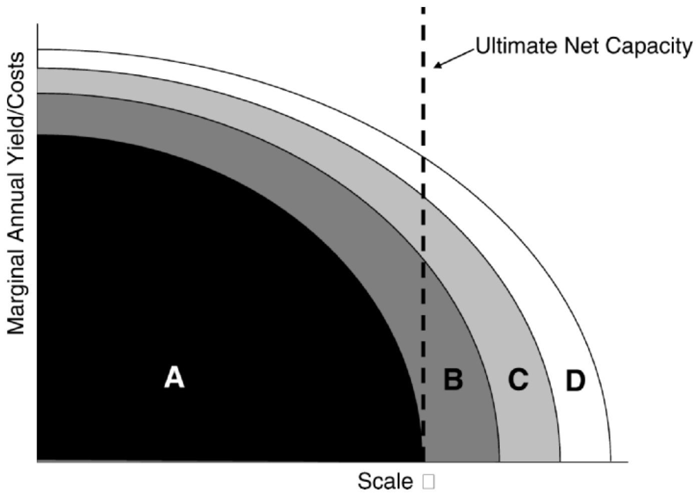

Figure 4. Annual marginal costs and yields from a given renewable energy source. As the scale of development increases, marginal annual yields tend to decrease whereas energy costs and externalities increase. D = direct energy costs, C = indirect energy costs, and B = externality energy costs. Gross energy yield X = A + B + C + D. The curve A gives the net annual yield accounting for indirect costs and externalities with the vertical line showing the maximum net annual yield.

EROI and the Net Ultimate Capacity of Resources

The theoretical graph in Figure 4 summarizes the implication of the different levels of EROI analysis. The outer curve demonstrates the marginal annual energy yield from a given renewable energy resource X (e.g., liters of biodiesel per additional hectare of crop production. The area under the outer curve represents the total gross annual yield X. Because the most efficient areas of production are developed first (e.g., best cropland, best wind sites, etc. [56]), the annual yield tends to decline whereas energy costs tend to rise with scale of development. Externalities also tend to increase.

The maximum net energy yield, or energy available for distribution to the nonenergy producing sector of society, is represented by the area of A + B + C, A + B, or A, depending on the boundaries of the analysis (first, second, or third order). The EROI for each marginal unit of development is given by X/D, X/(C + D), or X/(B + C + D) for first, second, and third order EROI, respectively.

As can be seen, early in the development of an energy technology, the percentage of the total energy that is used in production, under any of the three scenarios, is small. As a resource becomes further developed, the sum of B, C, and D becomes greater in relation to the net energy A. This relationship is quantified by a declining EROI in all three of its forms. Figure 4 shows that the peak yield in terms of net benefits to society is reached much more quickly than is the peak in gross yield.

CONCLUSION

How or whether we transition from a stock-based energy system (i.e., fossil fuels) to one based largely on flows from renewable sources may be one of the defining tasks of this generation. New energy technologies require enormous capital investments and significant lead time as well as well-defined research and planning. Aggregating decisions surrounding new 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. 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 EROI analysis in ways that are meaningful and comprehensive. Accounting for the subtle and intricate details in net energy analysis is difficult, and we do not presume that this contribution will resolve the controversy regarding what the appropriate boundaries of EROI analysis should be. However, in a growing world constrained by both energy and, increasingly, by environmental concerns, adherence to a common framework that still provides some methodological variability is essential for policymakers to accurately assess alternatives.

References and Notes

1. Lincoln, S. 2005. Fossil fuels in the 21st century. *Ambio 34*, 621–627.
2. British Petroleum. 2005. Quantifying Energy: BP Statistical Review of World Energy. Beacon Press, London, 42 pp.
3. Tainter, J.A., Allen, T.F.H., Little, A. and Hoekstra, T.W. 2003. Resource transitions and energy gain: contexts of organization. *Conservat. Ecol. 7*, 4. (http://www.consecol.org/vol7/iss3/art4/)
4. Hill, J., Nelson, E., Tilman, D., Polasky, S. and Tiffany, D. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proc. Natl. Acad. Sci. U S A 103*, 11206–11210.
5. Hanegraaf, M.C., Biewinga, E.E. and Van der Bijl, G. 1998. Assessing the ecological and economic sustainability of energy crops. *Biomass and Bioenergy 15*, 345–355.
6. Kaylen, M. 2005. An economic analysis of using alternative fuels in a mass burn boiler. *Bioresour. Technol. 96*, 1943–1949.
7. Farrell, A.E., Plevin, R.J., Turner, B.T., Jones, A.D., O'Hare, M. and Kammen, D.M. 2006. Ethanol can contribute to energy and environmental goals. *Science 311*, 506–508.
8. Cleveland, C. 2005. Net energy from the extraction of oil and gas in the United States. *Energy 30*, 769–782.
9. Ulgiati, S. 2001. A comprehensive energy and economic assessment of biofuels: when green is not enough. *Crit. Rev. Plant Sci. 20*, 71–106.
10. Environmental Protection Agency. 2002. *A Comprehensive Analysis of Biodeisel Impacts on Exhaust Emissions*. US Environmental Protection Agency, Washington D.C.
11. Kim, S. and Dale, B. 2005. Environmental aspects of ethanol derived from no-tilled corn grain: nonrenewable energy consumption and greenhouse gas emissions. *Biomass and Bioenergy 28*, 475–489.
12. Giampietro, M., Ulgiati, S. and Pimental, D. 1997. Feasibility of large-scale biofuel production. *Bioscience 47*, 587–600.
13. Pimental, D. and Patzek, T.W. 2005. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. *Nat. Resour. Res. 14*, 65–76.
14. Odum, H.T. 1973. Energy, ecology, and economics. *Ambio. 2*, 220–227.
15. Keoleian, G. 1998. Application of life cycle energy analysis to photovoltaic module design. *Progress in Voltaics 5*, 287–300.
16. Cleveland, C. 1992. Energy quality and energy surplus in the extraction of fossil fuels in the U.S. *Ecol. Econ. 6*, 139–162.
17. Gingerich, J. and Hendrickson, O. 1993. The theory of energy return on investment—a case-study of whole tree chipping for biomass in Price Edward Island. *Forest. Chron. 69*, 300–306.
18. Hammerschlag, R. 2006. Ethanol's energy return on investment: a survey of the literature 1990-present. *Environ. Sci. Tech. 40*, 1744–1750.
19. Kidd, S. 2004. Nuclear: is there any net energy addition? *Nucl. Eng. Int. 49*, 12–13.
20. Tyner, G., Costanza, R. and Fowler, R. 1988. The net energy yield of nuclear power. *Energy, 13*, 73–81.
21. Pimentel, D. 2003. Ethanol fuels: energy balance, economics, and environmental impacts are negative. *Nat. Resour. Res., 12*, 127–134.
22. Baines, J. and Peet, M. 1983. Assessing alternative liquid fuels using net energy criteria. *Energy 8*, 963–972.
23. Berglund, M. and Borjesson, P. 2006. Assessment of energy performance in the life-cycle of biogas production. *Biomass and Bioenergy 30*, 254–266.
24. Chui, F., Elkamel, A. and Fowler, M. 2006. An integrated decision support framework for the assessment and analysis of hydrogen production pathways. *Energy and Fuels 20*, 346–352.
25. Berndt, E. 1983. From technocracy to net energy analysis: engineers, economists, and recurring energy theories of value. In: *Progress in Natural Resource Economics*. Scott, A. (ed). Clarendon, Oxford, pp. 337–366.
26. Gilliland, M. 1975. Energy analysis and public policy. *Science 189*, 1051–1056.
27. Cleveland, C.J., Costanza, R., Hall, C.A.S. and Kaufmann, R. 1984. energy and the united states economy–a biophysical perpsective. *Science 225*, 890–897.
28. Spreng, D.T. 1988. *Net-Energy Analysis and the Energy Requirements of Energy Systems*. Praeger, New York, Praeger, 289 pp.
29. Letters to Science. 2006. *Science 312,* 1746–1747.
30. Southwide Energy Committee. 1980. *Petroleum Product Consumption and Efficiency in Systems Used for Energy Wood Harvesting*. American Pulpwood Association, Washington DC.
31. American Wind Energy Association. 2006. Comparative Air Emissions Of Wind And Other Fuels. (http://www.awea.org/pubs/factsheets.html)
32. Odum, H.T. 1983. *Systems Ecology: An Introduction*. Wiley, New York. 644 pp.
33. International Standard Organization (ISO). 1997. Environmental Management–Life Cycle Assessment–Principles and Framework, ed. s.e. ISO 14040. ISO, Geneva, 17 pp.
34. Macedo, I.C., Leal, M.R.L.V. and da Silva, J.E.A.R. 2004. *Assessment of Greenhouse Gas Emissions in the Production And Use of Fuel Ethanol in Brazil*. Government of the State of Sao Paulo, Sao Paulo, Brazil, 37 pp.
35. Pimentel, D. and Patzek, T.W. 2005. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. *Nat. Resour. Res. 14*, 65–76.
36. Costanza, R. 1980. Embodied energy and economic valuation. *Science, 210*, 1219–1224.
37. Wichelns, D. 2001. The role of 'virtual water' in efforts to achieve food security and other national goals, with an example from Egypt. *Agr. Water Manag. 49*, 131–151.
38. Pimentel, D., Rodrigues, G., Wane, T., Abrams, R., Goldberg, K., Staecker, H., Ma, E., Brueckner, L., et al. 1994. Renewable energy–economic and environmental issues. *Bioscience 44*, 536–547.
39. Rees, W. 1996. Revisiting carrying capacity: area-based indicators of sustainability. *Popul. Environ. 17*, 195–215.
40. Hardin, G.J. 1999. *The Ostrich Factor: Our Population Myopia*. Oxford University Press, New York, 168 pp.
41. Barlow, M. and Clarke, T. 2002. *Blue Gold: The Fight to Stop the Corporate Theft of the World's Water*. New Press, New York, distributed by W.W. Norton, 278 pp.
42. Patzek, T. 2004. Thermodynamics of the corn-ethanol biofuel cycle. *Crit. Rev. Plant Sci. 23*, 519–567.
43. Patzek, T. and Pimentel, D. 2005. Thermodynamics of energy production from biomass. *Crit. Rev. Plant Sci. 24*, 327–364.
44. Ayres, R., Ayres, L. and Martinas, K. 1998. Exergy, waste accounting, and life-cycle analysis. *Energy 23*, 355–363.
45. Ayres, R. and Martinas, K. 1995. Waste potential entropy: the ultimate ecotoxic? *Economie Appliquees 48*, 95–120.
46. deBoer, I. 2003. Environmental impact assessment of conventional and organic milk production. *Livest. Prod. Sci. 80*, 69–77.
47. Kim, S. and Dale, B. 2002. Allocation procedure in ethanol production system from corn grain-I. System expansion. *International Journal of Life Cycle Assessment 7*, 237–243.
48. Mortimer, N.D., Elsayed, M.A. and Matthews, R. 2003. *Carbon and Energy Balances for a Range of Biofuel Options*. Resources Research Unit, Sheffield Hallam University, Sheffield, 341 pp.
49. Sheehan, J., Camobreco, V., Duffield, J., Graboski, M. and Shapouri, H. 1998. l. 1998. An Overview of Biodiesel and Petroleum Diesel Life Cycles. National Renewable Energy Laboratory, Golden.
50. Pimentel, D., Herz, M., Glickstein, M., Zimmerman, M., Allen, R., Becker, K., Evans, J., Hussain, B., et al. 2002. Renewable energy: current and potential issues. *Bioscience 52*, 1111–1120.
51. Bender, M. 1999. Economic feasibility review for community-scale farmer cooperatives for biodiesel. *Bioresource Technology 70*, 81–87.
52. US Department of Energy. *Energy Systems Emissions and Material Requirements*. Prepared by the Meridian Corporation, Washington, DC.
53. Cleveland, C. and Costanza, R. 1984. Net energy analysis of geopressured gas-resources in the united states gulf coast region. *Energy 9*, 35–51.
54. Hagens, N., Costanza, R. and Mulder, K. 2006. Energy returns on ethanol production. *Science, 312*, 1746.
55. Smil, V. 1991. *General Energetics: Energy in the Biosphere and Civilization*. Wiley, New York, 369 pp.
56. Ricardo, D. 1819. *On the Principles of Political Economy, and Taxation* (1st American ed). Milligan, J. Georgetown, DC.
57. Pearce, J. and Lau, A. 2002. Net energy analysis for sustainable energy production from silicon based solar cells. In: *Proceedings of American Society of Mechanical Engineers Solar 2002: Sunrise on the Reliable Energy Economy*. Cambell-Howe, R. (ed). American Society of Mechanical Engineers, New York.
58. DeNocker, L., Spirinckx, C. and Torfs, R. 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.
59. European Commission, ExternE, Externalities of Energy, Methodology Report (Vol. 1). European Commission DG Research, Brussels, 287 pp. (http://ec.europa.eu/research/energy/pdf/kina_en.pdf)
60. Schleisner, L. 2000. Life cycle assessment of a wind farm and related externalities. *Renew. Energ. 20*, 279–288.

61. We would like to thank Charlie Hall, Ana Unru Cohen, Tad Patzek, John Goodnow, Cutler Cleveland, and an anonymous reviewer for comments made on earlier drafts of this work.
62. First submitted 16 February 2007. Accepted for publication 27 March 2007.

Kenneth Mulder is an adjunct assistant professor of Environmental Studies at Green Mountain College. His address: Green Mountain College, 1 College Circle, Poultney, VT 05764, USA.
E-mail: mulderk@greenmtn.edu

Nathan John Hagens is a Graduate Research Assistant at the Gund Institute for Ecological Economics at University of Vermont. His address: Gund Institute for Ecological Economics, University of Vermont, 617 Main Street, Burlington, VT 05405, USA.
E-mail: nhagens@uvm.edu