TOWARDS AN APPLIED NET ENERGY FRAMEWORK

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ABSTRACT

Energy sources require energy and non-energy inputs in order to find, process, and deliver services to society. The size and quality of the remaining 'net' energy is what powers modern civilization. As fossil fuels deplete this biophysical ratio of energy return on energy input (EROI) tends to decline, gradually freeing up less surplus energy for the productive economy. Due to its reliance on fiat currencies with no resource backing, standard economic analysis does not accurately account for this physical depletion of our resource base. As such, new biophysical frameworks that measure our balance sheet in natural resources terms would be of great value in assessing viable energy trajectories after hydrocarbons peak. However, biophysical analysis in general and EROI in particular are in need of further refinement and development if they are to be used as tools in the upcoming energy transition.

EROI analysis lacks a consistent framework and has yielded apparently conflicting results in the literature. A framework establishing appropriate boundaries of analysis is suggested in this dissertation that would make net energy and life cycle analyses commensurate across studies. Specifically, parsing EROI analysis into two different dimensions based on energy costs included and quantification of non-energy resource inputs (like water or land) would be of great value. Furthermore, incorporating the opportunity costs of internally produced and consumed energy stocks when applied to important chained production technologies would result in a more consistent application of net energy analysis.

Toward these ends, a comparative analysis for estimating the energy return on water invested (EROWI) for several renewable and non-renewable energy technologies reveals that the most water-efficient, fossil-based technologies have an EROWI one to two orders of magnitude greater than the most water-efficient biomass technologies, implying that the development of biomass energy processes in scale sufficient to be a significant source of energy may produce or exacerbate existing water shortages. Furthermore, when a time factor is introduced, many renewable technologies (e.g. wind and solar) experience a large handicap due to their frontloading of energy inputs (and investment). Additionally, the omission of output variability ignores the preference for energy systems with stable returns and low dispersion versus equivalent returns that are intermittent or volatile. This has a direct relationship to many new energy technologies with outputs of much larger volatility in comparison to traditional energy sources. For instance, the impact of intermittence on the energy return of wind power is significant. Similarly, the constant flow of baseload electricity in the form of nuclear energy also undergoes a net energy handicap relative to fluctuating human demand systems.

This dissertation is a step towards accurate evaluation of our energy balance sheet in resource terms relative to societal demand and usage. By expanding the boundary conditions of net energy analysis to include non-energy inputs, as well as explicitly addressing the timing and risks of energy delivery systems, we can better assess our available means, and therefore invest more wisely in our energy future.

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CHAPTER 1: INTRODUCTION

1.1 Overview

Modern civilization is built on a planetary energy subsidy that humanity largely takes for granted. The energy footprints attached to everyday modern conveniences make kings and queens of a few centuries ago seem like energy paupers. One barrel of oil contains around 5.7 million BTUs – a heat content that would take an average man several years of manual labor to generate. The average American as of 2007 consumes 57 barrels of oil equivalents in energy per year, equating to over a hundred years of human labor output (BP 2007). We indeed are the kings and queens of our species history, with fossil fuels as our slaves.

Looked at from an evolutionary perspective, the history of life on planet earth is also a history of the use of energy. Living things require energy to live. Throughout biological history, organisms that most efficiently located, harvested and utilized high-quality energy sources have had survival advantages (Macarthur 1966). Net energy gain, the difference between how much energy an organism receives for its effort and how much energy it expends, has been integral in the evolution of the structure and form of present day organisms (Lotka 1923, Odum 1995). Thus the true value of energy to an organism or an entire species is the net energy that is left over after subtracting the costs of finding, extracting, refining and delivering the energy (Odum 1971). Whether it was honeycomb for a black bear, termites for an anteater, or natural gas for a Russian businessman, the benefit conferred through a direct increase in surplus energy and from any subsequent excess transferred to offspring has been favored in the process of natural selection.

Humanity's own history on the planet is one of using the condensed energy of the sun. For millennia, our ancestors hunted animals and harvested plants that used photosynthesis to grow. For most of earth's past, there were not enough humans on the planet to consume much of the primary production from sunlight embodied in plants. Excess plant matter was then buried and eventually decayed and formed into what we now refer to as fossil fuels (oil, natural gas, and coal). A few hundred years ago, humans developed the technology to fully scale the concentrated energy in coal deposits, followed shortly thereafter by crude oil and natural gas, thereby freeing up vastly more energy that could be eaten directly. Today the vast majority of our per capita energy production (98%) is spent on non-nutritive exosomatic consumption (Price 1995, EIA 2008). In a very brief span of history, humanity has collectively switched from living a hunter gatherer existence, to leveraging wood, then coal, then the highly energy dense deposits of ancient sunlight in oil and natural gas (Cleveland 2006). We have gradually, with rapidity at times, advanced modern human civilization to a global scale, with liquid fuel in jets, trucks, and automobiles providing the glue that links people and products together. When coal is included, fossil fuels make up 87.7% of global primary energy use (BP 2007), which means we have nearly completely moved our culture from one based on energy flows to one based on stocks.

These high quality fossil fuels, in a momentary span of planetary history, have been run through the human thermodynamic demand machine, providing people with needs and wants and eventually ending up as unnoticed dissipated heat and waste. But it may not always be so. Exponential growth of world energy production peaked in 1970 (Duncan 2009). In 1979, we began a 30 year plateau in per capita energy consumption in the United States and the World (BP 2007, Duncan 2009) (Figure 1).

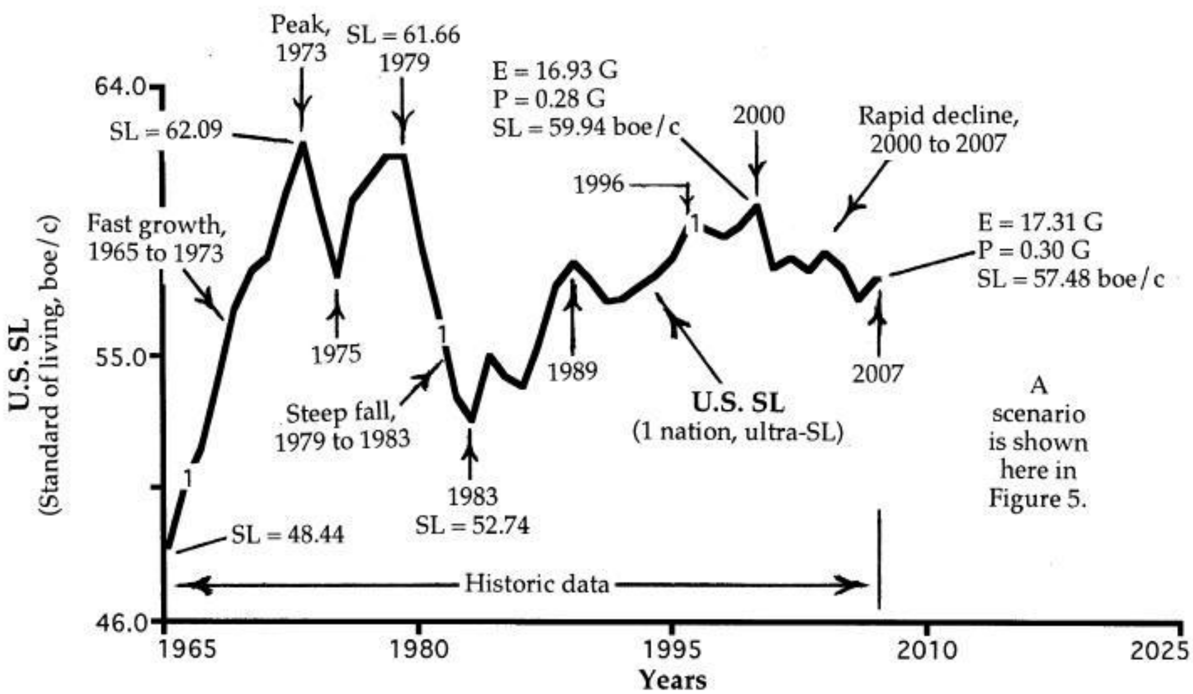

Figure 1 U.S. Energy Per Capita (Duncan 2007)

Though the percentage of renewable energy the world uses has gone from nearly 100% three centuries ago to around 10% today (mostly hydroelectric), acknowledgement is growing that fossil fuels are not only finite, but that we may reach geological production limits sooner than we are prepared for (Hirsch 2005). Natural limits combined with an unfolding sovereign credit crisis, has many stating that 2005 was the year of so called ‘Peak Oil’, the point when maximum sustained production will have globally been passed. Peak Natural Gas and Peak Coal are expected to follow (Energy Watch Group 2007).

After the point in time of maximum global production, roughly 50% of the world's ultimate recoverable oil will still be underground, but it will on average be of lower quality, found in deeper and harder to locate deposits in increasingly environmentally or politically sensitive areas (Deffeyes 2005). The 2^{nd} law of thermodynamics (the entropy law) suggests that at some point, the human ascent up the energy density ladder will run out of new steps, which will at best leave us with no increase in energy available and at worst manifest in a rapid decline in the energy available per capita (Hubbert 1949, Georgescu-Roegen 1971). We know from the work of historian Joseph Tainter (1988, 2006) that past civilizations unable to match increases in complexity with increases in net energy eventually collapsed. The majority of historical violence and war was due to drops in resource availability per capita (Bannon 2003, Keeley 1997). Today, the net energy available to the average human is in decline (Hall 2009). Our socio-economic system combines energy with a myriad of other minerals and natural resources which also are finite both in absolute and in their cost to harvest. The challenge we now face is to realign our expectations with what's possible in the transition from fossil to solar energy. Work funded by the US Department of Energy, termed the 'Hirsch Report', suggests we need 10–20 years of lead time before a global peak in oil production to prepare alternative infrastructure and new energy systems to avoid dramatic liquid fuel shortfalls (Hirsch 2005). Unfortunately, the alternatives proposed in that report, even were they to be timely – oil shale, tar sands, and coal-to-liquids using Fischer-Tropsch technology – all have deleterious impacts on environmental health (Jaramillo 2008).

Development of energy systems from renewable sources such as wind, solar, and biomass, are considered an important priority use for our existing high net energy assets. However, the complexity of our daily routines cannot easily be replicated by sources with differing energy properties compared to fossil fuels such as; net energy; gravimetric, volumetric and power densities; intermittency; temporal and spatial distribution; and volatility (Cleveland 2007). Additionally, the recent bonanza of nearly free energy has liberated historical constraints of human impact on the planet, as we have created 'heat machines' and infrastructure that magnifies energy's impact in the pursuit of the modern barometer of relative fitness: economic growth. This pursuit has in turn accelerated impact on the planet's ecosystems through measures of anthropogenic increases of carbon in the atmosphere, reduced depth of topsoil, water shortages, and myriad other environmental factors (Cleveland, 2007). Water is already a limiting resource in many contexts (Gleick 2000), and increasing human withdrawals will have a dramatic effect on the earth's ecosystems and biodiversity (Alcamo 2005). As such, energy supply choices will have to be studied not only for the energy properties they exhibit, but also on their external impacts.

Energy has been increasingly joined by debt as the two primary drivers of GDP growth. Soddy was the first to suggest that virtual wealth (credit) facilitated the introduction of flow of primary wealth into tertiary wealth (Soddy 1928). But once energy per capita peaked in the early 1970s, we have replaced this driver with increasing amounts of borrowing. Since 1966, debt increases have grown faster than national income in every single year (Figure 2). Total net annual tax receipts (individual plus corporate taxes less social security outlays) to the government are now only 15% of annual expenditures, the difference being procured via new debt issuance (OMB 2010). We now have total debt levels (government, individual, corporate and financial) both in the US and in the developed world approaching north of 500% of GDP, a ratio that not only will be unlikely to be paid back, but is also unlikely to be serviceable at some future date. This debt has functioned as a spatial and temporal reallocator of resources away from the periphery and future towards the center and present. Though debt technically is a zero sum game, i.e. one man's debt is another's retirement asset, the relationship between primary wealth (natural resources) and digital claims on the future availability of these resources is becoming increasingly disconnected.

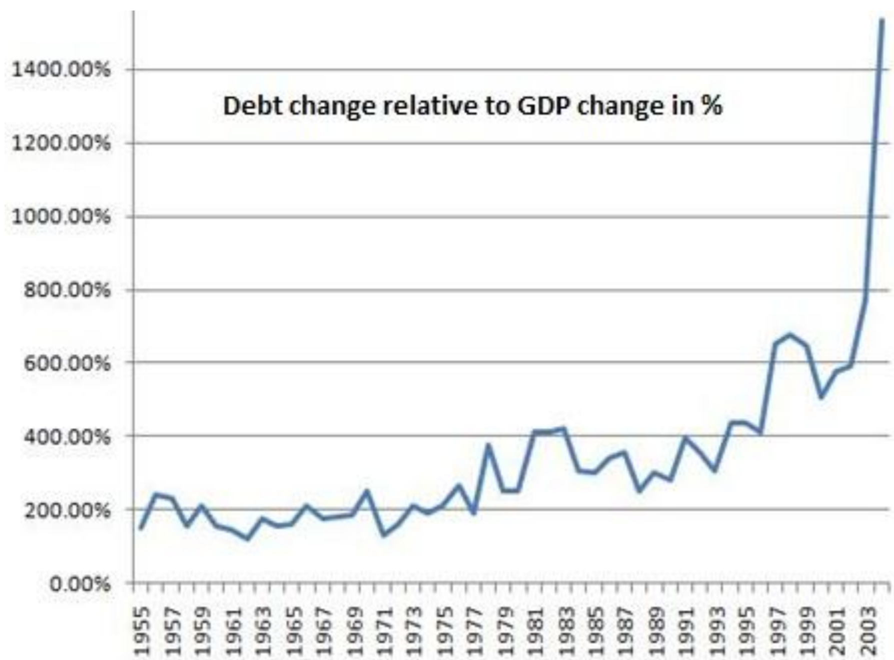

Figure 2 Total U.S. Debt Change vs U.S. GDP Change

(Source: Federal Reserve Standards Board 2008)

A relevant question to this dissertation then, is if society is overextended due to the lack of capital constraints on leverage and debt, will we be able to afford the prices needed by energy companies to initiate drilling to procure the remaining fossil fuel prospects. Indeed, it appears by many counts that the ‘affordable energy’ era is reaching a close, partly due to higher costs for energy but equally due to general insolvency from over-indebtedness of OECD bloc nations. Fifteen consecutive decades (1830-1970) showed real wage increases in America – from 1973 onwards – however real wages have more recently been flat and or in decline (Wolff 2009). The productivity gains and resulting corporate profits since have been primarily shared by the wealthiest 10% of society. (FRB 2009). To keep consuming positional goods, Americans increasingly turned to leverage starting in the 1970s, and if we include unfunded social security and medicate are now the most heavily indebted nation in the world to the tune of over $700,000 per individual (Walker 2009, FRB 2009). Each marginal oil barrel consumed comes 70% from within other nations borders, yet it is paid for by growing debt and the willingness of the few nations with surplus savings to loan, most significantly China. Many are beginning to question the sustainability, let along the desirability, of this path.

With an average marginal cost for new wells of over $60 in the US (Figure 3), any economic contraction brought about by unwinding of the overinflated global credit supply will cause oil, priced at the marginal barrel, to even go lower in price. The lower it goes, the more it shuts out future higher cost production and steepens the decline rate of aggregate production. (This same dynamic is present in North American Natural Gas (Wolff 2008). Though it is most effective as a conceptual tool, better understanding of Energy Return on Investment metrics could enlighten policymakers to some very real impacts on our economy and societal trajectories going forward. At some point, oil (and other energy sources) will cease to have prices that are both affordable to consumers but still profitable for producers. It is at that time we start to slide down the net energy cliff.

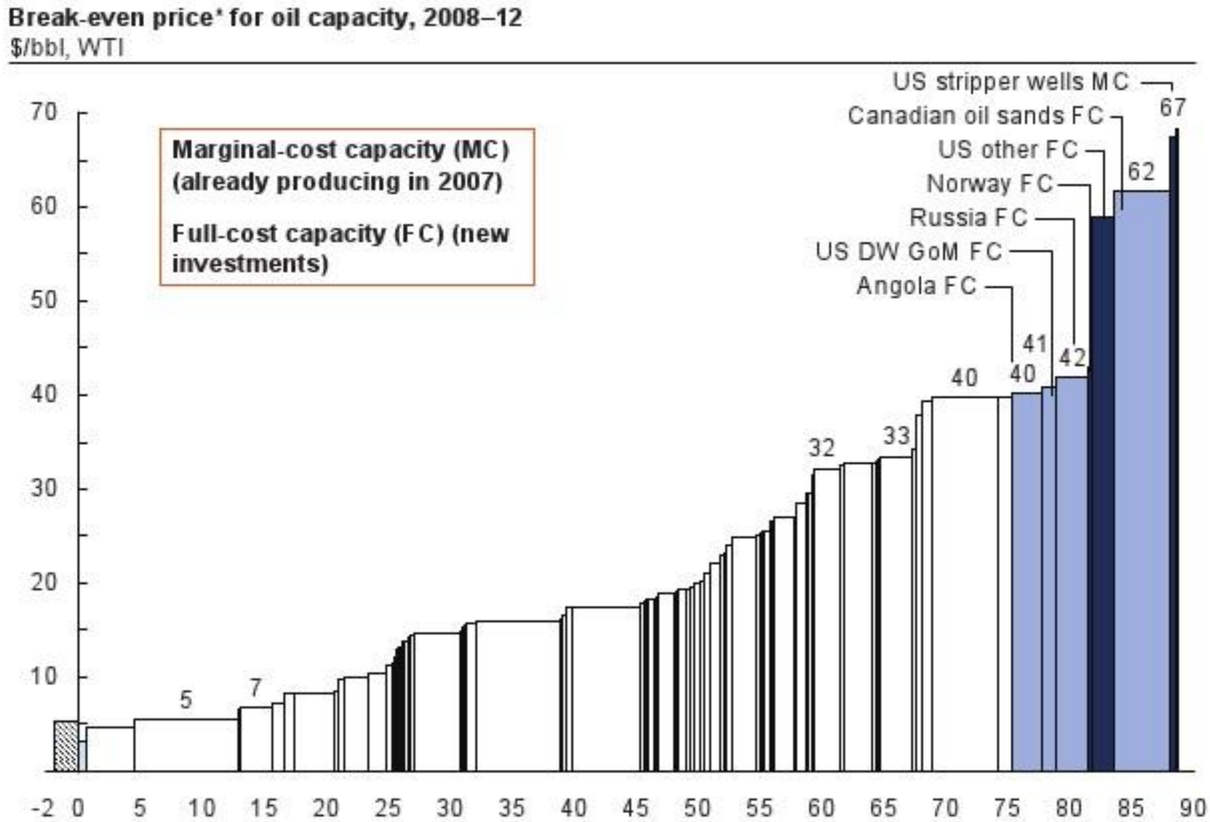

Figure 3 Break Even Oil Price by Capacity

(Source: McKinsey GEM, 2010 using IEA, Wood Mackenzie, Interstate Oil and Gas Compact Commission)

Available energy is what has always enabled us and continues to allow us to realize our plans in the physical world. If aggregate net energy continues its declines, a greater percentage of society will have to be involved in the energy sector (equivalently, more human labor will substitute for fossil). Recent attention to corn-derived ethanol suggests that we could replace a large portion of our highly energy dense crude oil from a low energy density agricultural product. Even if the energy gain of ethanol were an aggressive 2:1 ratio, it would suggest that a large percentage of society would need to work in corn planting and harvesting, ethanol processing and distribution, and so on. High EROI sources allow us to invest very little and keep excess resources for other areas of society. At an aggregate energy gain of 20:1, only 5% of society's energy budget would be required by the energy sector itself. But to procure 85+ million barrels per day of oil equivalent at a 2:1 energy gain then, we would need to grow the equivalent of 170 million barrels per day of corn ethanol (thus freeing up 85 million barrels for the non-energy sector). Even if we had the acreage to accomplish this feat, such an endeavor would displace land, labor and inputs previously assigned to other productive endeavors. At the same time, if we switch away from liquid fueled transportation, this may have impact on other non-energy social inputs. For example, if hybrid/electric cars would fully replace gasoline vehicles using the same electricity technology, approximately three times more water is consumed and 17 times more water is withdrawn, primarily due to more water cooling of increased thermoelectric generation (Webber 2008).

In conclusion, due to its reliance on fiat currencies as a metric, standard economic analysis does not accurately account for the physical depletion of a resource. Energy is treated the same as any other input to the production process, though it is a *requirement* for the production of everything. It is important to understand that supply side energy analysis cannot be accurate if the demand side is ignored –specifically how much of what scarce resources can be afforded by how many. The unfolding international credit crisis highlights the dangers of relying on strictly monetary measures for biophysical planning – credit and debt can be created with no underlying physical foundation. In a growing world constrained by both energy and increasingly by environmental limitations, adherence to a more pluralistic, multi-criteria framework for natural capital will be essential for policymakers to assess energy and other limiting alternatives. Such a framework will help us to discard energy dead-ends that would be wasteful uses of our remaining high quality fossil sources and perhaps equally as important, of our time and effort. Analysis that examines our energy and environmental balance sheets may highlight finite limits to human growth aspirations, and thus will be best married to a similar framework in the social sciences. In a transition from stock-based to flow-based resources, our modern world is in great need of science that both quantifies our available means, and reassesses the appropriate ends.

1.2 Description of Papers

1.2.1 Net Energy: Towards a Consistent Definition

Energy Return on Investment (EROI) is an important statistic for evaluating alternative energy technologies and is frequently cited by policy makers. However, the traditional definition of EROI is flawed and produces inconsistent estimates when applied to important chained production technologies such as cellulosic ethanol. This is because it ignores the opportunity costs of internally produced and consumed energy stocks. We present a consistent definition for EROI and demonstrate how it provides a different assessment of the net energy contribution of chained production technologies. In particular, our definition helps clarify the distinction between energy harvesting and energy conversion.

For example, Brazilian ethanol double counts the bagasse (the lignin from the sugar cane) and therefore overestimates true EROI by a factor of 2. This is because it ignores the opportunity costs of internally produced and consumed energy stocks. A more consistent definition for EROI provides a different assessment of the net energy contribution of chained production technologies as well as clarifies the distinction between energy harvesting and energy conversion. The important takeaway from this paper is the net energy estimates for Brazilian ethanol and other cellulosic pro-forma estimates are over-exaggerated as the energy from the bagasse is not counted as an input, and could have other energy uses for society.

1.2.2 Net Energy: Towards a Consistent Framework

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 (EROI), can measure the biophysical properties of a resources progression over time. There has been sporadic and disparate use of net energy analysis for 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 paper attempts to place these analyses in a common framework that includes both energy and non-energy inputs, environmental externalities, and non-energy co-products. It also assesses 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.

Net energy analysis attempts to steer decisions more towards physical principles, but its usage since being temporarily adopted in 1970s by the Federal Nonnuclear Energy Research and Development Act has been sporadic (Gilliland 1975). The problem is that everyone is speaking different languages in their analyses. Some analyses are inclusive in their treatment of inputs and outputs while others are very narrow. This disparity in what is included and how it is measured has led to difficulty of accurate comparisons of energy research in policy discussions, and thereby hampered their use. This paper attempts to place these analyses in a common two dimensional framework that incorporates both energy and non-energy inputs, environmental externalities, and non-energy co-products. The framework presented can in theory be expanded beyond energy return to a formula for maximizing the return on any limiting natural resource input, quantified in natural resource terms as opposed to market metrics. This type of accounting for the subtle and intricate details in net energy analysis will not be easy, and it is acknowledged that ultimately EROI will function more as a blunt instrument than one with laser precision.

This paper starts with a review of the majority of extant literature on EROI, net energy analysis, energy profit ratio, energy gain, life cycle analysis of energy, etc. It then attempts to parse the various analyses into a common framework suggested to make future analyses commensurate. The results provide a framework for *what* is included in the energy boundaries of analysis and *how* it is included formulaically.

1.2.3 Energy Return on Water Invested

While various energy-producing technologies have been analyzed to assess the amount of energy returned per unit of energy invested, this type of comprehensive and comparative approach has rarely been applied to other potentially limiting inputs such as water, land, and time. This paper conducts a comparative analysis for estimating the energy return on water invested (EROWI) for several renewable and non-renewable energy technologies using various life cycle analyses (LCA). The results suggest that the most water-efficient, fossil-based technologies have an EROWI one to two order of magnitude greater than the most water-efficient biomass technologies, implying that the development of biomass energy technologies may produce or exacerbate water shortages around the globe and be limited in scale by the availability of fresh water.

Water is similar to oil in that it is embedded in all human systems, even if it is not directly recognized as such. Water withdrawals are ubiquitous in most energy production technologies. Indeed, by sector, the two largest consumers of saltwater and freshwater in the United States are agriculture and electrical power plants, both prominent players in the future energy landscape (Berndes 2002). If only fresh water is considered, fully 81% of the US use is for irrigation (Hutson 2004). Implicit in the attention to energy return on energy invested (EROI) as a policy criterion is the assumption that energy is the sole limiting resource of importance, with the determining factor generally being whether and by how much EROI exceeds unity. All other potentially limiting factors are implicitly assumed proportional to the energy needed to drive a process (Cleveland 1984). Even studies that seek to move the focus away from EROI, such as the analysis of ethanol, restrict their focus to energy inputs (Farrell 2005). A partial exception to this is the fact that some studies examining the EROI of a technology also estimate its potential impact upon the production of greenhouse gases (Sheehan 1998) Desalination in particular is alarming because it is approximately ten times more energy-intensive than production from surface freshwater sources such as rivers and lakes. But measuring the input and output of one scarce resource in terms of itself can be enhanced by including the costs of other potential limiting resources. For example, growing biofuels consumes more than 1000 gallons of water for every gallon of fuel that is produced (NRC 2008). Sometimes this water is provided naturally from rainfall, however for a non-trivial proportion of our biofuels production, irrigation is used. Irrigated biofuels from corn or soy can consume twenty or more gallons of water for every mile traveled (Webber 2008). Furthermore, fully half of the water withdrawn in the US is used for thermo-electric plant cooling.

To calculate a gross EROWI we attempted to estimate the total water requirements per unit of energy produced. Where data allowed, we estimated separate EROWI measures for both water withdrawals and water consumed. Water consumed is likely to be much smaller than that which is actually withdrawn, and for this reason the data available generally only indicate water withdrawals. Ideally, EROWI is estimated for a given technology by applying the life cycle analysis (LCA) methodology (ISO 1997) to calculate freshwater usage per unit energy produced (in liters per megajoule, L/MJ) for a given technology. In particular, for each technology assessed, we sought to do the following:

1) Define the technology precisely including the context of production and all assumptions regarding inputs;
2) Find data in the literature for direct water inputs into the technology as well as indirect inputs defined as the water required to produce non-water inputs;
3) Set the system boundaries clearly and sufficiently wide so that remaining water requirements are negligible.

Where co-products are produced at a stage in the production process (e.g. soybean meal in the production of soy biodiesel) and data allowed, price allocation was chosen to apportion the water inputs. Where data were available, we calculated the energy produced per unit of water consumed in addition to the EROWI for water withdrawals.

The analysis used estimates of each technology's EROI to calculate a 'net EROWI'. From both a policy and technology perspective it is the net EROWI that we are interested in because for the process to be sustainable, some of the energy yield must be reinvested as indicated by the EROEI. These methods and calculations were used for each of 16 energy technologies assessed. While the methodology described above is the generally accepted procedure for LCA, it should be noted that there are many potential costs, both in terms of water and energy that are still ignored. In particular, costs associated with environmental externalities are generally not accounted for.

Ultimately, both water and energy can be enabling for the other: with unlimited energy, we could have unlimited freshwater; with unlimited water, we could have unlimited energy. There are costs to each, with the other being an input. The development of bioenergy will likely have a strong, negative impact upon the availability of fresh water. Assuming the water requirements for infrastructure development are minimal, technologies such as solar and wind which do not require on-going water inputs will be at an advantage in many contexts. Above all, the analysis demonstrates that energy technologies must be assessed in a multi-criteria framework and not just from the perspective of energy alone. As such, we should strive to have a renewable portfolio aggregating the highest returns on our most limiting inputs.

1.2.4 Net Energy and Time

Net energy analysis is a key metric used to compare different energy technologies. This is typically done by measuring total energy outputs against expended energy inputs over the life cycle of an energy procuring technology, for example a wind power generation plant or an natural gas well. Results are typically presented in the form of net energy gain, energy payback time or EROI (energy return on energy investment). In these methodologies, the time between energy inputs and energy outputs is not factored into the calculations, and the summary net energy statistic essentially values energy inputs at time t nominally versus energy outputs at time t+n**,** where n is any year during the life cycle of a production or extraction method.

Biological organisms, including human societies both with and without market systems, discount future outputs over those available at the present based on the risks associated with an uncertain future. This preference for current returns, rooted in biology, is represented in the world of finance and economics by the concept of net present value, which handicaps future values using implied costs for time.

As energy generation technologies vary greatly on a temporal continuum and energy and infrastructure investments must compete amongst an increasing diversity of technologies, there is a strong case to incorporate time into net energy analysis/EROI models as a measure of energy quality. For example, solar panels or wind power engines, where the majority of energy (and monetary) investment happens before they begin producing, will need to be assessed differently when compared to fossil fuel extraction technologies, where a large portion of the energy (the fuel) will only be applied at the time of energy output consumption. This paper introduces a theoretical model to correctly account for time in net energy/EROI calculations and applies this concept to a number of energy technologies.

The timing of energy output relative to input for most renewable energy technologies, provides a moderate to large handicap to their nominal energy gain. However, surprisingly, due to a) relative constant input of energy inputs and b) a high degree of early depletion per well/field, the nominal energy gain from many fossil fuels doesn't change much, and in many cases actually increases, following application of some discount factor.

1.2.5 Net Energy and Variability

One key approach to analyzing the feasibility of energy generation and extraction technologies is to understand the net energy they contribute to society. These analyses most commonly focus on a simple comparison of expected energy outputs of a source to the required energy inputs, measured in the form of net energy, energy payback time, or energy return on investment (EROI).

What is not factored into net energy and EROI calculations is the influence of output variability. This omission ignores a key attribute of biological organisms and societies alike: the preference for stable returns with low dispersion versus equivalent returns that are intermittent or volatile (Sharpe 1994, Kacelnik 1996). This biologic predilection, observed and refined in academic financial literature, has a direct relationship to many new energy technologies whose outputs typically show much larger volatility in comparison to traditional energy sources and also are often not or only partially controllable.

This paper investigates the impact of risk on net energy metrics by developing a theoretical framework that applies financial and biological risk models to energy systems. The impact of variability on energy return is then illustrated using a number of sample technologies in electricity generation, with more detailed analysis on wind power, where intermittence and stochastic availability of hard-to-store electricity is factored into returns.

The intermittency impact of flow based energy creates a significant handicap to stock based energy sources vis a vis its higher standard deviation relative to human demand systems. The studied cases of wind, solar and nuclear show energy 'handicaps' of between 20-70% due to intermittency. Ultimately, this paper is aimed at developing a broader conceptual framework that assesses energy technologies against their specific variability risks in generation and application.

1.2.6 Conclusions

The issues of net energy and natural resources presented in this dissertation have been discussed before, many of them for decades. Yet little progress has been made towards an alternative economic system that either recognizes limits to our supply side balance sheet or differentiates between wants and needs based on our evolved role as adaptation-executors (Gigerenzer 2002, 2008). Given the amount of debt amassed in OECD nations, it is likely that social/behavioral limits will be hit before societies recognize and act upon hard resource (source) and environmental (sink) limits. Even though resource depletion underlies many of the fundamental problems in our economies, it is unlikely that biophysical analysis will ever be integrated into our *current* economic system. Though energy and natural resources, not dollars, are what we really have to budget and spend, this recognition will likely come only after the dollar-as-marker regime is disrupted, not before. As such, this dissertation attempts to move towards a framework that might be used if and when a new economic system emerges more tethered to natural capital.

REFERENCES

Alcamo, J., van Vuuren, D., Ringler, C., Cramer, W., Masui, T., Alder, J., & Schulze, K. (2005). Changes in nature's balance sheet: model-based estimates of future worldwide ecosystem services. *Ecology and Society*, *10*(2), 19.

Bannon, I. & Collier, P. (2003). *Natural Resources and Violent Conflict.* The International Bank for Construction and Redevelopment, Washington DC.

Cleveland, C.J., Costanza, R., Hall, C.A.S., & Kaufmann, R. (1983). Energy and the United States economy: a biophysical perspective. *Science*, *225*, 890-897.

Deffeyes, K. (2005). *Beyond oil: the view from Hubbert's peak*. Hill and Wang. New York.

Duncan, R. (2005-2006, winter). Energy, population and industrial civilization. *The Social Contract.*

Duncan, R. (2009, spring). Olduvai theory: toward re-equalizing the world standard of living. *The Social Contract.*

Erickson, J., & Gowdy, J. (2007). *Frontiers in ecological economics*. Williston, VT: Elgar Publishing.

Energy Watch Group. (2007, April). *Coal: resources and future production.* Retrieved Mar 15, 2010 from http://www.energywatchgroup.org/files/Coalreport.pdf.

Farrell, A., Plevin, R., Turner, B., Jones, A., O'Hare, M., & Kammen, D. (2006). Ethanol can contribute to energy and environmental goals. *Science*, *311*, 506-508.

Federal Reserve Bank. (2009, March 12). *Flow of funds of the United States fourth quarter 2008*.

Gigerenzer, G. (2008). *Gut feelings, the intelligence of the unconscious*. New York: Penguin.

Gigerenzer, G. (2002). *Bounded rationality, the adaptive toolbox.* Boston: MIT Press.
Gleick, H. (2000). *The world's water.* Washington, D.C.: Island Press.

Hagens, N., & Mulder, K. (2008). A framework for energy alternatives: net energy, Liebig's law and multi-criteria analysis. In *Biofuels, solar and wind as renewable energy systems.* Netherlands: Springer.

Hall, C.A.S., Balogh, S., & Murphy, D. (2009). What is the Minimum eroi necessary for civilization? *Energies*, *2*(1), 25-47.

Hirsch, R., Bezdek, R., & Wendling, R. (2005). *Peaking of world oil production: impacts, mitigation, and risk management.* Washington D.C.: Department of Energy.

Hubbert, M. (1949). The Energy from fossil fuels. *Science*, *109*, 103-109.

Hutson, S., Kenny, J., Barber, N., Linsey, K., Lovelace, J., & Maupin, M. (2004). *Estimated use of water in the United States in 2000*. US Geological Survey. Washington DC.

Jaramillo, P., Griffin, M.W., & Matthews, H. (2008). Comparative analysis of the production costs and life-cycle ghg emissions of ft liquid fuels from coal and natural gas. *Environmental Science Technology*, *42*(20), 7559-7565.

Kacelnik, A., & Bateson, M. (1996). Risky theories - the effects of variance on foraging decisions. *American Zoologist*, *36*(4), 402-434.

Keeley, L. (1997). *War before civilization: the myth of the peaceful savage*. New York: Oxford University Press.

Lotka, A.J. (1922). Natural selection as a physical principle. *Proc of National Academy of Science*, *8*, 151-154.

MacArthur, R.H., & Pianka, E.R. (1966). On the optimal use of a patchy environment. *American Naturalist*, *100*(916), 603-609.

McKinsey Global Institute. (2009, March). *Averting the next energy crisis: the demand challenge.* McKinsey & Company.

National Resource Council - Committee on Water Implications of Biofuels Production in the US. (2008). *Water implications of biofuel production in the United States.* Washington D.C.

Odum, H.T. (1971). *Environment, power, and society*. New York: Wiley-Interscience.

Odum, W.E., Odum, E.P., & Odum, H.T. (1995). Nature's pulsing paradigm. *Estuaries, 18*, 547-555.

Office of Management and Budget. (2010). *Historical Tables – Budget of the* United States Government *2010.* Retrieved August 8, 2010 from http://www.gpoaccess.gov/usbudget/fy10/pdf/hist.pdf .

O'Malley, C. (producer), & Creadon, P. (director). (2009). *IOUSA.* [motion picture]. USA: O'Malley Creadon Productions.

Price, D. (1995). Energy and human evolution. *Population and Environment: A Journal of Interdisciplinary Studies*, *16*(4), 301-319.

Sharpe, W.F. (1994). The Sharpe ratio. *Journal of Portfolio Management*, *21*(1), 49-58.

Soddy, F. (1926). *Wealth virtual wealth and debt*; *the solution of the economic paradox*. London: George Allen and Unwin LTD.

Tainter, J. (1988). *The Collapse of complex societies*. Cambridge, UK: Cambridge University Press.

Webber, M., & King, C. (2008). The Water intensity of the plugged-in automotive economy. *Environmental Science & Technology*, *42*(12), 4305-4311.

Wolff, J. (2008). Marginal cost for North American natural gas production. (2008). *Credit suisse equity research*.

Wolff, R. (2009, July 16). *Peak oil and peak capitalism*. Retrieved from http://www.theoildrum.com/node/5245

CHAPTER 2: NET ENERGY: TOWARDS A CONSISTENT DEFINITION

2.1 Abstract

Energy Return on Investment (EROI) is an important statistic for evaluating alternative energy technologies and is frequently cited by policy makers. However, the traditional definition of EROI is flawed and produces inconsistent estimates when applied to important chained production technologies such as cellulosic ethanol. This is because it ignores the opportunity costs of internally produced and consumed energy stocks. We present a consistent definition for EROI and demonstrate how it provides a different assessment of the net energy contribution of chained production technologies. In particular, our definition helps clarify the distinction between energy harvesting and energy conversion.

2.2 Introduction

The transition from fossil fuels to renewables will require consistent and meaningful metrics for comparison of alternative energy development pathways. Energy quantity, energy quality and ecosystem impacts will be among the relevant criteria for assessing new energy choices as society shifts away from oil, gas and coal [1, 2]. One important measure of the utility of a renewable energy technology is its net energy, or how much of a gross energy resource is available after the energy required to procure it is subtracted [3]. One statistic of net energy prevalent in the literature is Energy Return on Investment (EROI) equal to the ratio of the energy produced to the energy required for production [4, 5]. The higher the EROI of a new energy technology, *ceteris paribus*, the better it functions as a source of energy. An EROI of 1.0 implies that every energy unit of output requires an equal amount of energy input and hence, ignoring the issue of energy quality, does not create any "new" energy. Net energy and EROI have had a distinct influence on decision-making regarding energy technologies [6], and there has been a resurgence in interest evidenced by the passionate debate over the energy return of corn ethanol [7, 8] and other biofuels [9].

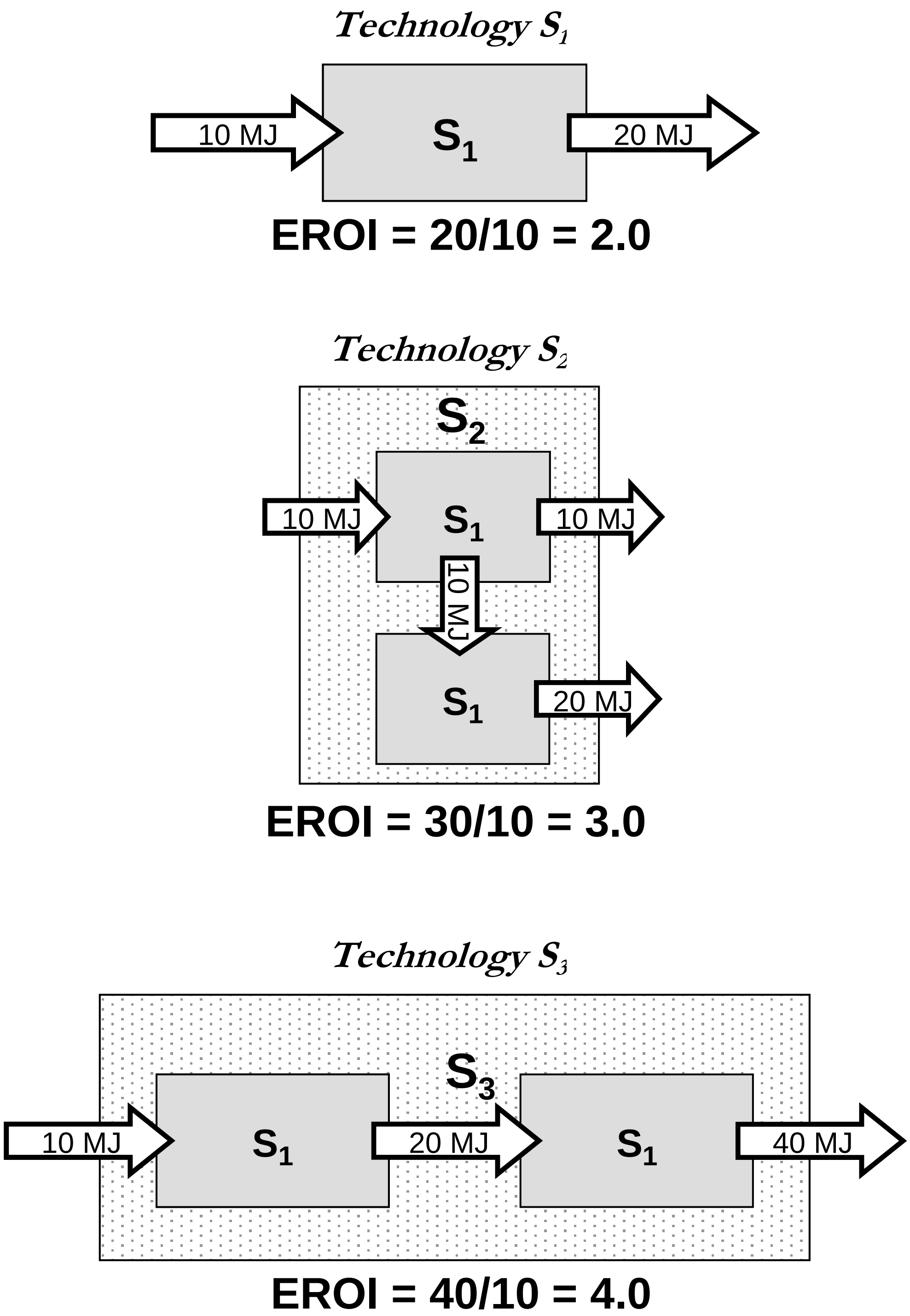

Figure 4 Three Hypothetical Energy Technologies

2.3 EROI Chaining

However, the following paradox in the calculation of EROI suggests that, in some cases, the intuitive and commonly used definition may give an inappropriate measure of the utility of an energy production technology. Consider three "technologies" as depicted in Figure 4. By taking technology S_1 with an EROI of 2.0, two alternative systems (S_2 and S_3) are easily created through serial chaining yielding seemingly incrementally higher measures of net energy. Few would argue that S_2 and S_3 are truly different technologies from S1. However, what if the sub-processes in S_2 and S_3 are not identical but instead are distinct technologies, each with an EROI measure of 2.0, that have been chained together for industrial and/or financial convenience?

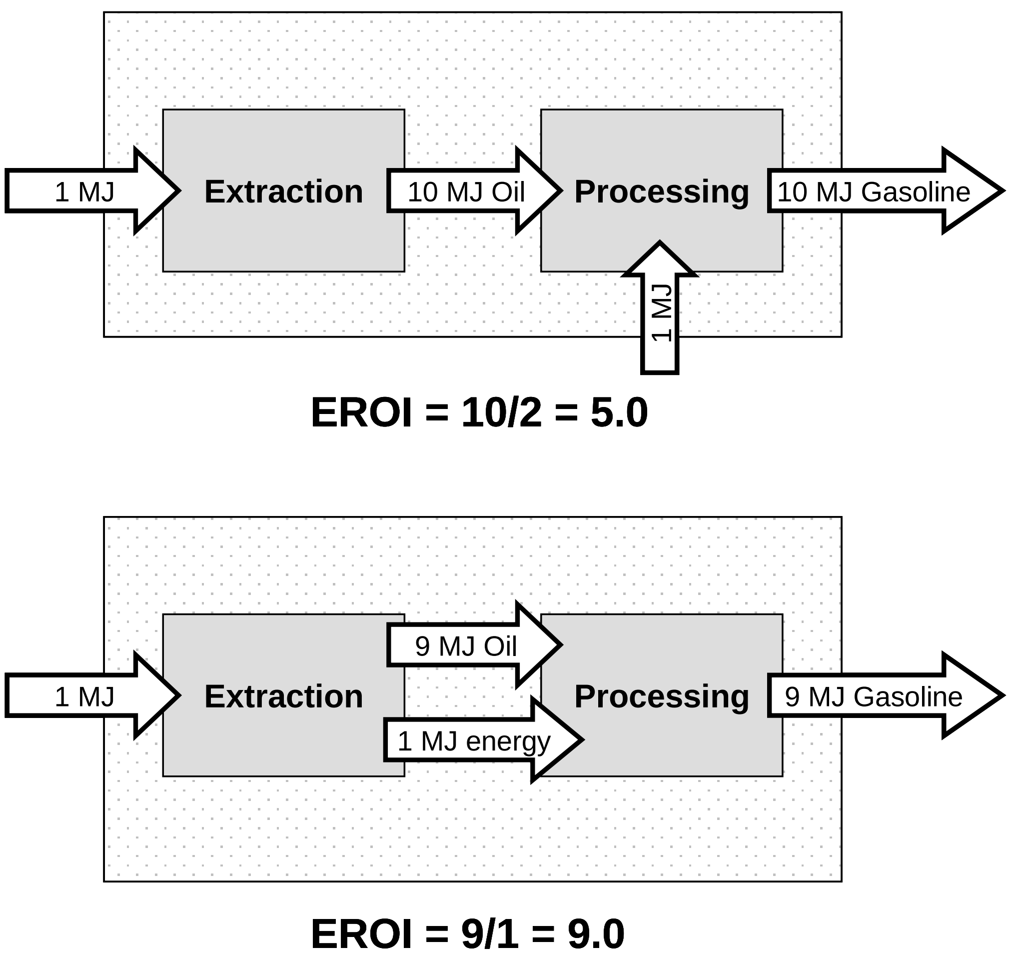

Figure 5 Two Ways of Depicting the EROI of Gasoline Production from Crude Oil

Consider another example. Two energy economists recently disagreed over the EROI of gasoline. Currently, it takes approximately 1 MJ of energy to find and extract 10 MJ of crude oil. It takes another 1 MJ to refine 10 MJ of crude oil into gasoline [10]. Economist One pictured the process as shown in Figure 5a and concluded the EROI of gasoline to be 5:1. Economist Two imagined Figure 5b and thereby calculated the EROI of gasoline to be 9:1. Although it is less clear than in the first example which depiction is correct, some would argue against the representation in 5b because the energy needs for oil processing are not met by an input of crude oil but rather by a variety of energy forms.

This leads to example three, a multistage energy production technology. The first stage produces two forms of high-energy content biomass, products A and B, using an energy input of K_1 MJ. Biomass A has an energy content of K_2 that is readily useable as a source of energy production. Biomass B has an energy content of K_3 which is marginally greater than K_2. However, B is in a low quality form that is not readily useable. It can be converted into a high quality form with minimal loss of energy content but requiring an energy input of approximately K_2. The resultant technology, a rough approximation to the current technology for producing cellulosic ethanol, can also be depicted two ways, as shown in Figure 6. In the case of cellulosic ethanol, Biomass A represents the lignin fraction that is generally burned in order to provide energy for the ethanol processing.

As with the previous examples, the two depictions lead to different EROI measures. Depending on the relative sizes of K_1, K_2, and K_3, this difference can be significant. The disparity between the two measures arises from a similar *chaining* process as seen in examples 1 and 2. However, while in the first two examples, the higher EROI measures intuitively seem the less correct, a similar depiction in example three represents how the EROI of cellulosic ethanol has been calculated by numerous researchers [11], while to our knowledge only one study has taken the first perspective [9].

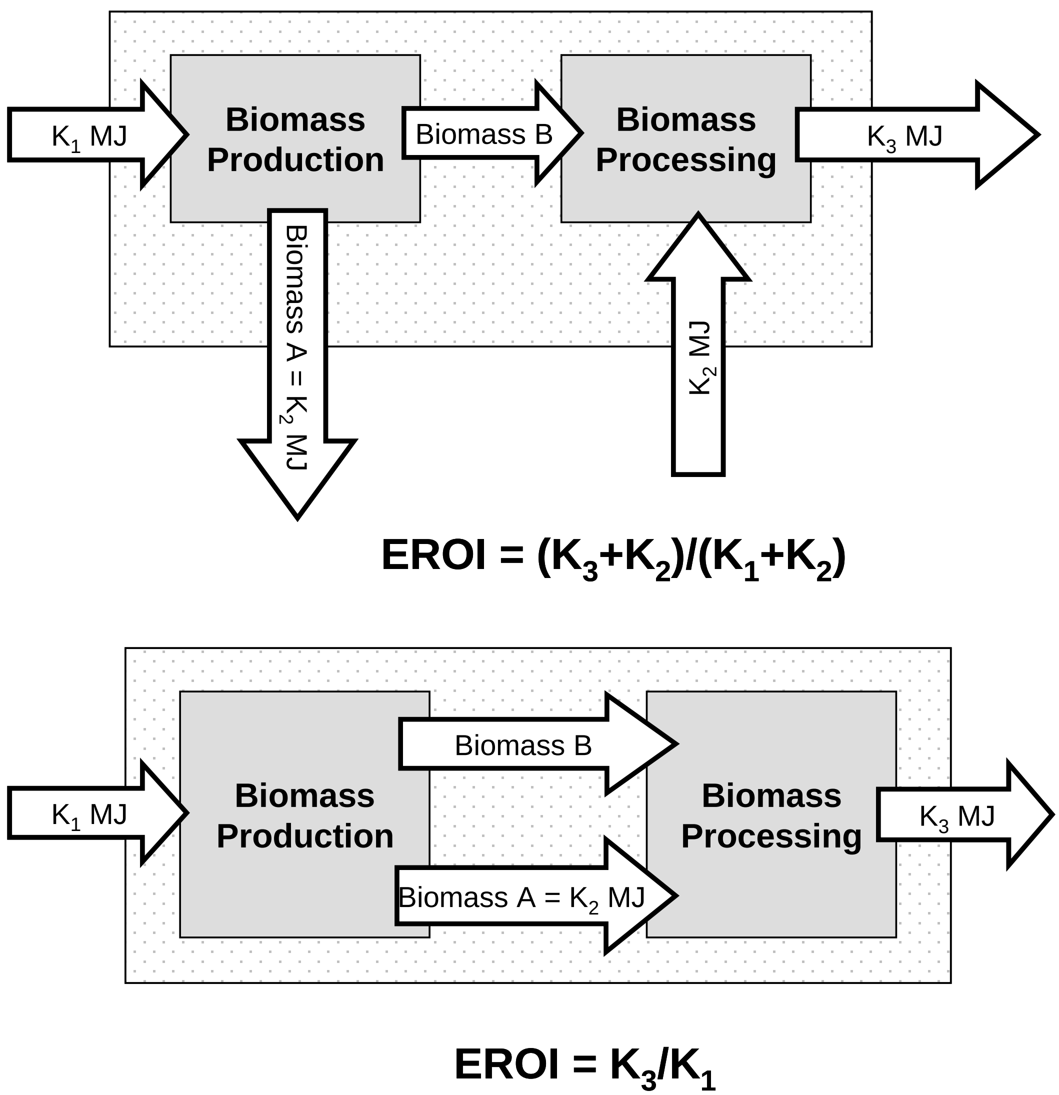

Figure 6 Two Hypothetical Energy Production Systems Analogous to Cellulosic Ethanol Production

Considering the analogy of EROI to the financial concept of return on investment, the second formulation in Figure 6 is troubling. If we set $K_1 = 1$, $K_2 = 6$, and $K_3 = 8$, then the financial corollary would be that for an investment of $1, the investor gets a return of $6 plus a low-value byproduct which, with a further investment of $6, can yield a total return of $8. Without knowledge of what is occurring internally, the investor might be pleased with an $8 return on $1. However, suppose the investor knew she had the option to discard (or sell) the low-value byproduct and reinvest her $6 in the first process that yielded a 6:1 return rather than in the second process that only gives her an 8:6 return. Surely she would choose the former.

We propose a modification to the intuitive definition of EROI that we believe is both logically consistent and more appropriate in terms of determining the utility of energy production technologies. Our first premise is that energy is only invested in a process when it is lost as waste heat. Second, any energy that is lost as waste heat is energy that must be accounted for as invested in the process, even if it was energy that was produced by an earlier stage of the process. *This lost energy must be added into the costs because of the "opportunity cost" related to other economic and/or energy-production processes in which the energy could have been invested.* This implies that the denominator in our new EROI ratio should not be the energy in (E_{in}), but rather the energy lost (E_{lost}).

In the numerator, we begin with the energy outputted from the process. However, it is possible that additional energy was created and then reinvested in the process. This would appear as E_{lost} being greater than E_{in}. Since this energy could have been outputted and replaced with additional inputs, the difference should get added to the output. This yields the following definition:

$$EROI = \frac{E_{out} + (E_{lost} - E_{in})}{E_{lost}}. \quad (1)$$

It is also possible to derive this formulation by analogy with return on investment. If P_i is the principle invested and $\triangle P$ is the increase in value of the principle after investment, then the rate of return is:

$$ROI = (P_i + \triangle P)/ P_i \quad (2)$$

Equation (1) follows from (2) by substituting E_{lost} for P_i and $(E_{out} - E_{in})$ for $\triangle P$.

We demonstrate the consistency of our formulation by referring to the three systems in Figure 1. In system S_1, E_{in} and E_{lost} are identical implying that (1) reduces to the traditional definition yielding an EROI measure of 2.0. This is how systems to which the EROI methodology is applied are conventionally perceived. In system S_2, $E_{in} = 10$ and $E_{out} = 30$. However, $E_{lost} = 20$ whereby (1) gives an EROI measure of 2.0. For S_3, $E_{in} = 10$, $E_{out} = 40$, and $E_{lost} = 30$. Again, (1) yields an EROI measure of 2.0. It is readily demonstrated that the calculations are consistent for examples 2 and 3 as well.

What does this imply for the EROI of cellulosic ethanol? Drawing on a review conducted by Hammerschlag [11] of four net energy studies, we averaged the energy inputs and outputs to produce estimates for system energy flows for cellulosic production. Flows follow Figure 6a with the exception that the available energy from

Biomass A (the lignin) is higher than the required input to the ethanol processing system, thus yielding an additional energy output. Estimates are as follows on a per liter of ethanol basis:

Energy In = 5.3 MJ.

Energy from Biomass A = 32.5 MJ.

Energy into the biomass processing system = 29.0 MJ.

The surplus energy from Biomass A that is outputted = 3.5 MJ.

Ethanol production (Biomass B) = 23.6 MJ.

Using the intuitive definition, the EROI measure would be E_{out} (= 23.6 + 3.5 = 27.1 MJ) divided by E_{in} (= 5.3 MJ) for an EROI of 5.5, significantly higher than soy biodiesel or starch ethanol. However, using equation (1), we have:

$$EROI = \frac{27.1 + (34.3 - 5.3)}{34.3} = 1.7 \qquad (3)$$

where E_{lost} = 5.3 + 29.0 = 34.3 MJ. This value is only marginally better than reported EROI measures for starch-based ethanol [7]. A similar exercise shows that the high EROI numbers for Brazilian sugar-cane based ethanol, which uses the bagasse as an intermediate input, are also overestimations.

Starch-based ethanol, depending on the analysis boundaries, has a marginally positive net energy return [7]. This has led many to question ethanol as a viable renewable energy technology [12, 13]. Much of the debate stems from a misunderstanding of two different and complementary requirements of our need to replace non-renewable fuel sources. First, we have a need to increase our available energy supply through energy production, or what may more aptly be called energy harvesting. Energy harvesting entails accessing energy sources such as wind, solar radiation, and below-ground fossil stocks that would not otherwise be available to society and thus have no energy opportunity cost. When energy is being harvested, using a statistic that reflects the energy being lost in the process is of paramount importance. This is why energy harvesting efficiency should be measured by the EROI of a technology using equation (1) above.

We also have a need to convert available energy sources, be they fossil-based or renewables such as biomass, into more useable sources as indicated by their quality versus their energy content [2]. The energy efficiency of such conversion processes should be measured by the ratio of E_{out} to E_{in}, but this should be referred to as the Conversion Ratio, or CR, rather than EROI since an increase in net energy is not the goal of this part of the process. Rather, CR measures the energy losses of the conversion process. Although CR is always less than unity, the processes it is applied to nonetheless have highly desirable outputs such as electricity that has been produced from coal. The benefit from an energy conversion process is always an increase in energy quality, ideally obtained at the highest possible CR.

Though starch-based ethanol comprises a decent energy conversion process that converts coal and natural gas (with corn as an intermediate product) into a substitute for gasoline—an argument recently made by Farrel et al. [7]—it is not an impressive energy harvesting technology. Our calculations show that cellulosic ethanol is only marginally better as an energy harvesting technology. More precisely, it is a combination of an excellent energy harvesting technology—biomass production of switchgrass, sugar-cane, etc—and a moderately efficient energy conversion technology—cellulosic fermentation.

A similar failure to appreciate the difference between energy harvesting and conversion has led many to criticize gasoline as an energy losing technology. It is frequently cited as having an EROI of 0.84, especially by policy makers seeking to boost the appearance of starch-based ethanol as an energy-harvesting technology [14]. However, an energy harvesting sequence must always begin with the underlying energy stock (e.g. in-ground oil or solar radiation), which because it is otherwise inaccessible comes without an energy opportunity cost. The 0.84 statistic is a measure of the conversion efficiency, or CR, of gasoline from in-ground crude oil, and from this perspective implies a very high level of efficiency. When EROI is calculated in such a way as to take into account the high energy return on crude oil, the total process of gasoline production (discovery, extraction, and refining) has a very high EROI.

Ultimately, the dichotomy between energy harvesting and conversion is erased when we adjust our EROI definition to account for energy quality as suggested by Cleveland [2]. Energy quality accounts for the value of different energy sources to society, taking into consideration such elements as energy density, transportability, and utility with regard to the current infrastructure. Quality adjusted EROI would be measured by equation (1) with each flow weighted according to some measure of quality such as price per unit energy. It is a suitable statistic for a conversion process such as coal to electricity, balancing the losses in energy quantity with the gains in quality. It is ideal for assessing chained processes such as cellulosic ethanol. This is due to the fact that while it does not hide the internal energy investment of the lignin, neither does it treat the lignin, a low-quality energy source, as an equal on a per-BTU-basis with ethanol, a high quality liquid fuel.

The path toward alternative energy must involve statistics and technologies that address both components of an energy production process—energy harvesting and energy conversion. Ignoring the opportunity costs associated with intermediate production can only serve to mask inefficiencies and lead to incorrect decisions. Cellulosic fermentation is an energy-intensive conversion process that draws down gross energy stocks. However, those that question it should criticize it as an energy conversion process and offer alternatives that can lead to similar increases in energy quality at lower energy costs. Finally, instead of one umbrella net energy statistic comparing energies of different quality and/or purpose, it may instead be useful to divide energy into primary point of use categories for human demand systems, e.g. transportation fuels, agriculture, heating, electricity, etc.

References

1. Pimentel, D., et al., *Renewable energy - economic and environmental issues.* BIOSCIENCE, 1994. **44**(8): p. 536-547.

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

3. Odum, H.T., *Energy, Ecology, and Economics.* AMBIO, 1973. **2**: p. 220-227.

4. Gilliland, M., *Energy analysis and public policy.* SCIENCE, 1975. **189**(4208): p. 1051-1056.

5. Hall, C.A.S., C.J. Cleveland, and R. Kaufmann, *Energy and resource quality : the ecology of the economic process*. Environmental science and technology. 1986, New York: Wiley. xxi, 577 p.

6. Berndt, E., *From technocracy to net energy analysis: engineers, economists, and recurring energy theories of value.*, in *Progress in Natural Resource Economics*, A. Scott, Editor. 1983, Clarendon: Oxford. p. 337-366.

7. Farrell, A., et al., *Ethanol can contribute to energy and environmental goals.* SCIENCE, 2006. **311**(5760): p. 506-508.

8. Letters to *Science* 23 June 2006.

9. Pimentel, D. and T.W. Patzek, *Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower.* Natural Resources Research, 2005. **14**(1): p. 65-76.

10. Cleveland, C., *Net energy from the extraction of oil and gas in the United States.* ENERGY, 2005. **30**(5): p. 769-782.

11. Hammerschlag, R., *Ethanol's energy return on investment: A survey of the literature 1990 - Present.* ENVIRONMENTAL SCIENCE & TECHNOLOGY, 2006. **40**(6): p. 1744-1750.

12. Giampietro, M., S. Ulgiati, and D. Pimentel, *Feasibility of Large-Scale Biofuel Production.* Bioscience, 1997. **47**(9): p. 587-600.

13. Pimentel, D., *Ethanol Fuels: Energy Balance, Economics, and Environmental Impacts are Negative.* Natural Resources Research, 2003. **12**(2): p. 127-134.

14. See Vinod Khosla's comments in *Wired Magazine* **14**, 10 (2006) (available at http://wired.com/wired/archive/14.10/ethanol.html) or Michael Wang's

presentation "Updated Energy and Greenhouse Gas Emissions from Fuel Ethanol" (Sept. 26, 2005, available at www.transportation.anl.gov/pdfs/TA/354.pdf).

CHAPTER 3: NET ENERGY: TOWARDS A CONSISTENT FRAMEWORK[1]

3.1 Abstract

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 paper, 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 non-energy 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.

3.2 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 [3]. When coal is included, fossil fuels make up 87.7% of global primary energy use [4]. 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

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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 [5].

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 [6]. When faced with these choices, policymakers, corporations and end-users will require a comprehensive and consistent framework for accurately comparing all aspects of an alternative fuel.

Several criteria have been used in the past to assess energy production technologies based on their absolute and relative yields and assorted costs [7]. Some assess strictly economic flows [e.g. 8] while others focus solely on energy flows [1, 9, e.g. 10] or emissions [e.g. 11]. Low greenhouse gas emissions in particular are a frequent measure of the desirability of an alternative technology [12]. Other assessments rely on a broad range of costs in terms of energy as well as environmental and social inputs [e.g. 2, 7, 13].

Since 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 [5], and energy payback [15]. In this paper we focus on an equivalent concept—the Energy Return on Energy Investment (EROI) [16, 17]. While 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 recently been used as a synthesizing concept for multiple analyses of biofuels [1, 18]. It has been used to examine nuclear energy [19, 20], ethanol [1, 18, 21], other biofuels [2, 22], wood energy [17], and other alternative energies [23, 24]. It has also been used to assess the energy efficiency of various fossil fuels [9, 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 Nonnuclear 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 over 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 over the energy return of ethanol production is a relevant example. A recent publication [1] 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 in particular the *concept is not precisely defined*, that paper has not ameliorated the polarization of the debate but rather heightened it (see response letters in *Science* 23 June 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.

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

3.3 Framework for Analyzing EROI

Figure 7 presents the physical flows of an energy producing technology (T) e.g. 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 co-products ($\{O_j\}$) 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 non-energy inputs to be negligible. This narrowest definition yields $EROI = ED_{out}/ ED_{in}$.

While EROI has rarely been used in such a simple form [examples being 17, 29], statistics regarding different technologies are commonly reported that ignore the energy costs associated with infrastructure and non-energy inputs [30]. 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 co-products.

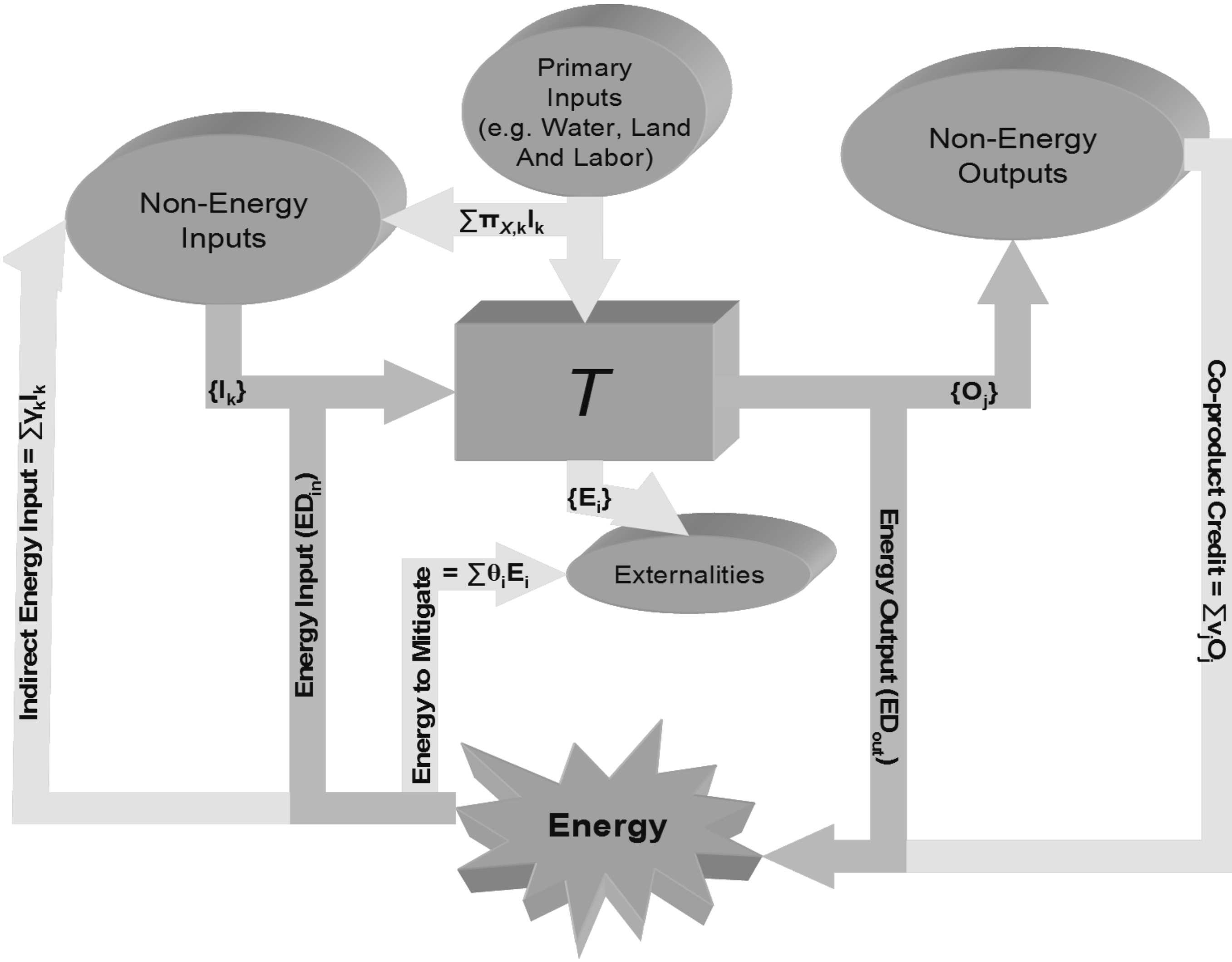

Figure 7 - Direct (darker arrows) and indirect (lighter arrows) inputs and outputs for technology T.

All primary inputs (energy and non-energy) 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, non-energy co-products can be given an energy credit based on several potential allocation methods.

3.3.1 Non-energy 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 (Figure 2, lighter arrows). This energy is embodied in the non-energy direct inputs [31], for example the agricultural energy required to grow oilseeds for biodiesel [6]. Precise calculation of the energy embodied in non-energy inputs can lead to infinite regress. 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 [28]. The latter is the accepted approach for Life Cycle Analyses (LCAs) [32].

The most common form of EROI applies an appropriate methodology to assess the embodied energy costs of the non-energy 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 $tonne^{-1}$ soybean). This yields the following version of EROI:

$$EROI = ED_{out}/(ED_{in} + \sum\gamma_k I_k). \quad (1)$$

The study of Brazilian ethanol by Macedo et al. [33] 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 while excluding the energy cost of others, something that clearly creates incommensurabilities between studies [1, 34]. The embodied energy costs of labor in particular are difficult to define but can be significant [6, 35].

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 non-energy *resources* so as to distinguish them from non-energy inputs. Non-energy resources can have direct as well as indirect components [36]. 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, 37].

Such direct and indirect non-energy 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 non-energy resource X, EROI_X is given by:

$$\mathrm{EROI}_X = \mathrm{ED}_{\mathrm{out}}/(\sum \pi_{X,\mathrm{k}} \mathrm{I}_\mathrm{k}) \qquad (2)$$

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

While this perhaps increases the complexity, this method has at least two distinct advantages. First, it yields a measure of production efficiency that can be utilized 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 allows for contextual assessment of a technology. Different countries will be limited in their growth by different resources [38], a Liebig's law of the minimum for economic growth [39]. Some resources (e.g. water) may be more limiting than energy [40]. 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 non-energy primary inputs is to convert them into energy equivalents via some set of coefficients ($\{\psi_X\}$) for all non-energy 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 [41]. An approach adopted by Patzek [41] and Patzek and Pimentel [42] is to assign energy costs based on a resource's exergy [43, 44], 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 that would be required to reconstitute a given level of order.

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

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

(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.

3.3.2 Non-energy Outputs

Just as consideration of the non-energy inputs yields a fuller, and more complex, EROI, so too can the non-energy outputs be incorporated to provide a more complete indicator of the desirability of a process (Figure 1). To begin, many technologies yield co-products in addition to the primary energy product. It is assumed in most studies that a credit should be given for these co-products which is added to the numerator and thereby increases the EROI for the process. To do this, each co-product 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 co-products an explicit energy value based on their thermal energy content [13] or their exergy [42]. However, co-products 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 [6], a methodology equivalent to expanding the boundaries of the technology [45, 46]. Non-energy metrics that can establish relative value include economic value and mass, both of which are frequently used in life cycle analyses [32, 45].

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

$$EROI = \frac{ED_{out} + \sum \nu_j O_j}{ED_{in} + \sum \gamma_k I_k}. \quad (4)$$

For example, for biodiesel from oilseeds, oilseed meal is a valuable co-product most commonly used as a source of protein for livestock. An energy credit can be assigned to this co-product based on its actual thermal content [34], its market value [e.g. 47], or its mass [e.g. 48]. The calculated EROI can vary by a factor of 2 or more depending on allocation method.

Note that all co-product credit assignments will also work for determining the energy return from non-energy resources since they only affect the numerator.

3.3.3 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 (Figure 1). A full assessment of the desirability of an economic endeavor should include such impacts since they ultimately affect the net benefit to society [6]. Negative externalities can include soil erosion, ground and water pollution, loss of habitat, and loss of food production capacity [7, 49]. Externalities also can be positive such as the creation of jobs and the maintenance of rural communities [50].

As with the handling of non-energy 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 [51], Giampietro et al. [2], and Hengraaf et al. [7]. 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 [1, 13, 52]. If we assume a set of externalities $\{E_i\}$ with energy equivalency coefficients $\{\theta_i\}$, 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. While 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.

3.4 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. While all 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.

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 (37)	Soy/Sunflower Biodiesel (13) Solar Cells [56]	Corn Ethanol (1) Soy Biodiesel (48)
Primary Input(X)	Cost = X	Cost = $\sum\pi_{X,k} I_k$	Numerator = $ED_{out} + \sum\upsilon_j O_j$
	Hydroelectric, X = Land (37) Various Technologies, X = Water (7)	Corn Ethanol, X = Various Inputs (13,41) Rapeseed Biodiesel, X = Various Inputs (7)	Soy Biodiesel, X = Various Inputs (48) Rapeseed Biodiesel, X = Water [57]
Externality (E)	Cost = E	Cost = $\sum\pi_{E,k} I_k$	Numerator = $ED_{out} + \sum\upsilon_j O_j$
	Wind, E = Emissions (30) Various Technologies, E = Soil Loss (7)	Various Technologies, E = Emissions [58] Wind, E = Emissions [59]	Biodiesel, E = Emissions (48) Ethanol, E = GHG (47)
Energy Equivalents	1) Conversion of externalities into energy: Cost = $ED_{in} + \sum\gamma_k I_k + \sum\nu_i E_i$ (1,41) 2) Conversion of primary inputs into energy: Cost = $ED_{in} + \sum\gamma_k I_k + \sum\psi_X \pi_{X,k} I_k$ (13,41)		

3.5 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 policy-makers, it is essential that the methodology become uniform and well-specified. Such standardization has been successfully accomplished with life cycle analyses [32]. However, unlike with LCA, 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.*

	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	$\frac{ED_{out}}{\alpha\left(ED_{in} + \sum_k \gamma_k I_k\right)}$	$\frac{ED_{out}}{\alpha\left(ED_{in} + \sum_k \gamma_k I_k + \sum_k \psi_k \pi_{X,k} I_k\right)}$	$\frac{ED_{out}}{\alpha \sum_k \pi_{X,k} I_k}$
3rd Order		$\frac{ED_{out}}{\alpha\left(ED_{in} + \sum_k \gamma_k I_k + \sum_k \psi_k \pi_{X,k} I_k + \sum_i \upsilon_i E_i\right)}$	$\frac{ED_{out}}{\alpha \sum_k \pi_{E,k} I_k}$

Figure 8 Framework for EROI Methodologies

The side axis determines what to include (direct inputs, indirect inputs, and/or externalities). The top axis dictates how to include non-energy resources (ignore, convert to energy equivalents, or treat as irreducible.) Note that since simple EROI *ignores non-energy inputs, it does not have a 3rd order form which accounts for externalities.*

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 (Figure 8). 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 First Order EROI as, while it is the most precise form of EROI, it is also the most superficial, missing many critical energy inputs as well as ignoring co-products. The next level, Second Order 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.

Note that Second Order 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. To qualify as Second Order EROI, we suggest that the boundaries should be drawn such that ignored indirect energy inputs are expected to be less than 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 (Figure 9) in that it presents the fullest measure of the net energy available to society.

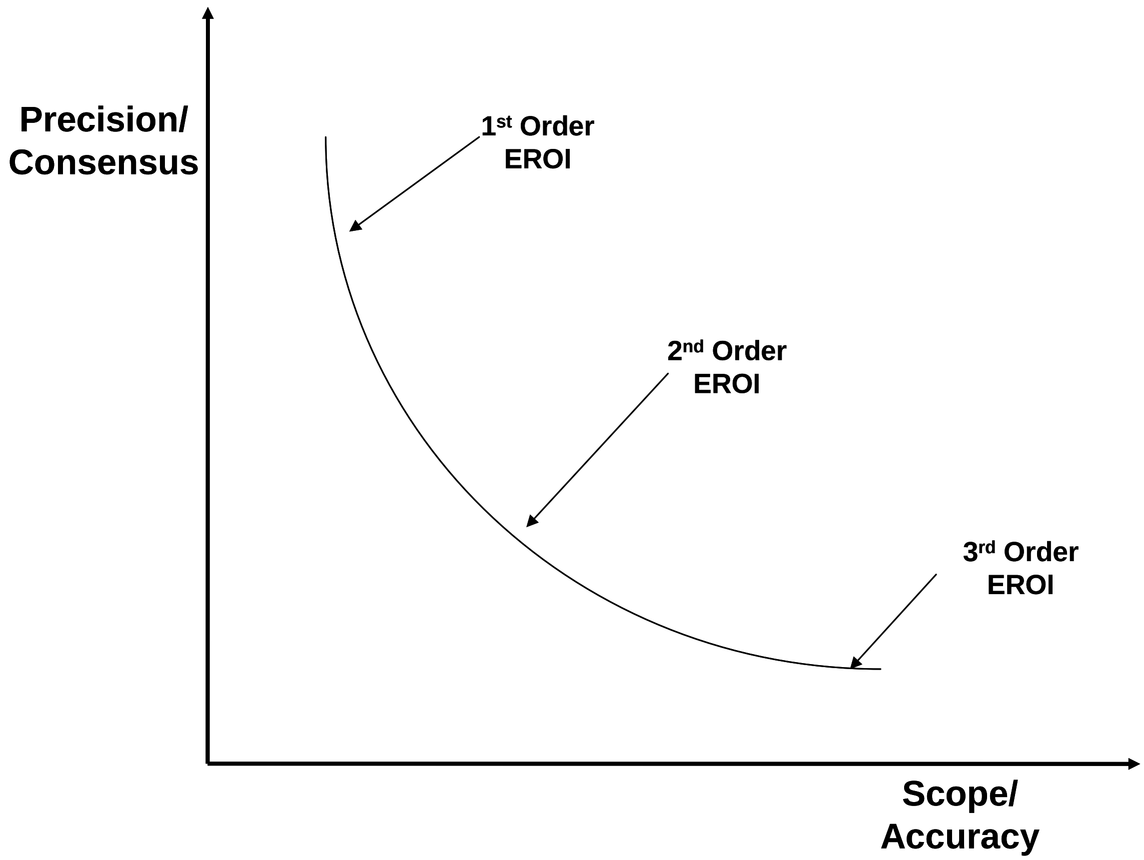

Figure 9 Relationship between EROI Scope and Detail and Level of Precision and General Acceptance

As EROI measures become more comprehensive in scope and thereby more accurate, their precision decreases as does the level of consensus around their values.

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 non-energy 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 8. Note that while the grid is 3x3, it yields only 8 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 factor of production 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 [2, 6, 53]. 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 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 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 meta-study of ethanol by Farrell et al.[1].

3.6 Other Considerations

3.6.1 EROI, Non-energy 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 non-energy resources as EROI approaches 1 [2].

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, this is not worrisome since all costs have been covered. However, regarding non-energy resources, this perspective changes.

Let $EROI_X$ be the energy return for 1 unit of non-energy 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 $EROI_X/\omega$. 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 resources. For energy production processes with significant non-energy resources such as biofuels, this suggests a low EROI can imply strong limitations on their ability to be scaled up [2, 6].

3.6.2 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. [1] 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 sub-unity EROI energy production depending on context.

However, the study of prior civilizations suggests low energy gain for society as a whole will have negative implications [5]. The more energy required to harvest, refine and distribute energy to society, the less will be left over for non-energy 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 [54]. 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.

3.5.4 EROI and the Net Ultimate Capacity of Resources

The theoretical graph in Figure 10 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. Since the most efficient areas of production are developed first (e.g. best cropland, best wind sites, etc. [55]), the annual yield tends to decline while 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 non-energy 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.

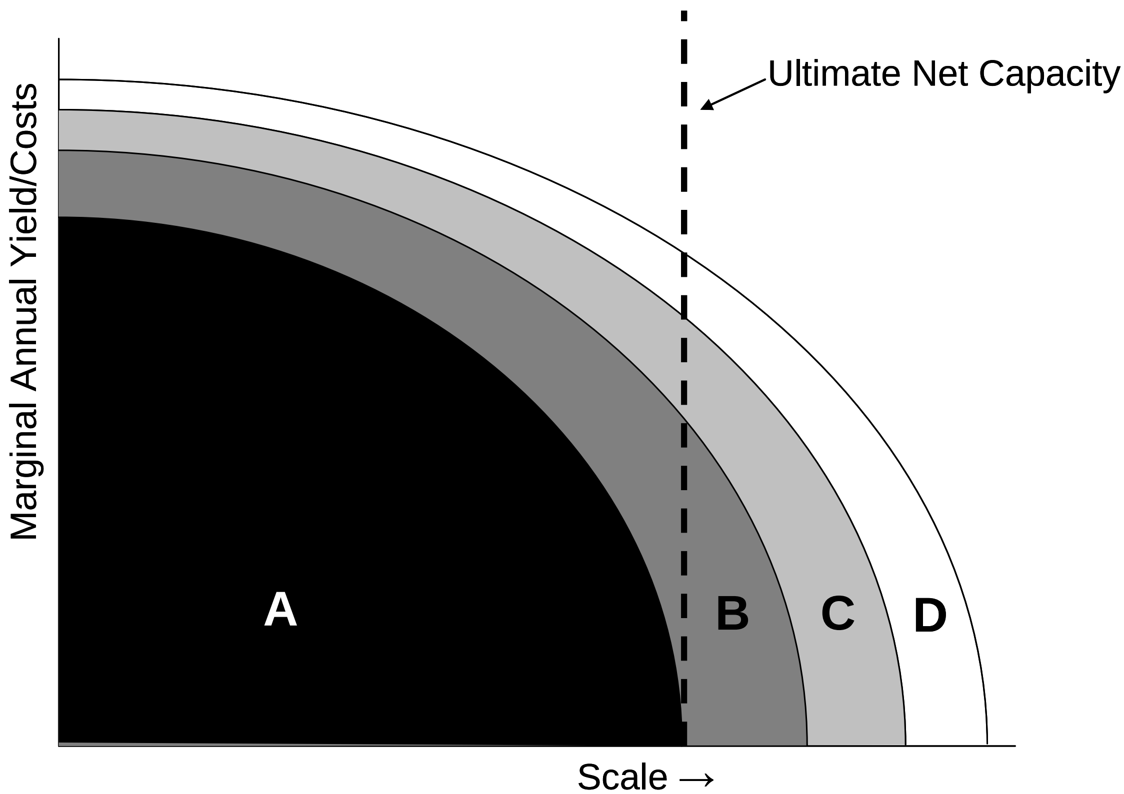

Figure 10 Annual Marginal Costs and Yields from a Given Renewable Energy Source

As the scale of development increases, marginal annual yields tend to decrease while 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.

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 10 shows that the peak yield in terms of net benefits to society is reached much more quickly than is the peak in gross yield.

3.7 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 over 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 allows for some methodological variability will be essential for policy-makers to accurately assess alternatives.

References

1. Farrell, A., et al., *Ethanol can contribute to energy and environmental goals.* SCIENCE, 2006. **311**(5760): p. 506-508.

2. Giampietro, M., S. Ulgiati, and D. Pimental, *Feasibility of Large-Scale Biofuel Production.* Bioscience, 1997. **47**(9): p. 587-600.

3. Lincoln, S., *Fossil fuels in the 21st century.* AMBIO, 2005. **34**(8): p. 621-627.

4. British Petroleum, *Quantifying Energy: BP Statistical Review of World Energy 2005*. 2005, London: Beacon Press.

5. Tainter, J.A., *Resource transitions and energy gain: Contexts of organization.* CONSERVATION AND ECOLOGY, 2003. **7**(3).

6. Hill, J., et al., *Environmental, economic, and eneretic costs and benefits of biodiesel and ethanol biofuels.* Proceedings of the National Academy of Sciences, 2006. **103**(30): p. 11206-11210.

7. Hanegraaf, M.C., E.E. Biewinga, and G. Van der Bijl, *Assessing the ecological and economic sustainability of energy crops.* Biomass & Bioenergy, 1998. **15**(4-5): p. 345-355.

8. Kaylen, M., *An economic analysis of using alternative fuels in a mass burn boiler*. BIORESOURCE TECHNOLOGY, 2005. **96**(17): p. 1943-1949.

9. Cleveland, C., *Net energy from the extraction of oil and gas in the United States.* ENERGY, 2005. **30**(5): p. 769-782.

10. Ulgiati, S., *A Comprehensive Energy and Economic Assessment of Biofuels: When Green is not Enough.* Critical Reviews in Plant Sciences, 2001. **20**(1): p. 71-106.

11. EPA, *A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions*. 2002, US Environmental Protection Agency: Washington DC.

12. Kim, S. and B. Dale, *Environmental aspects of ethanol derived from no-tilled corn grain: nonrenewable energy consumption and greenhouse gas emissions.* BIOMASS & BIOENERGY, 2005. **28**(5): p. 475-489.

13. Pimentel, D. and T.W. Patzek, *Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower.* Natural Resources Research, 2005. **14**(1): p. 65-76.

14. Odum, H.T., *Energy, Ecology, and Economics.* AMBIO, 1973. **2**: p. 220-227.

15. Keoleian, G., *Application of Life Cycle Energy Analysis to Photovoltaic Design.* PROGRESS IN VOLTAICS, 1998. **5**(4).

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

17. Gingerich, J. and O. Hendrickson, *The theory of energy return on investment - A case-study of whole tree chipping for biomass in Prince Edward Island.* FORESTRY CHRONICLE, 1993. **69**(3): p. 300-306.

18. Hammerschlag, R., *Ethanol's energy return on investment: A survey of the literature 1990 - Present.* ENVIRONMENTAL SCIENCE & TECHNOLOGY, 2006. **40**(6): p. 1744-1750.

19. Kidd, S., *nuclear: is there any net energy addition?* NUCLEAR ENGINEERING INTERNATIONAL, 2004. **49**(603): p. 12-13.

20. Tyner, G., R. Costanza, and R. Fowler, *The net energy yield of nuclear power.* ENERGY, 1988. **13**(1): p. 73-81.

21. Pimentel, D., *Ethanol Fuels: Energy Balance, Economics, and Environmental Impacts are Negative.* Natural Resources Research, 2003. **12**(2): p. 127-134.

22. Baines, J. and M. Peet, *Assessing alternative liquid fuels using net energy criteria.* ENERGY, 1983. **8**(12): p. 963-972.

23. Berglund, M. and P. Borjesson, *Assessment of energy performance in the life-cycle of biogas production.* BIOMASS & BIOENERGY, 2006. **30**(3): p. 254-266.

24. Chui, F., A. Elkamel, and M. Fowler, *An integrated decision support framework for the assessment and analysis of hydrogen production pathways.* ENERGY & FUELS, 2006. **20**(1): p. 346-352.

25. Berndt, E., *From technocracy to net energy analysis: engineers, economists, and recurring energy theories of value.*, in *Progress in Natural Resource Economics*, A. Scott, Editor. 1983, Clarendon: Oxford. p. 337-366.

26. Gilliland, M., *Energy analysis and public policy.* SCIENCE, 1975. **189**(4208): p. 1051-1056.

27. Cleveland, C., et al., *Energy and the United States Economy - A Biophysical Perpsective.* SCIENCE, 1984. **225**(4665): p. 890-897.

28. Spreng, D.T., *Net-energy analysis and the energy requirements of energy systems*. 1988, New York: Praeger. xii, 289 p.

29. Southwide Energy Committee, *Petroleum product consumption and efficiency in systems used for energy wood harvesting*. 1980, American Pulpwood Association: Washington DC.

30. American Wind Energy Association, *Comparative air emissions of wind and other fuels*. http://www.awea.org/pubs/factsheets.html. 2006: http://www.awea.org/pubs/factsheets.html.

31. Odum, H.T., *Systems ecology : an introduction*. 1983, New York: Wiley. xv, 644 p.

32. International Standard Organization, *Environmental Management--Life Cycle Assessment--Principles and Framework.*, ed. s.e. ISO 14040. 1997, Geneva: ISO.

33. Macedo, I.C., M.R.L.V. Leal, and J.E.A.R. da Silva, *Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil*. 2004, Government of the State of Sao Paulo: Sao Paulo, Brazil.

34. Pimentel, D. and T.W. Patzek, *Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower.* Natural Resources Research, 2005. **14**(1): p. 65-76.

35. Costanza, R., *Embodied energy and economic valuation.* SCIENCE, 1980. **210**(4475): p. 1219-1224.

36. Wichelns, D., *The role of 'virtual water' in efforts to achieve food security and other national goals, with an example from Egypt.* Agricultural Water Management, 2001. **49**(2): p. 131-151.

37. Pimentel, D., et al., *Renewable energy - economic and environmental issues.* BIOSCIENCE, 1994. **44**(8): p. 536-547.

38. Rees, W., *Revisiting carrying capacity: Area-based indicators of sustainability.* POPULATION AND ENVIRONMENT, 1996. **17**(3): p. 195-215.

39. Hardin, G.J., *The ostrich factor : our population Myopia*. 1999, New York: Oxford University Press. 168 p.

40. Barlow, M. and T. Clarke, *Blue gold : the fight to stop the corporate theft of the world's water*. 2002, New York: New Press : distributed by W.W. Norton. xviii, 278 p.

41. Patzek, T., *Thermodynamics of the corn-ethanol biofuel cycle.* CRITICAL REVIEWS IN PLANT SCIENCES, 2004. **23**(6): p. 519-567.

42. Patzek, T. and D. Pimentel, *Thermodynamics of energy production from biomass.* CRITICAL REVIEWS IN PLANT SCIENCES, 2005. **24**(5-6): p. 327-364.

43. Ayres, R., L. Ayres, and K. Martinas, *Exergy, waste accounting, and life-cycle analysis.* ENERGY, 1998. **23**(5): p. 355-363.

44. Ayres, R. and K. Martinas, *Waste potential entropy: the ultimate ecotoxic?* Economie Appliquees, 1995. **48**: p. 95-120.

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

46. Kim, S. and B. Dale, *Allocation procedure in ethanol production system from corn grain - I. System expansion.* INTERNATIONAL JOURNAL OF LIFE CYCLE ASSESSMENT, 2002. **7**(4): p. 237-243.

47. Mortimer, N.D., M.A. Elsayed, and R. Matthews, *Carbon and Energy Balances for a Range of Biofuel Options*. 2003, Resources Research Unit, Sheffield Hallam University: Sheffield, England.

48. Sheehan, J., et al., *An Overview of Biodiesel and Petroleum Diesel Life Cycles*. 1998, National Renewable Energy Laboratory: Golden, CO.

49. Pimentel, D., et al., *Renewable energy: Current and potential issues.* BIOSCIENCE, 2002. **52**(12): p. 1111-1120.

50. Bender, M., *Economic feasibility review for community-scale farmer cooperatives for biodiesel.* Bioresource Technology, 1999. **70**(1): p. 81-87.

51. US Department of Energy, *Energy Systems Emissions and Material Requirements*. 1989a, Prepared by the Meridian Corporation: Washington, DC.

52. Cleveland, C. and R. Costanza, *Net Energy Analysis of Geopressured Gas-Resources in the United States Gulf Coast Region.* ENERGY, 1984. **9**(1): p. 35-51.

53. Hagens, N., R. Costanza, and K. Mulder, *Energy Returns on Ethanol Production.* SCIENCE, 2006. **312**: p. 1746.

54. Smil, V., *General Energetics: Energy in the Biosphere and Civilization*. 1991, New York: John Wiley.

55. Ricardo, D., *On the principles of political economy, and taxation*. 1st American ed. 1819, Georgetown, D.C.: J. Milligan. viii, 448, [8].

56. Pearce, J. and A. Lau. *Net energy analysis for sustainable energy production from silicon based solar cells*. in *Proceedings of Solar 2002*. 2002. Reno, Nevada.

57. DeNocker, L., C. Spirinckx, and R. Torfs. *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*. 1998. Brussels: VITO.

58. European Commission, *ExternE, Externalities of Energy, Methodology Report, Vol. 1*. 1997, Brussels: European Commission DG Research.

59. Schleisner, L., *Life cycle assessment of a wind farm and related externalities.* RENEWABLE ENERGY, 2000. **20**(3): p. 279-288.

CHAPTER 4: ENERGY RETURN ON WATER INVESTED[2]

4.1 Abstract

While various energy-producing technologies have been analyzed to assess the amount of energy returned per unit of energy invested, this type of comprehensive and comparative approach has rarely been applied to other potentially limiting inputs such as water, land, and time. We assess the connection between water and energy production and conduct a comparative analysis for estimating the energy return on water invested (EROWI) for several renewable and non-renewable energy technologies using various Life Cycle Analyses. Our results suggest that the most water-efficient, fossil-based technologies have an EROWI one to two orders of magnitude greater than the most water-efficient biomass technologies, implying that the development of biomass energy technologies in scale sufficient to be a significant source of energy may produce or exacerbate water shortages around the globe and be limited by the availability of fresh water. *"Some scientists now proudly claim that the food problem is on the verge of being completely solved by the imminent conversion on an industrial scale of mineral oil into food protein - an inept thought in the view of what we know about the entropic problem. The logic of this problem justifies instead the prediction that, under the pressure of necessity, man will ultimately turn to the contrary conversion, of vegetable products into gasoline (if he will still have any use for it)."* --Nicholas Georgescu-Roegen (1)

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[2] Published as Mulder, K., Hagens, N., Fisher B., "Burning Water – A Comparative Analysis of Energy Returned on Water Invested", AMBIO: A Journal of the Human Environment, Vol. 39- 1, p30-39, Mar. 2010

4.2 Introduction

With recent increases in oil prices and the mounting evidence of upcoming peaks in global oil and gas production, much attention has been given to the search for alternative energy sources and technologies . Similar effort has been devoted to research focused on measuring the desirability of different energy technologies (3,4). Much of this research has been concerned with estimating the Energy Return On Energy Investment (EROEI) of different technologies, defined as the ratio of the energy produced by a technology to the energy, both direct and indirect, consumed by the production process (5). EROEI is known variously as net energy, energy yield, and the fossil energy ratio (5,6). Net energy is central to an energy theory of value, which asserts that energy, not money, is what we have to spend . (5,7) Variations of net energy analysis have been widely applied since the 1970s as a first order filter of the viability of energy harvesting technologies(7). While its utility is currently the subject of heated debate, much of the disagreement centers around appropriate boundaries applied to inputs and outputs, not only on *what* to include but *how* they are methodologically included (12). One significant application of net energy analysis is the comparison of the EROEI of an alternative fuel to what it is replacing. If a large portion of societies' high 'net' energy fuel mix were replaced by a much lower net energy source, the energy sector itself would begin to require a majority of the energy produced, leaving less available for the non-energy sectors.

However, implicit in the attention to EROEI as a policy criterion is the assumption that energy is the sole limiting resource of importance, with the determining factor generally being whether and by how much EROEI exceeds unity. All other potentially limiting factors are implicitly assumed proportional to the energy needed to drive a process (8). Even studies that seek to move the focus away from EROEI, such as the analysis of ethanol by Farrell et al. , restrict their focus to energy inputs. A partial exception to this is the fact that some studies examining the EROEI of a technology also estimate its potential impact upon the production of greenhouse gases (9).

Certainly the energy derived from finite and renewable resources is a function of multiple inputs including land, labor, water, and raw materials. A technology might have a high EROEI and yet require sufficient levels of scarce, non-energy inputs as to be extremely restricted in potential scale. For example, the amount of land required for biofuels is between two and three orders of magnitude more than the land area required for conventional fossil fuels (10). Another example is the recent curtailing of planned solar voltaic projects caused by a shortage of polysilicon (11).

In addition to non-energy inputs, energy technologies vary on their waste outputs and impact on environment. Within the biofuels class itself, there is a large disparity of pesticide and fertilizer requirements. Per unit of energy gained, soybean biodiesel requires just 2% of the nitrogen, 8% of the phosphorous, and 10% of the pesticides that are needed for corn ethanol (2). Ultimately, if net energy analysis is to be a useful decision criterion for energy projects, it must be complemented by other measures that estimate the energy return from the investment of non-energy resources (12).

Water is similar to oil in that it is embedded in all human systems, even if it is not directly recognized as such. Water withdrawals are ubiquitous in most energy production technologies. Indeed, by sector, the two largest consumers of saltwater and freshwater in the United States are agriculture and electrical power plants, both prominent players in the future energy landscape (Figure 11) (13). If only fresh water is considered, fully 81% of the US use is for irrigation (14).

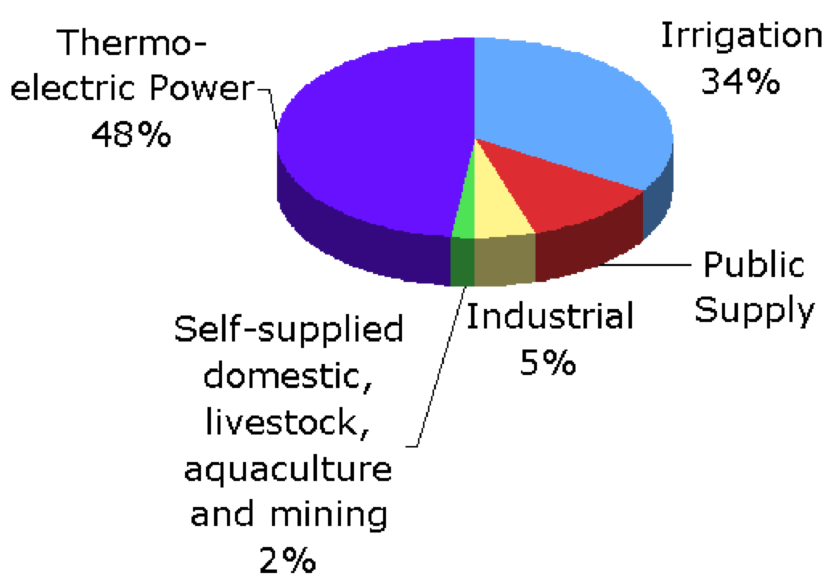

Figure 11 Estimated Water Usage by Sector in the United States in 2000 (Berndes 2002)

Internationally, several assessments suggest that up to 2/3 of the global population could experience water scarcity by 2050 (15,16). These projections demonstrate that human demand for water will greatly outstrip any climate induced quantity gains in freshwater availability (15,17). This will be driven by the agricultural demand for water which is currently responsible for 90% of global freshwater consumption (19). Water shortages could become much more acute if there is wide-spread adoption of energy production technologies that require water as a significant input (3,20). The need to leverage our declining fossil fuel supplies and efficiently allocate fresh water resources in the face of increasing demand and a changing hydrologic cycle are intimately linked and must be investigated as interdependent issues.

To explore the role of water in energy production, we apply the EROEI methodology to calculate the Energy Return On Water Invested (EROWI) for several energy production technologies. We combine this parameter with EROEI to account for the energy costs and thereby calculate what we term 'net EROWI', a preliminary measure of the desirability of an energy technology in contexts where water is, or may become, a limiting factor. Our estimates for gross EROWI and EROEI are taken from Life Cycle Analyses and other studies of energy and water usage taken from the literature. We did not use studies where we suspected significant water costs had been neglected.

Fresh water is unique in its potential for reusability. Globally the current water stock in rivers is 2000 km^3; the anthropogenic water withdrawals from these rivers is 3800 km^3/yr; and the global river discharge is 45,500 km^3/yr (18). Unlike other resources, water is continually recycling. While this does not mean there are no limits on water withdrawals, it does imply that water that is withdrawn is not necessarily lost. For example, cooling water withdrawn for use by a nuclear power plant may be returned and withdrawn farther downstream to irrigate biofuels crops. However, some water does get consumed, either by being lost as steam or by being contaminated.

In this study we attempted to parse water usage into two categories—water withdrawals and water consumed. We define water withdrawals as the diversion of freshwater from its natural hydrologic cycle, either at the surface or from below the ground, for anthropogenic purposes. Water consumed is defined as water used in the energy production process that is either lost to a given watershed as steam or contaminated beyond cost-effective remediation.

4.3 Methods

To calculate a gross EROWI we attempted to estimate the total water requirements per unit of energy produced. Where data allowed, we estimated separate EROWI measures for both water withdrawals and water consumed. Water consumed is likely to be much smaller than that which is actually withdrawn, and for this reason the data available generally only indicate water withdrawals. Ideally, EROWI is estimated for a given technology by applying the Life Cycle Analysis (LCA) methodology (1) to calculate freshwater usage per unit energy produced (L/MJ) for a given technology. Variations of the LCA methodology are generally used to calculate the EROEI for a technology (2) and the application to water is analogous. In particular, for each technology assessed, we sought to do the following:

1. Define the technology precisely including the context of production and all

assumptions regarding inputs;

2. Find data in the literature for direct water inputs into the technology as well as indirect inputs defined as the water required to produce non-water inputs;

3. Set the system boundaries clearly and sufficiently wide so that remaining water requirements are negligible.

Where co-products are produced at a stage in the production process (e.g. soybean meal in the production of soy biodiesel) and data allowed, price allocation was chosen to apportion the water inputs (1,3). Where data were available, we calculated the energy produced per unit of water consumed in addition to the EROWI for water withdrawals. Sample calculations for soy biodiesel are given in Table 2 as are details for each technology.

Table 2 Sample Calculations for Soy Biodiesel

Production Process	Water Usage (l/MJ)	Energy Usage (MJ/MJ)	Proportion of Value for BD	Allocated Water Usage (l/MJ)	Allocated Energy Usage (MJ/MJ)
Soybean Agriculture	76.82[1]	0.355	0.344*0.821[2]	21.70	0.100
Soybean Transport	0[3]	0.019	0.344*0.821	0	0.005
Soybean Crushing	0[3]	0.379	0.344*0.821	0	0.107
Oil Transport	0[3]	0.007	0.821	0	0.006
Soy Oil Conversion	0.14	0.165	0.821	0.11	0.135
Biodiesel Transport	0[3]	0.004	1.00	0	0.004
Total	76.96	0.929		21.81	0.357[4]

$$\textbf{EROWI} = \frac{1}{21.81} = 0.0461$$

$$\textbf{EROEI} = \frac{1}{0.357} = 2.80$$

$$\textbf{Net EROEI} = \frac{2.80 - 1}{2.80} * 0.0461 = 0.030$$

[1]Includes irrigation according to production averages.
[2]Assumes a yield of 0.111 kg of soybean meal at a value of $0.212/kg, 0.028 kg of soy oil at a value of $0.441/kg, 0.20 kg of biodiesel at a value of $0.65/kg and 0.043 kg raw glycerin at a value of $0.66/kg.
[3]Less than 0.001 l/MJ.
[4]Note that Sheehan et al. used mass allocation instead of price allocation and thereby calculated an allocated energy usage of 0.313 MJ per MJ of biodiesel produced.

Water usage data is from Sheehan et al. (4) and prices are five year averages from the US Department of Agriculture (1999-2003) (5) and the US Department of Energy (2000-2004) (6).

Table 3 Data Sources and Methodology for Table 2

Technology	Key Specifications	Data Sources
Nuclear Electric	- Once-through cooling - National average	(7,8)
Nuclear Electric	- Recirculating - National average	(7,8)
Coal Electric[1]	- Once-through, sub-critical - National average	(8)
Coal Electric[1]	- Recirculating, sub-critical - National average	(8)
Coal Electric[1]	- Cooling pond, sub-critical - National average	(8)
Tar Sands[2]	- (SAGD) Steam Assisted Gravity Drainage - in situ – Alberta, Canada	(9) (10-11)
Biomass Electric[3]	- 113 MW Biomass IGCC – US - Non-irrigated hybrid poplar	(12)
Biomass Electric[4]	- IGCC - Irrigated hybrid poplar – Italy	(13)
Biomass Electric[5]	- IGCC with various feedstocks -Irrigated at a rate of 400 L/kg dry biomass.	(14)
Petroleum Electric[6]	- 250 MW plant – Singapore - 25 yr. expected plant lifetime	(15)
Petroleum Diesel	- Average data for US refining	(16) (4)
Soy Biodiesel[7]	- 1990 average US soy production - 18.4% oil content	(16) (4)
Methanol from Wood[5]	- Prototype technology only - Various feedstocks - Irrigated at a rate of 400 l/kg dry biomass.	(14)
Hydrogen from Wood[5]	- Prototype technology only - Various feedstocks - Irrigated at a rate of 400 l/kg dry biomass.	(14)
Corn Ethanol[8]	- Dry milling technology - 8700 kg/ha corn yield, 0.37 l/kg ethanol yield	(17,18)
Sugar Cane Ethanol	- From non-irrigated sugar cane production in Brazil	(19,20)

- Bagasse burned to process ethanol

[1]Assumes wet flue gas desulphurization which adds approximately 0.065 l/MJ to both withdrawals and consumption.
[2]Assumes *in situ* bitumen production only, which is expected to account for approx. 50% of tar sands production over next 20-30 years. The *mining* of bitumen (the other 50%) lacked sufficient data for EROWI calculations. Water data from (9)
[3]Water data taken from Table 22 in (12). Only water used in gasification plant was considered direct withdrawals.
[4]Direct water inputs are not reported and so are taken from Mann and Spath (12).
[5]All energy inputs are assumed derived from biomass with proportional water requirements.
[6]Data did not include water usage in oil recovery. Water from dedicated desalination plants could be used at an energy cost of 0.006 MJ per MJ produced. This would reduce the EROEI to 3.65 but reduce freshwater withdrawals to zero.
[7]Data was adjusted to account for price allocation instead of mass allocation of co-products which was used by Sheehan et al. (4) This also adjusted the EROEI.
[8]Water input data from Pimentel and Patzek (18). EROEI and allocation data from Shapouri et al. (17).

While the gross energy returned per unit of water invested is of interest, some technologies demand a relatively large energy investment as indicated by the EROEI. For this reason, following Giampietro et al. (3), we used estimates of each technology's EROEI to calculate a 'net EROWI'. From both a policy and technology perspective it is the net EROWI that we are interested in because for the process to be sustainable, some of the energy yield must be reinvested as indicated by the EROEI. Thus:

$$netEROWI = \frac{grossEROWI}{\omega}$$

where ω = EROEI / (EROEI – 1), which is the amount of energy production required to yield 1 unit of net energy (4). Note that ω increases non-linearly with declining EROEI, approaching infinity as EROEI approaches 1. Equivalently, Net EROWI approaches 0**.**

4.3.1 Methodological Example: Calculation of Net EROWI: Soy Biodiesel

Table 2 provides a sample data table for the methodology used on each technology. First, all water inputs for each process stage were identified (see Table 3 for all data sources). In the production of soy biodiesel, two co-products—soybean meal and raw glycerin—are also produced. Water usage is allocated between the co-products based on their relative economic values as this gives the best estimate of the relative value to society of the co-products (1,2). EROWI is calculated as the inverse of total water requirements per unit of energy produced. EROEI is similarly calculated as the inverse of the total energy requirements. Since 2.80 MJ gross energy production only yields 1.80 MJ net energy, the net EROWI is given by: $\frac{1.80}{2.80} * \text{EROWI}$.

These methods and calculations were used for each of the 16 energy technologies assessed. While the methodology described above is the generally accepted procedure for LCA, it should be noted that there are many potential costs, both in terms of water and energy, that are still ignored. In particular, costs associated with environmental externalities are generally not accounted for (3).

Table 4 EROWI, EROEI, and Net EROWI by Technology

Technology	Key Specifications	Water Use (l/MJ)[1] *Direct*[2]	*Indirect*[3]	EROWI (MJ/l)[2]	EROEI	Net EROWI[2]
Nuclear Electric	- Once-through cooling - National average	33.25 (0.145)	NA	0.030 (6.897)	10	0.027 (6.21)
Nuclear Electric	- Recirculating - National average	1.162 (0.659)	NA	0.861 (1.517)	10	0.775 (1.37)
Coal Electric	- Once-through, sub-critical - National average	28.62 (0.146)	NA	0.0349 (6.849)	NA	NA
Coal Electric	- Recirculating, sub-critical - National average	0.560 (0.488)	NA	1.786 (2.049)	NA	NA
Coal Electric	- Cooling pond, sub-critical - National average	18.922 (0.849)	NA	0.0528 (1.178)	NA	NA
Tar Sands	- Steam Assisted Gravity Drainage - in situ – Alberta, Canada	(0.061– 0.122)	NA	(16.39 – 8.19)	3.75	(12.02 – 6.01)
Biomass Electric	- 113 MW Biomass IGCC – US - Non-irrigated hybrid poplar	0.238	0.021	3.86	15.6	3.61
Biomass Electric	- IGCC - Irrigated hybrid poplar – Italy	0.238	3.85	0.245	1.60	0.092
Biomass Electric	- IGCC with various feedstocks -Irrigated at a rate of 400 L/kg dry biomass.	40	NA	0.025	5.0	0.02
Petroleum Electric	- 250 MW plant – Singapore - 25 yr. expected plant lifetime	0.01943	0.00057	50.0	3.73	36.6
Petroleum Diesel	- Average data for US refining	0.0035	NA	285.3	5.01	228.4
Soy Biodiesel	- 1990 average US soy production	0.011	21.7	0.0461	2.80	0.030

	- 18.4% oil content					
Methanol from Wood	- Prototype technology only - Various feedstocks - Irrigated at a rate of 400 l/kg dry biomass.	36.8	NA	0.0271	5.5	0.022
Hydrogen from Wood	- Prototype technology only - Various feedstocks - Irrigated at a rate of 400 l/kg dry biomass.	28.3	NA	0.0353	4.67	0.028
Corn Ethanol	- Dry milling technology - 8700 kg/ha corn yield, 0.37 l/kg ethanol yield	1.86	9.60	0.0873	1.38	0.024
Sugar Cane Ethanol	- From non-irrigated sugar cane production in Brazil - Bagasse burned to process ethanol	0.973	NA	1.027	8.3	0.903

[1]These totals primarily include the processing water required and irrigation as noted. They do not include evapotranspiration which is treated later (see Table 4).
[2]Numbers in parentheses are for water consumption i.e. contaminated or evaporated.
[3]Indirect water usage refers to the water required to produce the necessary feedstock. NA implies that the data used did not allow us to differentiate between direct and indirect water usage.

4.4 Results

Using these formulae, our estimates of gross EROWI and net EROWI by technology are shown in Table 4. Gross EROWI ranged from 0.025 MJ/L for electricity production from biomass up to 285.3 MJ/L for petroleum diesel. Net EROWI for the same technologies was 0.02 and 228.4 MJ/L respectively. However, amongst the renewable energy sources listed, the highest values, from a study by Mann and Spath

(21), were 3.86 and 3.61 MJ/L, gross EROWI and net EROWI respectively for biomass electricity from non-irrigated tree crops. However, these numbers appear anomalous, especially when compared to the data from a study by Berndes (13). Mann and Spath (21) used LCA software that did not necessarily incorporate comprehensive data on water inputs because water was not the focus of the paper (Mann –per. comm.). Setting this data aside, the best net EROWI for renewables is for sugar cane ethanol at 0.90, over two orders of magnitude lower than the most water efficient fossil energy sources (Fig. 12).

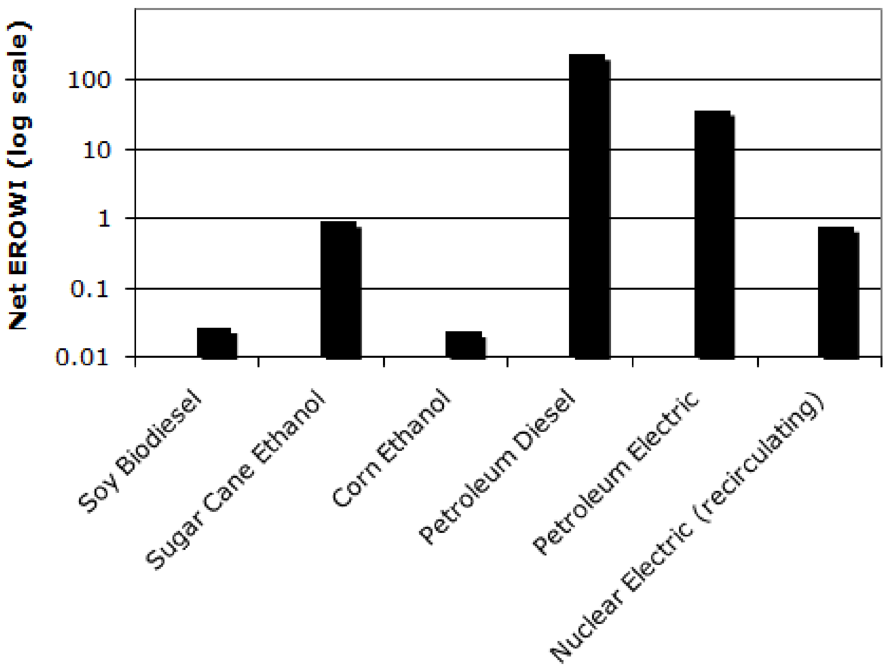

Figure 12 Net Energy Returned on Water Invested (net EROWI) for Selected Energy Technologies

The suite of technologies reviewed for Table 4 was chosen because of data availability. To augment this analysis, we also drew on a study by Berndes showing the range of evapotranspiration for various biofuels crops and then calculated the net EROWI again. These results (Table 5) are robust as they draw on a wide range of studies and the results are congruent with the data shown in Table 4. In particular, they confirm the significantly lower water efficiency of biomass-based technologies relative to non-renewable technologies.

Table 5 EROWI, EROEI, and Net EROWI for Biomass Energy Technologies

Biofuel/ Feedstock	Water Usage (l/MJ)	EROWI (MJ/l)	EROEI Estimate	Net EROWI
Biodiesel				
Rapeseed	100 – 175	0.010 – 0.0057	2.33	0.0057 – 0.0033
Ethanol				
Sugarcane	38 – 156	0.026 – 0.0065	8.3	0.023 – 0.0057
Sugar Beet	71 – 188	0.014 – 0.0053	2.25	0.0078 – 0.0029
Corn	73 – 346	0.014 – 0.0029	1.38	0.0039 – 0.00081
Wheat	40 – 351	0.025 – 0.0029	2.40	0.015 – 0.0017
Lignocellulosic Crops				
Ethanol	11 – 171	0.091 – 0.0058	4.55	0.071 – 0.0045
Methanol	11 – 138	0.091 – 0.0072	5.5	0.075 – 0.0059
Hydrogen	15 – 129	0.067 – 0.0078	4.67	0.053 – 0.0062
Electricity	13 – 195	0.077 – 0.0051	5.0	0.062 – 0.0041

Table adapted from Berndes (2002 - Tables 2 and 3). The first column shows the range of water consumption (evapotranspiration) in feedstock production. The low water usage numbers for lignocellulosic crops are based on non-irrigated M*iscanthus* production. EROEI estimates not used in Table 3 are from (40) Mortimer et al. (2003 - Rapeseed biodiesel and ethanol from sugar beet and wheat) and (41) Lynd and Wang (2004 - Lignocellulosic ethanol).

Indeed, the study by Kannan et al. (22) for a petroleum power plant in Singapore shows that even electricity production, generally one of the least water efficient forms of fossil energy production, can be made very water efficient when necessary. Singapore has perennial shortages of fresh water and the petroleum power plant studied there has a gross EROWI seven times higher than typical recirculating power plants. This is because direct water withdrawals are reduced to less than 0.02 L/MJ, a number dwarfed by the lower-bound water withdrawals of 13 L/MJ for biomass electricity production indicated by Berndes (13). This implies that the most water-efficient fossil electricity source we discovered yields almost 600 times as much energy per unit of water invested as does the most water efficient biomass source of electricity reviewed by Berndes (13).

4.5 Discussion

Few if any studies regarding the scalability of biofuels explicitly consider water requirements (13). Similarly, no assessments of future water needs incorporate increased irrigation demands related to biofuels production (13). For American corn production, an average of 7,950 liters of irrigation water is required per bushel (23). At 10.22 liters of ethanol per bushel, this equates to 778 liters of water needed per liter of ethanol prior to refining needs.

Evapotranspiration connected to feedstock cultivation that dominates the consumptive water use of bioenergy systems. Corn and other biofuel crops can be grown without irrigation, though the yields are both lower and more volatile. From 1947-2006, irrigated corn acreage in Nebraska had a 43% higher yield than dryland corn. (24). The proposed Renewable Fuel Standard in the recent US Energy Bill forecasts a domestic increase in ethanol and other biofuels to at least 13 billion gallons by 2012 and 36 billion gallons by 2022. Our work suggests that, due to the much higher return on water invested of fossil energy sources, an attempt to replace a significant portion of current fossil fuel consumption with biomass resources could lead to severe strains upon the world's water resources. However, changing feedstock to more drought tolerant varieties, improved rainwater harvesting techniques, and utilizing biomass residues and process by-flows from food and forestry industries may lessen the water intensity of bioenergy production.

Water is already a limiting resource in many contexts (25), and increasing human withdrawals will have a dramatic effect on the earth's ecosystems and biodiversity (17). Furthermore, water shortages are already limiting energy production. Numerous power plants in Europe were shut down during recent summers due to water shortages, and drought remains a significant threat to biomass production as evidenced by the impact of water rationing upon Australian agriculture in 2007 (26).

A related issue is that at least some freshwater inputs into energy production (e.g. water injections for enhanced petroleum recovery) can be replaced by saltwater where available. Both of these issues argue for assessing the scalability of energy production in a spatial context. Incorporating temporal variation in precipitation patterns and predicted changes related to global warming also seems prudent. Stephen Chu, in his first interview as Secretary of Energy hinted at the importance of the water/energy nexus in California when he commented about climate change, "*up to 90% of the Sierra snowpack could disappear, all but eliminating a natural storage system for water vital to agriculture".*

In a resource-limited context, water could be diverted from current uses to be invested in energy production, especially if the market dictates society's priorities. This could have significant impacts upon food production and human welfare (27). On the other hand, in many contexts, water may not be the most limiting input into bioenergy production—labor (3), land (2) and energy itself may become more limiting.

4.6 Study Limitations

Despite some early attempts at assessing water limitations on energy production which implied a clear potential for water to impact scalability (3), there are still very few studies that rigorously apply a methodology like LCA to determine water inputs into energy production. This is especially true in comparison to the wealth of studies that assess energy requirements and greenhouse gas emissions. Therefore, it was not always clear from the studies we drew on what boundaries were placed on the system, whether indirect water costs had been taken into consideration, or how costs were allocated for co-products. We discarded studies where significant water costs had been neglected. To do this, for each study under consideration we researched a given technology independently to be sure no major water costs had been left out. However, there is a need for more comprehensive data on water requirements of energy systems. Although this comparative analysis and methodology should be considered preliminary, we hypothesize that our results demonstrate significant variation in the water demands and thereby the scalability of different energy production technologies.

Related to the scarcity of available data is the difficulty of establishing a rigorous framework. At least three forms of water usage appear in the studies we cite—water withdrawals, water consumption, and plant evapotranspiration. Each of these represents a different type of cost, and they are not necessarily additive. Water that is used and then returned is available to downstream users. Evapotranspiration can only be interpreted as an opportunity cost since its capture or loss depends on what the alternative land-use would be. Even water consumption costs in the form of evaporation are not necessarily additive since they depend on where the water precipitates. Also, neither fossil nor renewable energy is spatially uniform around the world, which further complicates one uniform measure of net EROWI (10). The tar sands have a moderate energy return, but are all located in one unique geologic region in Alberta, putting enormous pressure on local water resources would they be scaled fully.

A related issue is that at least some freshwater inputs into energy production (e.g. water injections for enhanced petroleum recovery) can be replaced by saltwater where available. Both of these issues argue for assessing the scalability of energy production in a spatial context. Incorporating temporal variation in precipitation patterns and predicted changes related to climate change also seems prudent.

Energy can also be invested in the desalinization of seawater. According to Kannan et al. (22), the energy requirements to desalinize sufficient quantities of water to operate the petroleum power plant they studied in Singapore would only reduce the EROEI of the technology by 0.02. If waste heat from the plant is used for desalinization, the reduction in EROEI is only 0.01. In particular, from their data we calculate an energy cost for dedicated desalinization of 0.11 MJ/L. However, this is higher than any EROWI for all bioenergy technologies we review with the exception of sugar cane ethanol and the study by Mann and Spath (21).

Regarding our methodology for calculating net EROWI, there are several aspects that would benefit from further analysis of more intricate tradeoffs between these two vital commodities. Firstly, although much literature describes discrete levels of EROI, a large component of the net EROWI will depend on the boundaries used in the net energy analysis itself. For example, the below graph illustrates numerous EROI calculations from the same wheat-to-ethanol process, using different boundaries and formulas (42). A framework for parsing these differences into commensurate EROIs is an important step towards more meaningful net EROWI figures.

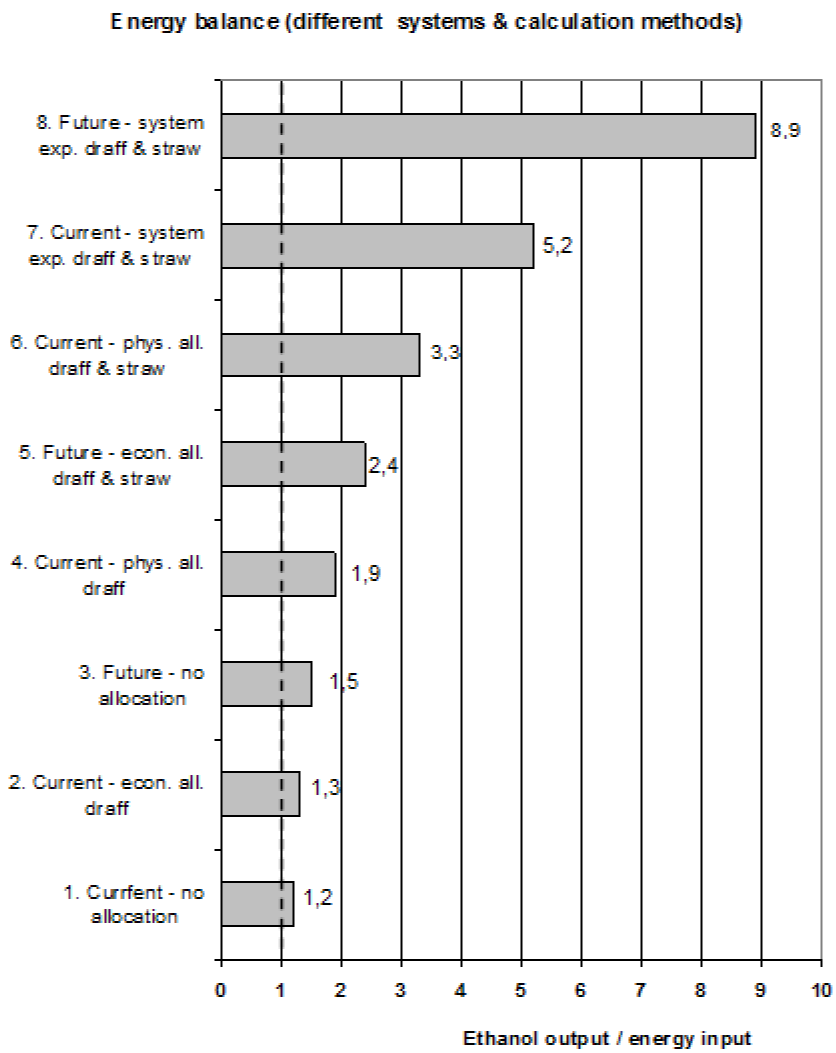

Figure 13 Energy Balance - Different System Boundaries (Borjesson 2008)

Furthermore, the mixing of the energy quality of both inputs and outputs highlights an ongoing problem with net energy studies. Not only are all BTUs unequal in their value to society, but the markets pricing hierarchy of energy 'types' by cost, may not correlate with long term scarcity. The quality issue is further complicated by cost/benefit tradeoffs within different energy/water technologies that could increase EROWI while decreasing EROI just by altering how an input is procured. For example, nitrogen fertilizers (the dominant energy cost of fertilizers) are mostly produced using natural gas, but future electricity could be generated from a different subset of primary energy sources, lowering the energy input for biofuels. As energy is also an input for irrigation and water delivery systems, an interesting and relevant follow-up to this paper might be an analysis of the Water Return on Energy Invested.

Finally, demand side policy changes may have water implications just as will the supply side. The current move towards electric vehicles, without a major change in the sources of electricity would create major new water demand. If hybrid/electric cars would fully replace gasoline vehicles, approximately three times more water is consumed and 17 times more water is withdrawn, primarily due to increased water cooling of increased thermoelectric generation. (43) Furthermore, demand side moves away from meat consumption would allow more land to be used for bioenergy as the water/land intensity is much lower for vegetarian than meat intensive diets. (44) As such, future refinements to an energy and water framework will likely have to extend beyond those two vital commodities.

4.7 Conclusion

There is increasing concern that conventional market mechanisms may not give correct or timely signals to a world dependent on the energy services obtained from fossil fuels. Energy return on investment attempts to focus on limited natural resources as opposed to conventional financial analysis which, by relying on a potentially infinite metric (currency), can give a false impression of the wealth available to the world (1,5,6,7,28). Energy (and other scarce resources including water) are what we have to spend –financial capital is just a marker for such real assets. However, despite the decades-old and ongoing debate over the energy balance of biofuels, we have demonstrated that the EROEI of an energy technology is only a partial indicator and will fail to correctly inform policy and investment if factors other than energy become limiting. Although it can be modified to account for issues such as energy quality (29) or refined to express returns in terms of specific energy inputs (4), it still suffers from a restrictive focus on energy alone—the one resource that we know an energy production technology can replace (30).

Past work has demonstrated that a primary advantage of fossil energy resources is their large EROEI (30,31). In this work, we have demonstrated that they also have a strong advantage in terms of their return on water invested. Biofuels have been touted as a key development that will stem future fossil fuel emissions and associated climate change impacts (32-34), and the development of biofuel production facilities and processing techniques has been supported by multinational oil corporations and federal governments alike (35). However, research assessing the future of biofuel production rarely considers the wider effects such as impacts on ecological systems and the availability of land and water resources (32,33). It has been shown that these impacts are potentially very large (36,37). Additionally, the demand for corn as a feedstock for biofuel production has had secondary consequences for corn prices and land demand

(38,39) and hence human welfare. The ripple effects of demand increases will likely include increasing land conversion, habitat destruction, fertilizer use and water withdrawals. All of these consequences should be considered in assessing how society should replace our reliance on fossil fuels.

Our work here, looking only at water demand, predicts:

- the development of bioenergy in scale sufficient to be a significant source of energy will likely have a strong, negative impact upon the availability of fresh water;

- Assuming the water requirements for infrastructure development are minimal, technologies such as solar and wind which do not require on-going water inputs will be at an advantage in many contexts.

Above all, we believe our analysis demonstrates that energy technologies must be assessed in a multi-criteria framework and not just from the perspective of energy alone. Ultimately, we should strive to have a renewable portfolio aggregating the highest returns on our most limiting inputs. (12)

References

1. N. Georgescu-Roegen, “The Entropy Law And The Economic Problem”. *in* H. E. Daly, editor. Toward a Steady State Economy. W. H. Freeman and Company, San Francisco (1973).

2. J. Hill, E. Nelson, D. Tilman, S. Polasky, and D. Tiffany. “Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels”, *Proc. Acad. Nat. Sci.* **103**:11206-11210 (2006).

3. M. Giampietro, S. Ulgiati, D. Pimentel, “Feasibility of large-scale biofuel production”, *Bioscience* **47**:587-600 (1997)

4. A. Farrell, et al., “Ethanol Can Contribute to Energy and. Environmental Goals”, *Science* **311**:506-508 (2006).

5. C.A. Hall, Cleveland C., Kaufmann R., 1986. “*Energy and Resource Quality : The Ecology of the Economic Process”*, Wiley, New York.

6. H. T. Odum, “Energy, ecology, and economics”, *Ambio* **2**:220-227 (1973).

7. D.T Spreng, *Net-Energy Analysis And The Energy Requirements Of Energy Systems*. Praeger, New York 1988.

8. C.J. Cleveland, R. Costanza, C. Hall, and R. Kaufmann, “Energy and the US Economy: A Biophysical Perspective”, *Science* **225**:890-897 (1984)

9. J. Sheehan, V. Camobreco, J. Duffield, M. Graboski, and H. Shapouri, “An Overview of Biodiesel and Petroleum Diesel Life Cycles”. (NREL/TP-580-24772, National Renewable Energy Laboratory, Golden, CO 1998).

10. V. Smil, 2006. "*21st century energy: Some sobering thoughts*". OECD Observer 258/59:

11. H. Flynn, T. Bradford, “Polysilicon: Supply, demand, and implications for the PV industry”, (The Prometheus Institute for Sustainable Development, Cambridge, MA 2006).

12. Mulder, K., Hagens N. “Energy Return on Investment – Towards a Consistent Framework”, *AMBIO* Vol. 37, No. 2 pp. 74–79

13. G. Berndes, “Bioenergy and water - the implications of large-scale bioenergy production for water use and supply”**,** *Global Environ. Change* **12**:253-271 2002).

14. S. Hutson,. et al (2004) "*Estimated Use of Water in the United States in 2000"*. US Geological Survey, Circular 1268

15. C.J. Vorosmarty, P. Green, J. Salisbury, and R. B. Lammers, "Global Water Resources: Vulnerability from Climate Change and Population Growth", *Science* **289**:284-288. (2000).

16. F.R. Rijsberman, "*Water* Scarcity: Fact or Fiction", *Agric. Water Mgmt* **80**:5-22 (2006).

17. J. Alcamo, et al., "Changes in Nature's Balance Sheet: Model Based Estimates of Future Worldwide Ecosystem Services", *Ecology and Society* **10**(2)19 (2005).

18. T. Oki, S. Kanae, "Global hydrological cycles and world water resources", *Science* **313**:1068-1072 (2006).

19. D. Renault, W. Wallender, "Nutritional Water Productivity and Diets", *Agric. Water Mgmt.* **45**:275-296 (2006).

20. G. Berndes, C. Azar, T. Kaberger, and D. Abrahamson, "The feasibility of large-scae lignocelluose-based bioenergy production, *Biomass & Bioenergy* **20**:371-383 (2001).

21. M.K. Mann, and P. Spath, "*Life Cycle Assessment Of A Biomass Gasification Combined-Cycle System*" (NREL/TP-430-23076, National Renewable Energy Laboratory, Golden, CO. 1997).

22. R. Kannan, C. Tso, R. Osman, and H. Ho., "LCA-LCCA of Oil Fired Steam Turbine Power ", *Energy Con. and Mgmt* **45**:3093-3107 (2004).

23. National Academy of Science "*Water Implications of Biofuels Production in the United States*", 2007

24. United States Department of Agriculture – National Agriculture Statistics Service 2007 http://www.nass.usda.gov/index.asp

25. P.H. Gleick, 2000. *The World's Water*. Island Press, Washington, D.C.

26. "*Drought Threatens Crop Catastrophe*", The Guardian Apr 20, 2007 www.guardian.co.uk/australia/story/0,,2061761,00.html.

27. D. Pimentel, *et al.*, "Water resources, agriculture, the environment and society", *Bioscience* **47**:97-106 (1997).

28. F. Soddy, 1933. *Wealth, Virtual Wealth And Debt; The Solution Of The Economic Paradox,* 2d edition. E.P. Dutton, New York,.

29. C.J. Cleveland, “Energy surplus and energy quality in the extraction of fossil fuels in the US”, *Ecol. Econ.* **6**:139-162 (1992)

30. C.J. Cleveland, “Net *energy* from oil and gas extraction in the United States”, *Energy* **30**:769-782 (2005).

31. J.A.Tainter, T. Allen, T. Hoekstra, “Energy Transformations and Post-Normal Science”, *Energy* **31**:44-58 (2006)

32. D. Tilman, P. Reich, J.M.H. Knops, “Biodiversity and ecosystem stability in a decade-long grassland experiment” *Nature* **441**:629-632 (2006)

33. J. Goldemberg, “Ethanol for a sustainable energy future”, *Science* **315**:808-810 (2007).

34. A.J. Ragauskas *et al.*, “The path forward for biofuels and biomaterials.”, *Science* **311**:484-489 (2006).

35. K. Sanderson, “A Field in Ferment”, *Nature* **444**:673-676 (2007).

36. N.J. Hagens, R. Costanza, K. Mulder. “Energy Returns on Ethanol Production”, *Science* **312**:1746-1746 (2006)

37. D. Tilman, J. Hill, C. Lehman, “Carbon Negative Biofuels from Low Impact High Diversity Grassland Biomass”, *Science* **314**:1598-1600 (2006).

38. D. Kennedy, “The Biofuels Conundrum”,*Science* **316**:515-515 (2007).

39. L. Odling-Smee, “Biofuels bandwagon hits a rut**”** *Nature* **446**:483-483 (2007).

40. N. D. Mortimer, M. A. Elsayed, R. Matthews, “Carbon and Energy Balances for a Range of Biofuel Options”, (Resources Research Unit, Sheffield Hallam University, Sheffield, England, 2003).

41. L. Lynd, M. Q. Wang, “A product-nonspecific framework for evaluating the potential of biomass-based products to displace fossil fuels” *J. Ind. Ecol.* 7:17-32 (2004).

42. Börjesson, P. (2008). “*Good or bad ethanol – what determines this?”* Report no. 65, Environmental and Energy Systems Studies, Department of Technology and Society, Lund University, Sweden.

43. Webber, M., King, C., "The Water Intensity of the Plugged-In Automotive Economy", *Environmental Science & Technology* 2008 *42* (12), 4305-4311

44. Berndes, G. (2008). "*Bioenergy - A New Large User of Scarce Water*?" In: Förare, J. (ed.) Food and water. Forskningsrådet för miljö, areella näringar och samhällsbyggande, Formas

CHAPTER 5: NET ENERGY AND TIME

5.1 Abstract

Net energy analysis is a key metric used to compare different energy technologies. This is usually done by measuring total energy outputs against expended energy inputs over the life cycle of an energy procuring technology, for example a wind power generation plant or an natural gas well. Results are typically presented in the form of net energy gain, energy payback time or EROI (energy return on energy investment). In these methodologies, the time between energy inputs and energy outputs is not factored into the calculations, and the summary net energy statistic essentially values energy inputs at time t nominally versus energy outputs at time t+n**,** where n is any year during the life cycle of a production or extraction method.

Biological organisms, including human societies both with and without market systems, discount future outputs over those available at the present based on the risks and uncertainties associated with the future. This preference for current returns, rooted in biology, is represented in the world of finance and economics by the concept of net present value, which handicaps future values using implied costs for time.

As energy generation technologies vary greatly on a temporal continuum and energy and infrastructure investments must compete amongst an increasing diversity of technologies, there is a strong case to incorporate time into net energy analysis/EROI models. For example, solar panels or wind power engines, where the majority of energy (and monetary) investment happens before they begin producing, will need to be assessed differently when compared to fossil fuel extraction technologies, where a large portion of

the energy (the fuel) will only be applied at the time of energy output consumption. This paper introduces a theoretical model to correctly account for time in net energy/EROI calculations and applies this concept to a number of energy technologies.

5.2 Net Energy Analysis

Besides perhaps water, energy is the most important contributor to life on our planet. Over time, natural selection has optimized towards the most efficient methods for energy capture, transformation, and consumption. (Lotka 1922, Odum 1974, Hall 2009) In order to survive, each organism is in need of procuring at least the amount of energy it consumes. Cheetahs that repeatedly expend more energy chasing a gazelle than they receive from eating it will not survive. In order for body maintenance and repair, reproduction, and the raising of offspring, the cheetah will need to obtain significantly more calories from its prey than it expends chasing it. This amount of energy left over after the calories used to locate, harvest (kill), refine and utilize the original energy are accounted for is termed 'net energy'. In the human sphere, this same concept applies. Energy sources need to return more energy than is used in their retrieval, and in order to secure an average modern human lifestyle including shelter, amenities, leisure activities and many more benefits beyond the bare necessities, this energy surplus needs to be significant.

Human history has been one of transitions in energy quantity and quality. The value of any energy transformation process to society is proportional to the amount of surplus energy it can produce in excess of what it needs for self-replication (Hannon 1982). Over time, our trajectory from using sources like biomass and draft animals, to wind and water power, to fossil fuels and electricity has enabled large increases in per capita output because of increases in the quantity of fuel available to produce non-energy goods. This transition to higher energy gain fuels also enabled social and economic diversification as less of our available energy was needed for the energy securing process, thereby diverting more energy towards non-extractive activities. (Cleveland 1992)

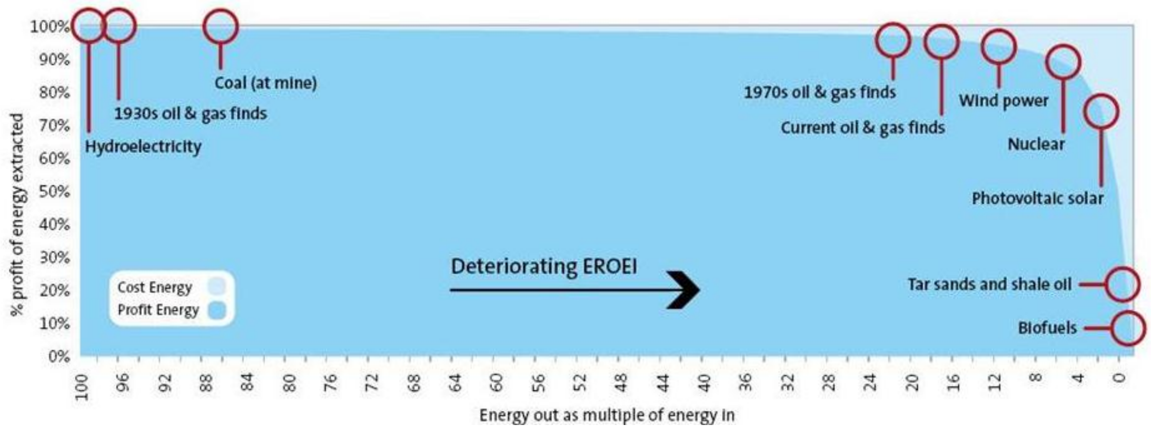

Figure 14 Net Energy Cliff (Morgan 2010)

As fossil fuels become more difficult to retrieve and thus more expensive, a move from higher to lower energy gain fuels will have important implications for both how our societies are powered, and structured. As illustrated in Figure 14, declines in aggregate EROI mean more energy is required by the energy sector (light blue) leaving less energy available for other areas of an economy (the dark blue). Declines in amounts of surplus energy have been linked to collapses of animal societies and historical human civilizations (Tainter 1990). Though research into precisely how much net energy we might need to sustain human civilization is an interesting and important question, but one not frequently addressed (Hall 2009).

In the past few decades, a number of concepts have been introduced to measure this relationship between energy input and energy gains for energy sources, for example energy profit ratio, Energy Return on Energy Invested (EROI), energy payback period, energy yield and net energy analysis. These biophysical statistics always describe the amount of energy procured for human use relative to the amount expended. Every energy system incurs initial energy expenditures during its own construction. The facility then produces an energy output for a number of years until the end of its effective lifetime is reached. Over time, additional energy costs are incurred in the operation and maintenance of the facility. The simplest statistic to measure these energy flows is 'energy gain', which is the sum of the total energy output less the sum of the total energy input over the life of the investment. A variation of this is EROI, which divides the total energy output by the energy input to arrive at a ratio, indicative of the energy harnessing return potential of the particular technology (EROI is sometimes also referred to as the 'Energy Profit Ratio'). Another popular statistic is the "energy payback period", which is the time it takes an energy procuring technology to "pay back" or produce an amount of energy equivalent to that invested in its construction. This method is limited in that it doesn't account for the total remaining energy output after the initial "payback period", which might differ significantly for technologies with the same pay-back time. In this paper, we will use the output/input ratio EROI, though the concepts presented here will be applicable to any biophysical statistic measuring net energy.

Net energy is central to an energy theory of value which asserts that natural resources, particularly energy, as opposed to dollars are what we have to budget and spend (Gilliland 1975). This mode of analysis was viewed as so fundamental that in 1974 Congress required every government sponsored technology for procuring energy to be subject to net energy analysis (Public Law 93-577 and 96-294). Net energy analysis, though popular during the energy crises of the 1970s had largely been subsumed in the academic literature by Life Cycle Assessment, until a recent resurgence in biophysical analysis in the last few years sparked by concerns about oil depletion. (Hall 2009).

Table 6 Examples of EROI Values/Studies (Murphy 2010)

Energy Technology	**EROI**	**Reference**
Global oil production	35	Gagnon, 2009
Coal (mine mouth)	80	Cleveland 2005
Nuclear	5-15	Lenzen 2005
Hydropower	>100	Hall 2008
Wind turbines	18	Kubiszewski 2008
Solar Photovoltaic	6-8	Battisti 2005
Corn based ethanol	0.8-1.6	Farrel, 2005

EROI in the studies above and others, is represented as a static integer representing the ratio of energy output to energy expense for the life of an energy technology. This graphically can be represented using an energy flow diagram such as depicted in Figure 15. The green shaded region represents the energy output beginning at time t+c (where c is the period required for construction of facilities) and ending at time t+e (where e is the total number of years with energy gains). The blue section is the initial energy investment needed from the beginning of an energy gathering project. The red section represents ongoing inputs in energy terms through time t+e. Depending on the boundaries, there may also be another energy expense at time T…T+n dealing with decommissioning and waste removal (the grey).

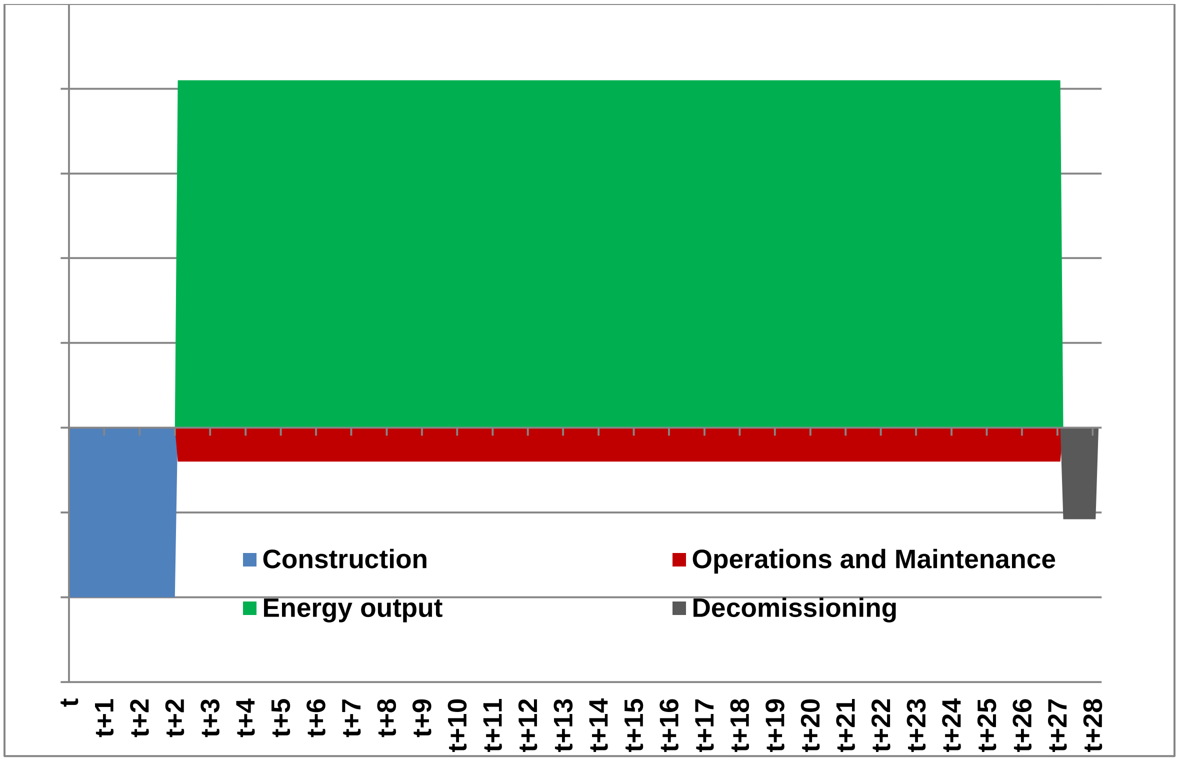

Figure 15 Sample Input/Output Timeline for an Energy Technology

In traditional net energy analysis, an energy input or output is treated the same irrespective of where it occurs temporally in the life cycle of the energy technology. However, human preferences across time periods have considerable influence on our energy use and our energy planning decisions. Even though a barrel of crude oil extracted today will have the same BTU content as one produced 10 years hence, its usefulness to society at any given point will change as a function of numerous economic, institutional, and technological factors. In this equation, time becomes an important variable.

A comparison of two graphs for energy retrieval might show the relevance of time. Both depictions in Figure 16 represent technologies that offer exactly the same energy return (EROI), but the first one returns the energy over 20 years and the second returns the energy within 10 years. The energy costs are identical at the start and during the life of the asset. Provided the quality of the energy retrieved is comparable, it is quite obvious that societies would prefer the technology that delivers more faster (the graph on the right), though standard EROI analyses treats them the same.

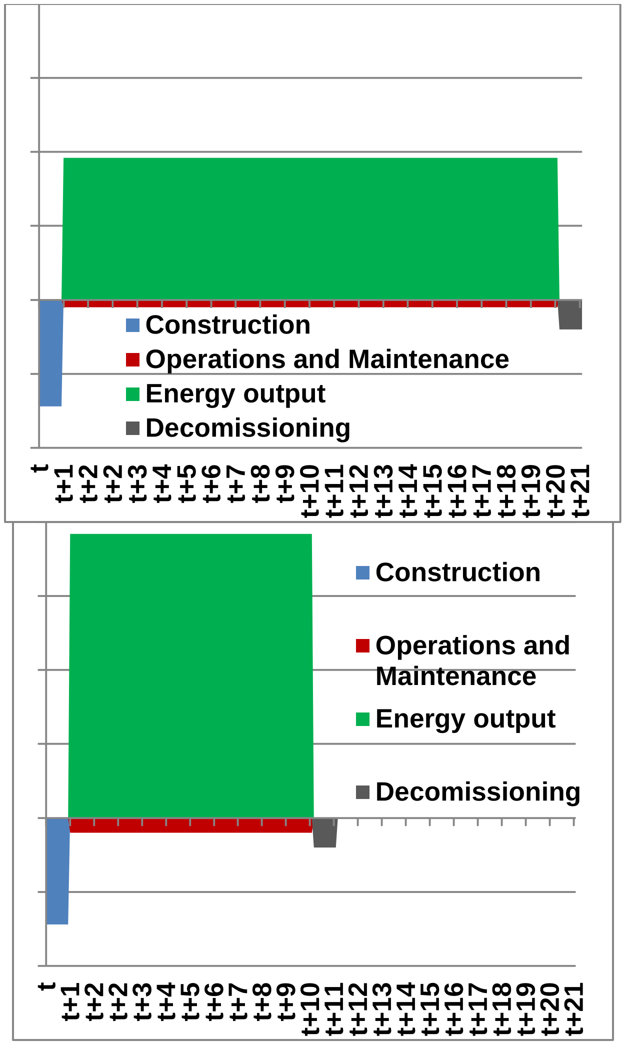

Figure 16 Different Time Horizons with Equivalent EROI

5.3 Discount Rates and Time

Humans prefer present over future consumption in most situations. The extent of this preference is measured using a **discount rate** - the rate at which and individual or society as a whole is willing to trade off present for future benefits. The behavior of discounting future returns has an evolutionary background (Robson 2002). The majority of organisms in nature do not live as long as their biological potential (Millar 1983). Thus in most animals, emotions and instincts drive behaviors with short-term goals, such as eating, drinking and mating. These automatic behaviors, rooted in older brain regions like the limbic system are inherently myopic (McClure 2004, Berns 2010). Essentially, all biological research finds positive preference for current versus future returns, and if returns are equal, most experiments show a large preference for immediate reward, except for situations when the immediate needs of the test subjects have just been satisfied (Bateson 2002). However, humans differ from other animals in that we worry about and/or experience immediate pleasure from considering delayed consequences. As such, our emotional systems also have the potential to motivate behaviors that have long term positive tradeoffs. Thus it is the extent to which we prefer the present over the future that is at issue, not whether or not this preference exists.

Though the majority of studies investigating human temporal choice involve low-cost choices about money, an evolutionarily novel reward to our species, a large body of research shows that discounting of the future is prevalent in human societies. The reality of temporal risk is present in many forms for both animals and humans, including but not limited to: entropy risk, risk of destruction, risk of non-survival (e.g. a healthy 30 year old male in the U.S. has a 7.96% chance of not experiencing his 50th birthday (SSA 2006), risk of limited access or government expropriation, risk of obsolescence, etc. These and other risks underlie the logic for favoring current returns over delayed future returns, or stated differently, demand sufficient excess returns to justify the risks of waiting for the arrival of future benefits.

Though some degree of time preference is present in all of us, certain demographics exhibit steeper discount rates than others. Studies on young people, gender differences, alcohol drinkers, drug users, gamblers, smokers, risk takers, low IQ individuals, individuals with full cognitive load, etc. all exhibit a stronger preference for immediate over delayed consumption with variations across these life-style and genetic differences (see Chabris 2009 for an overview). Unsurprisingly, stressed people exhibit higher preference for immediate versus delayed consumption. (Takahashi 2008)

Figure 17 highlights a meta-analysis by Frederick et al on individual discount rates showing the distribution (in panel Figure 1a) of a large sample of studies (Frederick 2002). In their Figure 1b, only decisions involving long time horizons are indicated. Each of the annual discount factors (1/(1-discount rate)) are graphed versus the time preference horizon– from near zero to nearly 60% with a median of around 20% per annum. This is consistent with other research on long term discount rates associated with durable goods purchases (Hausman 1979, Ruderman 1987). Ultimately, it seems that a relatively constant non-financial discount rate is applied after a certain period of several months, which seems to range between 5% and 50% for individual decisions, with an average near 20%.

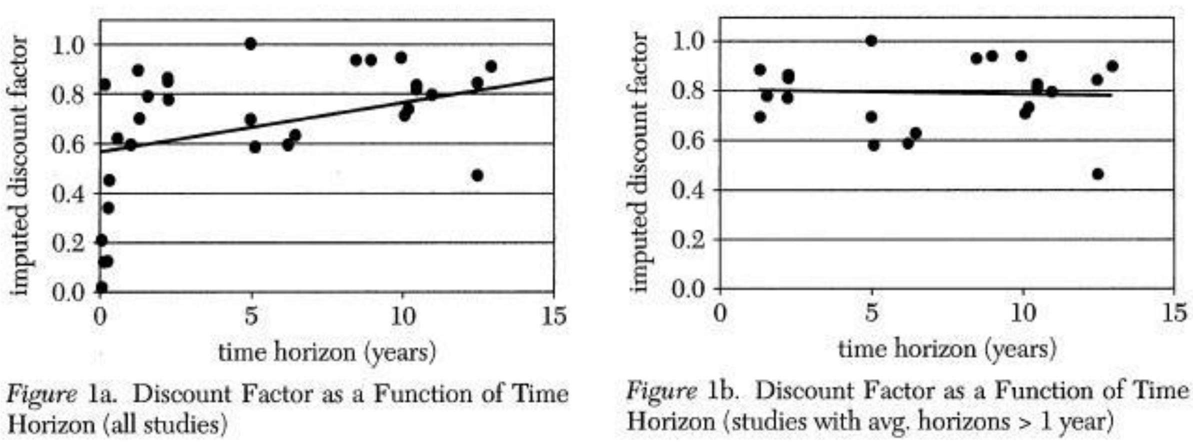

Figure 17 A Meta-Analysis Comparison of Discount Rates (Frederick 2001)

It is clear that human decision-making cannot be accurately predicted without reference to social context (Gowdy 2008) Moreover, many decisions, particularly pertaining to energy and related infrastructure are made by groups as opposed to individuals. The **social rate of time preference** is the rate at which society is willing to substitute present for future consumption of natural resources (Zhuang 2007). Overall, due to less risk of appropriation, longer life spans, etc., society-level discount rates should be lower than personal discount rates, but perhaps not significantly so. In fact, there is significant debate on what level of discount rate to use in policy decisions. The arguments center around what rates should be used (prescriptive) versus what rates people and societies actually use in real decisions (descriptive) (Arrow 1995). Many environmentalists assert that social discount rates should be less than 3% so as to properly weight future generations and the environmental costs they may face. In fact, in the Stern Review on climate change, the authors propose using a range between zero and

1.4% (Stern 2004). However, some advocate using higher discount rates in policy so that enough infrastructure and investment takes place in the near term so as to build a bridge to the future (Pearce 1989). A meta-analysis of social discount rates from countries around the world showed a range between 3% and 12%, the higher numbers not surprisingly from countries of the global south (Zhuang 2007). The United States Office of Management and Budget has applied a 7% discount rate towards civic projects since 1992. (OMB 1992). This paper does not weigh in on the prescriptive versus descriptive debate on discount rates other than to accept that some non-zero preference for immediate over future consumption exists for both individuals and societies.

5.4 Time and Financial Risk

Because a dollar received today is considered more valuable than one received in the future, time also becomes an important factor in financial and economic decisions. First, in a modern (and historical) fiat banking system where money supply increases over time, positive rates of inflation diminish the purchasing power of dollars as time passes. Also, since dollars can be invested today and earn a positive rate of return, this creates an opportunity cost for both monetary and scarce resource investments. Finally, there is uncertainty surrounding the ability to obtain promised future income which creates risk that a future benefit might never materialize. For all these reasons, the financial world simply copies the principles of nature, as detailed above. In economics and finance, discount rates are used to compress a stream of future benefits and costs into a single present value amount. The net present value is the value today of a stream of payments, receipts, or costs occurring over time, as discounted through the use of some interest rate. Mathematically, the present value of a future benefit or cost is computed as:.

$$PV = FV / (1+i)^{n}$$

Where PV = the present value of a benefit or cost, FV = its future value, i = the discount rate and n = the number of periods between the present and the time when the benefit or cost is expected to occur. Total net present value (NPV) is then simply:

$$NPV = \sum_{i=1}^{n} \frac{values_i}{(1+rate)^i}$$

5.5 Time Value of Energy

As discussed above, human societies discount future energy returns irrespective of monetary transactions or financial interest, simply in order to compensate for the uncertainties involved with time. There has been considerable academic literature on the inter-relationship between energy and time.   In physics**,** power is defined as the rate at which energy is converted to work Some have suggested that power (or energy transformed per unit time) has been a primary driver of both human and nonhuman biological systems (Lotka 1922, Odum 1963, Schneider 1995, Hall 2005). This "Maximum Power Principle" which was referred to as the Fourth Law of Thermodynamics by H.T. Odum states:

"…that systems which maximize their flow rate of energy survive in competition. In other words, rather than merely accepting the fact that more energy per unit of time is transformed in a process which operates at maximum power, this principle says that systems organize and structure themselves naturally to maximize power. Over time, the systems which maximize power are selected for whereas those that do not are selected against and eventually eliminated. ... Odum argues ... that the free market mechanisms of

the economy effectively do the same thing for human systems and that our economic evolution to date is a product of that selection process." (Gilliland 1978)

We see this tradeoff between energy and time in many areas. Airplanes get us to our destination much faster than cars or trains, but use significantly more energy. Similarly, people speed at 70 mph so as to arrive faster when driving 55mph would use less energy. Spreng suggested that in many human systems energy, time and information are substitutable for each other, and that time is especially relevant for issues pertaining to energy conservation (Spreng 1993)**.** Hannon derived the discount rates of various energy technologies producing the same type of energy and compared them. (Hannon 1982). He found that different energy systems had different discount factors associated with them and that applying an energy discount rate to EROI calculations had the largest impact on systems such as nuclear power and the solar based systems requiring large capital outlay (and hence indirect energy) before energy production started. It seems no scientific consensus has been reached on energy and time other than that they are interrelated. Below, we attempt to integrate time with net energy analysis.

The following section applies the above theoretical framework to several real energy examples; wind turbines, corn based ethanol and oil and gas production. Since specific year by year energy data was largely unavailable in each case, the analysis assumed energy was expended at roughly the same time and in same proportion as dollars were expended.

When introducing net present value to net energy gain or EROI calculations, both inputs and outputs get discounted more depending on how far in the future they occur. Figure 18 highlights an example based on available EROI data for wind power generation with an EROI of 19.2 (e.g. a net energy gain of 18.2) and relatively high initial investments, steady inputs and outputs for 20 years and comparably small ongoing cost or operations and maintenance, and a small cost of decommissioning.[3]

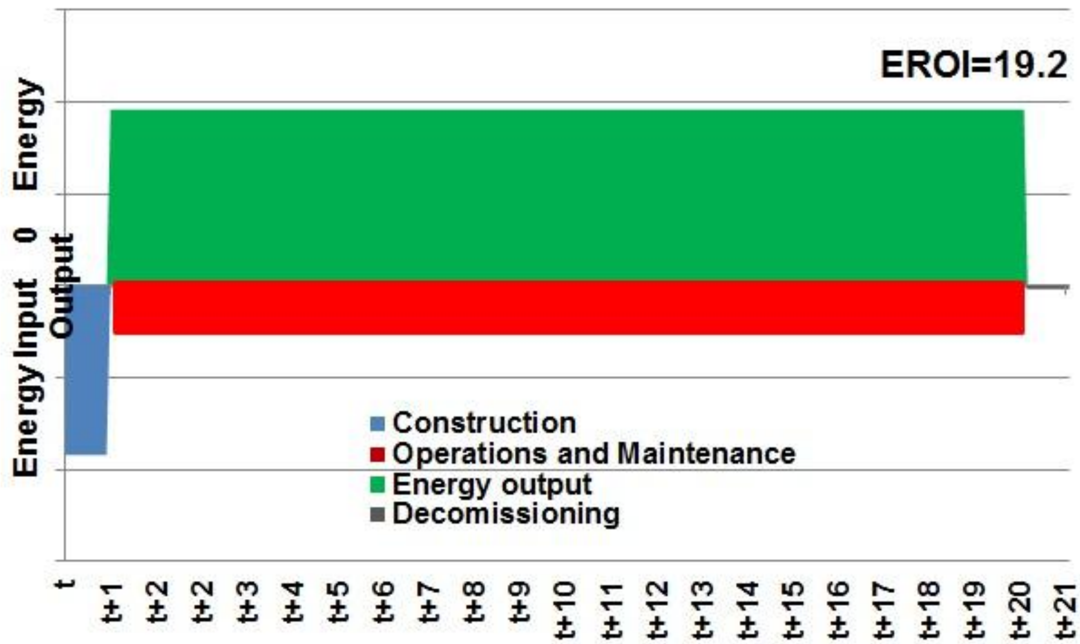

Figure 18 Nominal Energy Inputs and Outputs (not discounted) for Wind Power

When introducing a discount rate of 5%, which can be considered very low both in non-financial and in financial realms, and represents societies with very high expectations for

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[3] The average EROI in a recent meta-analysis (Kubiszewski 2010) for operational turbines was 19.8:1. We chose one of the wind farms studied (Ardente 2009) as representative of age, size and EROI (19.2:1) from the meta-analysis, and allocated energy inputs to the various times of dollar investment (construction, operations and maintenance, and disposal) and graphed these relative to the 19.2:1 energy return occurring over 20 years.

long-term stability (such as most OECD countries), the EROI of 19.2 of this particular temporal shape of future inputs and outputs is reduced to 12.4 after discounting.

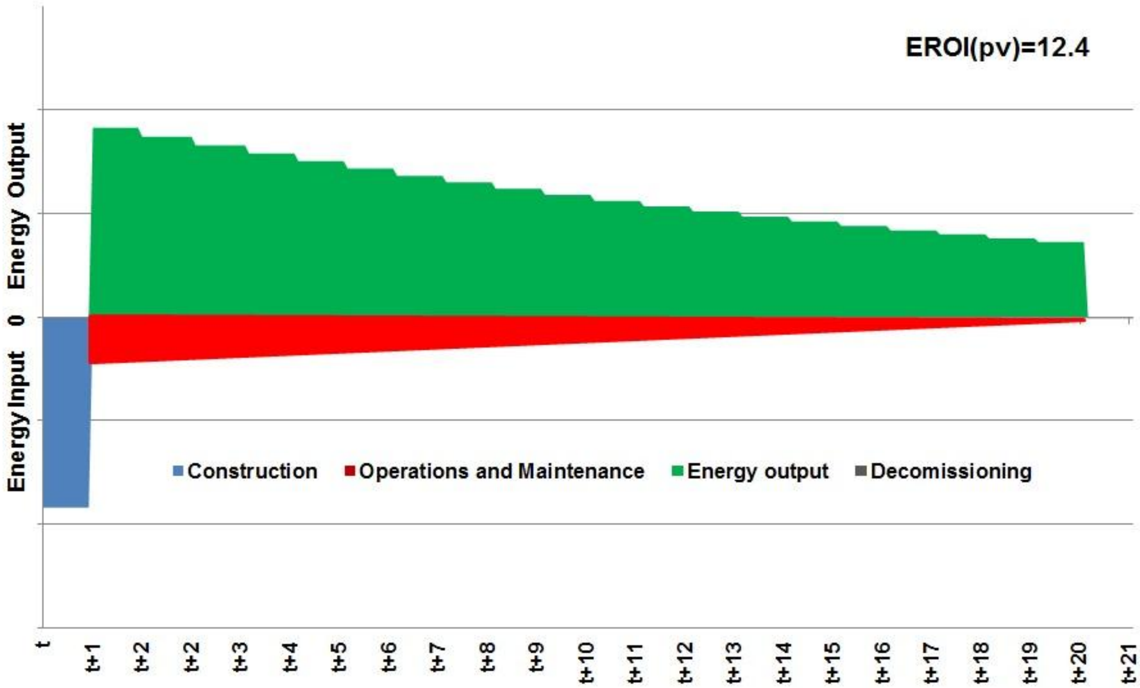

Figure 19 Energy Inputs and Outputs for Wind Power Discounted at 5%

But discount rates are not the same in all situations and societal circumstances. Investing into the same wind power plant in a relatively unstable environment, for example in an emerging economy, where discount rates of 15% are more likely, total EROI for this technology is reduced to a very low value of 6.4, nearly 1/3 of the original non-discounted value.

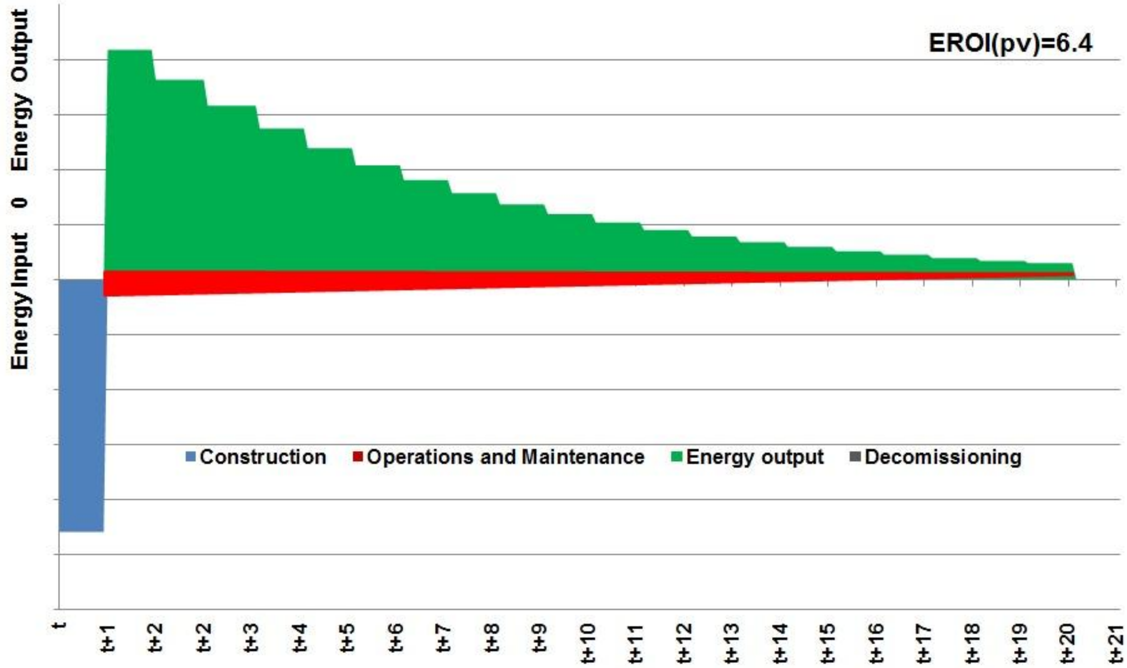

Figure 20 Energy Inputs and Outputs for Wind Discounted at 15%

The graphical depiction shown in figures 18-20 is representative of most renewable energy systems with significant upfront investments followed by linear returns thereafter. Other energy technologies often see a larger proportion of the inputs at the time of output generation, and a comparatively smaller amount of upfront investment. This pattern more resembles traditional fossil fuel extraction projects, like the exploration of an oil field or a coal mine, although this is changing for many fossil sources as prospecting costs are rapidly increasing.

Figure 21 shows an undiscounted flow diagram for the typical pattern of extraction related projects, a relatively steady (or even growing) effort yielding lower and lower returns over time after an early peak. When a discount rate is applied (Figure 22), the discounted EROI is actually slightly higher than undiscounted EROI.

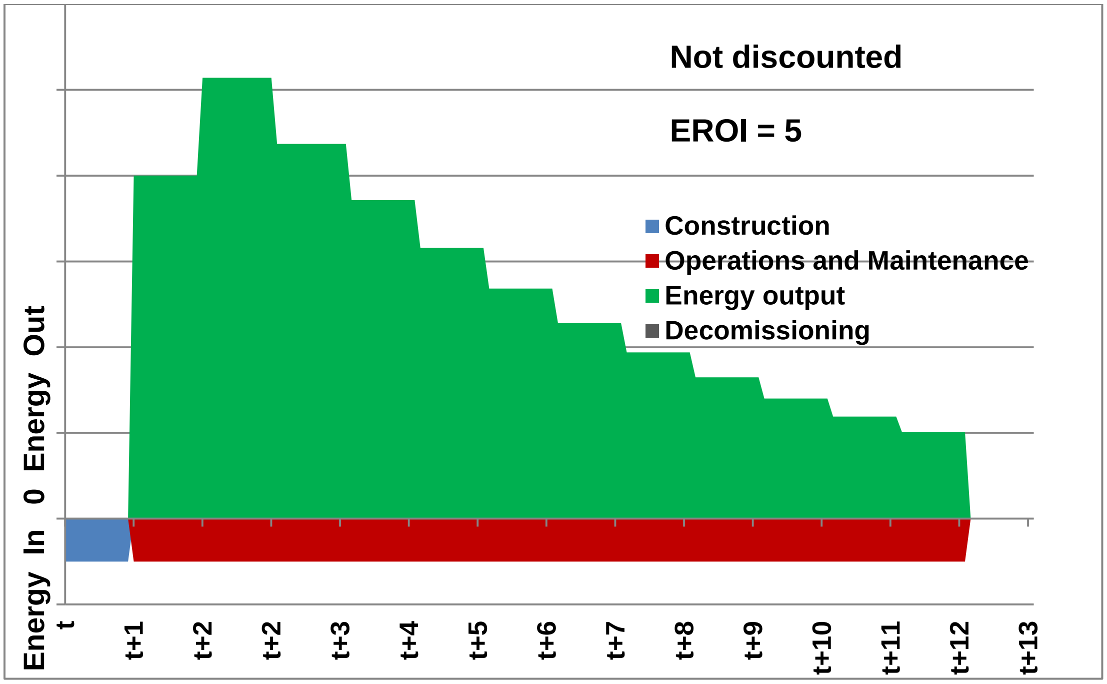

Figure 21 Undiscounted Extraction Project with Declining Flows

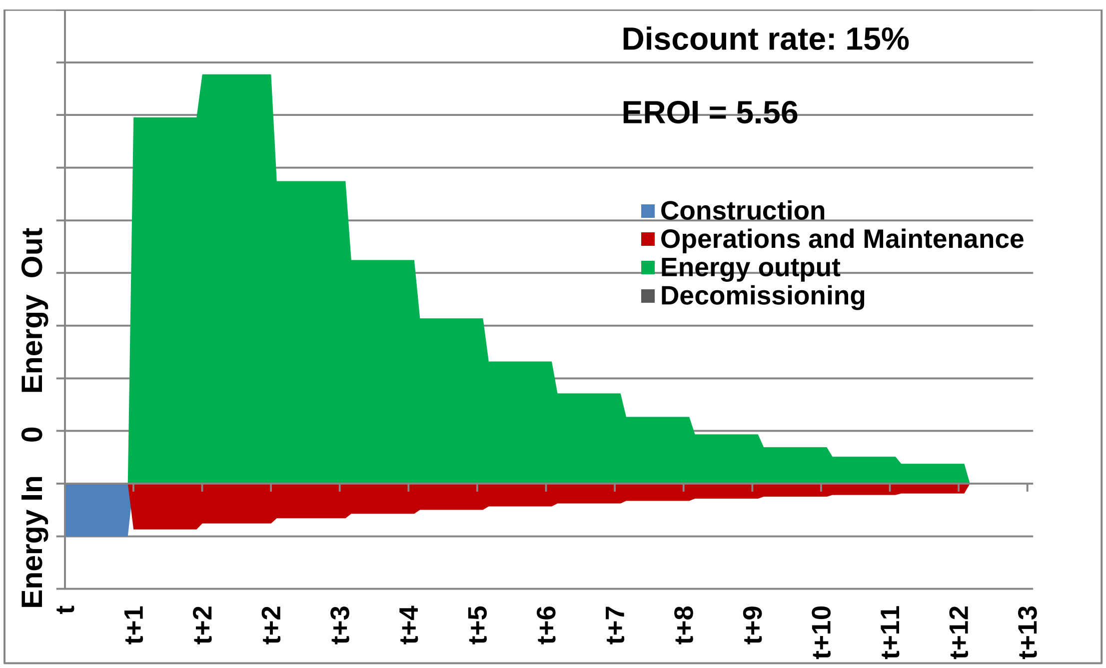

Figure 22 Extraction Technology with Declining Outputs at a 15% Discount Rate

In summary, the timing of energy inputs and outputs has an important impact on their 'time-adjusted EROI'. Energy technologies with a high upfront investment typically show significantly lower EROIs after discounting, whereas those with a relatively low upfront investment and comparatively high cost during extraction are less affected by discounting. The same pattern applies for energy conversion technologies, for example in electricity generation. This calculation can be converted into a mathematical formula with the following characteristics:

$$EROI_{pv} = \frac{\sum_{i=1}^{n} \frac{E_i(out)}{(1+rate)^i}}{\sum_{i=1}^{n} \frac{E_i(in)}{(1+rate)^i}}$$

Where n (total time from beginning of investment to decommissioning), E(out) the total gross energy output per period), E(in) the total gross energy input per period, rate (the applied discount rate) and I (the current period). This formula applies to the graphs indicated in this paper as is integer in nature. In reality energy is produced in real time which parses to the following integral:

$$EROI_{PV} = \frac{\int_0^T E_{out}(t)e^{-rt}dt}{\int_0^T E_{in}(t)e^{-rt}dt}$$

Table 7 shows the impact of discounting for typical wind and solar photovoltaic net energy. As the majority of the energy input required for wind turbines and solar panels is in the pre-production phase, the future (non-discounted) flow rates present as an almost flat production profile as the 'average' energy return is modeled as a pro-forma.

Table 7 The Impact of Discounting on Wind and Solar EROI

	Undiscounted EROI	5%	8%	10%	15%	20%
Wind (see fig 18-20)	**19.2**	**12.4**	**9.88**	**8.62**	**6.39**	**5**
Solar (photovoltaic)	**8**	**5.06**	**3.9**	**3.32**	**2.33**	**1.73**

With such an energy input/output schematic, the future energy gain associated with the turbines has decreasing value to human users when either a) the expected lifetime increases /or b) the effective discount rate increases. As can be seen above, an assumption of an 8% discount rate cuts the wind EROI essentially in half - from 19 down to 9. A discount rate of 15%, common in emerging markets, brings the time-adjusted effective EROI from 19.2:1 down to 6:1.

Fossil fuels are quite different than renewable energy technologies both on the timing of energy inputs and the shape of the energy outputs. Though there are large upfront costs, a larger percentage of energy input does occur after energy starts to be produced (contrary to wind, solar etc.). Also, the energy production trajectory, though sometimes lasting for decades, typically reaches its maximum within several years of first production. For example, a typical onshore gas well in North America produces 45-50% of its total energy output within 3 years (NEB 2010). Shale gas wells are 90% depleted within 18 months (Wolff 2008). Even unexplored regions containing oil, like the Arctic National Wildlife Reserve, are projected to attain peak production within 3-4 years and only maintain it for a few years before entering terminal production decline (IEA 2008).

Figures 23 and 24 were modeled after an oil and gas field in Louisiana which has completed its seven year production life cycle. We assumed it had an EROI of 10 which is the industry average based on the literature. We took real dollar expenditures of the drilling, completion, workover (in year 3), production/maintenance and all other costs including plugging and abandoning the wells and (as in the wind example above) allocated their percentages based on the time horizon they were expended (Denbury Resources 2010). We then discounted both the inputs (energy) and outputs (barrels of oil/mmbtu gas in dollar terms) to arrive at the input/output diagrams shown in Figures 23 and 24. This field (comprised of several wells), produced 3.37 million barrels of oil (equivalent) during its 7 years of production. 38% of production was in the first 2 years and 85% in the first 4 years.

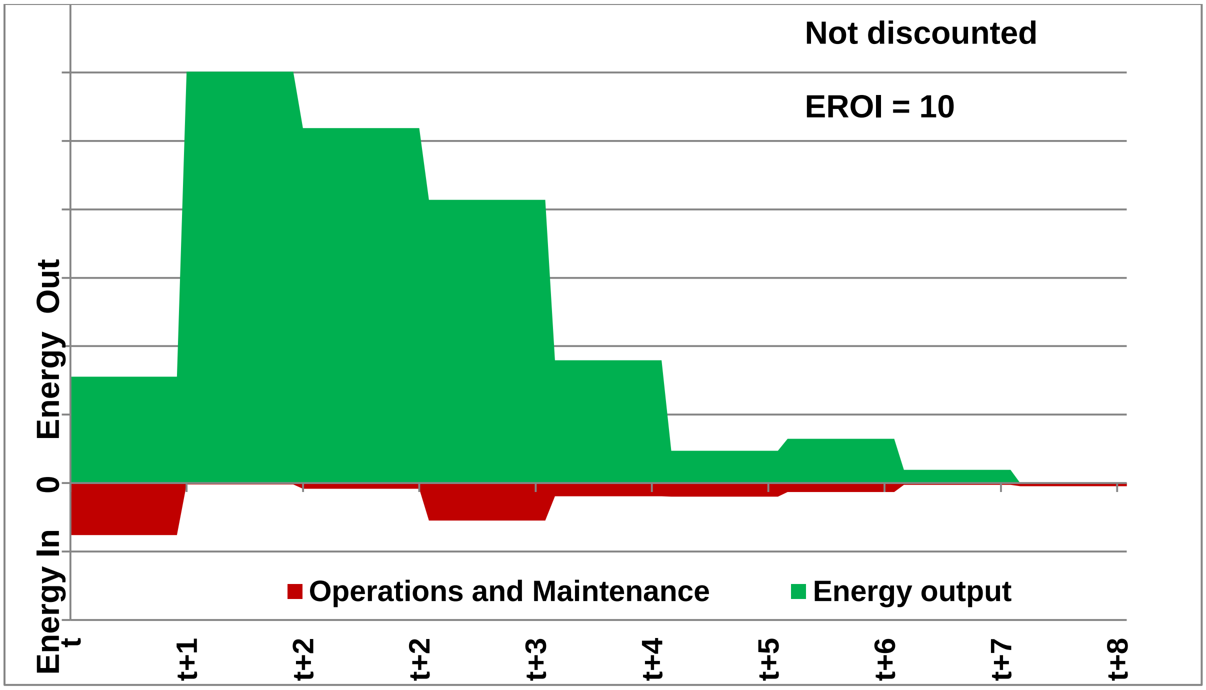

Figure 23 Profile of Leon Herbert Field with EROI of 10, non-discounted

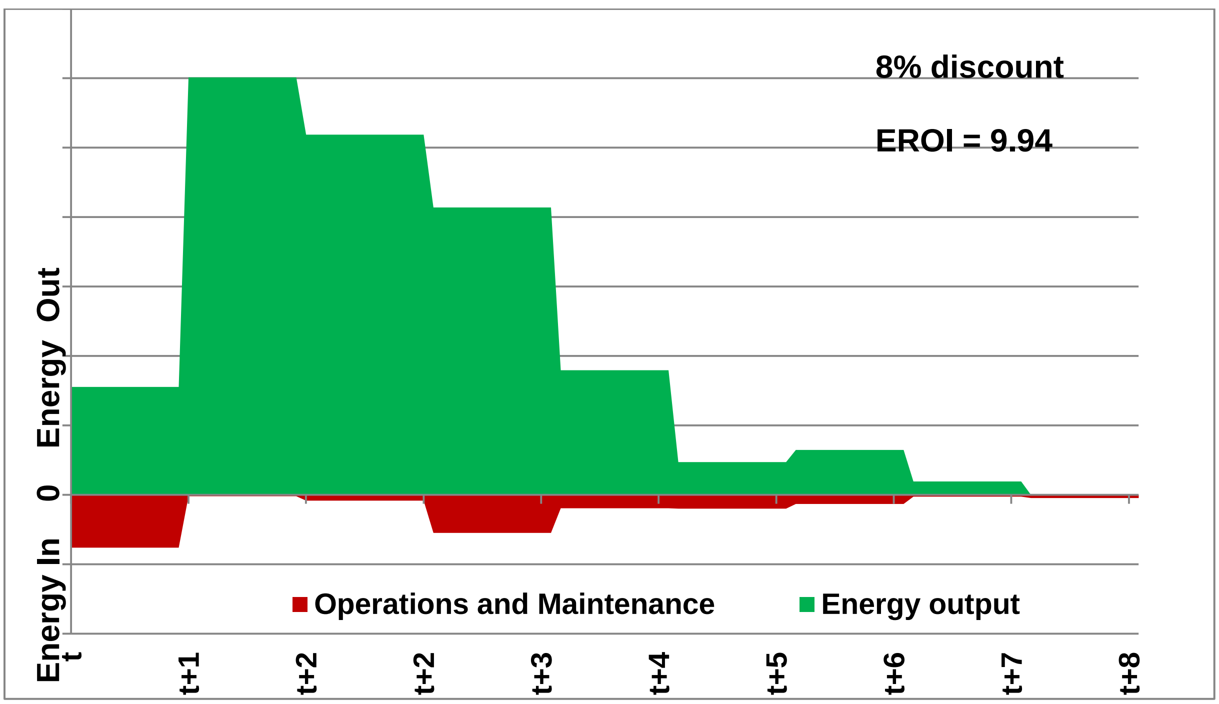

Figure 24 Profile of Leon Herbert Field Discounted at 8%5.6.3 Time adjusted

Corn ethanol, depending on the boundaries on inputs used, has an EROI of between 0.78:1 and 1.6:1. Figure 25 shows the discounted EROI of the lower bound energy estimates (0.78:1, which include the energy costs embodied in the tractor and other farm equipment), visible as regular input peaks every 10 years, the depreciated life of much of the equipment[4]. Two things can be noted: 1) at low energy gain (or sub-unity EROI as is the case here), discounting does not make a large difference to the NPVed EROI and 2) a good deal of energy input occurs in each year (at the time of application of fertilizers, pesticides, heat used to concentrate the mash, etc). In this light, ethanol, though having low overall energy gain and high externalities, has an input/output closer to fossil fuel extraction than to renewable solar flow based technology.

[4] Similar to the wind and oil calculations, we used real data on corn production and ethanol processing from: Patzek, T., 'Thermodynamics of the Corn Ethanol Cycle", Critical Reviews in Plant Sciences, 23(6):519-567 (2004) and Pimentel, D. and T.W. Patzek, *Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower.* Natural Resources Research, 2005. **14**(1): p. 65-76.,133 to establish time horizons for energy inputs for each component in percentage terms of the total.

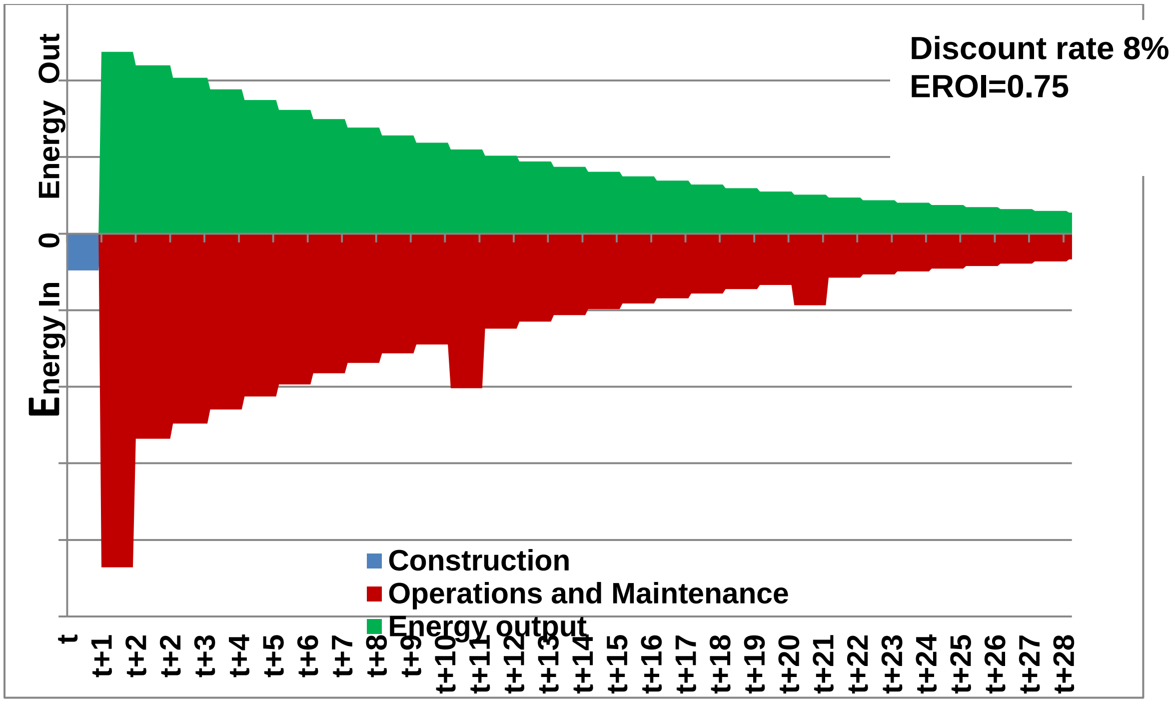

Figure 25 (Corn Ethanol) with an EROI of 0.78 discounted at 8%

Figure 26 provides a clear indication that time discounting implies significant changes in present values of various energy technologies. The x axis represents nominal EROI. The y axis represents expected lifetime of an energy technology. The darkest circles of each color represent nominal (non-discounted) EROIs from the literature for each energy source. The light circles represent the same energy output and input discounted at 15% and the intermediate shaded circles represent discounting energy flows at 8%. Particularly for renewable generation methods such as solar and wind, the implications of discounting change their position, even at relatively low discount rates. (The impact of applying discount rates to corn ethanol and offshore gas is negligible on

EROI. Based on the timing of oil flows (a near term peak followed by long tail), discounting actually ***increases*** the nominal EROI for oil.

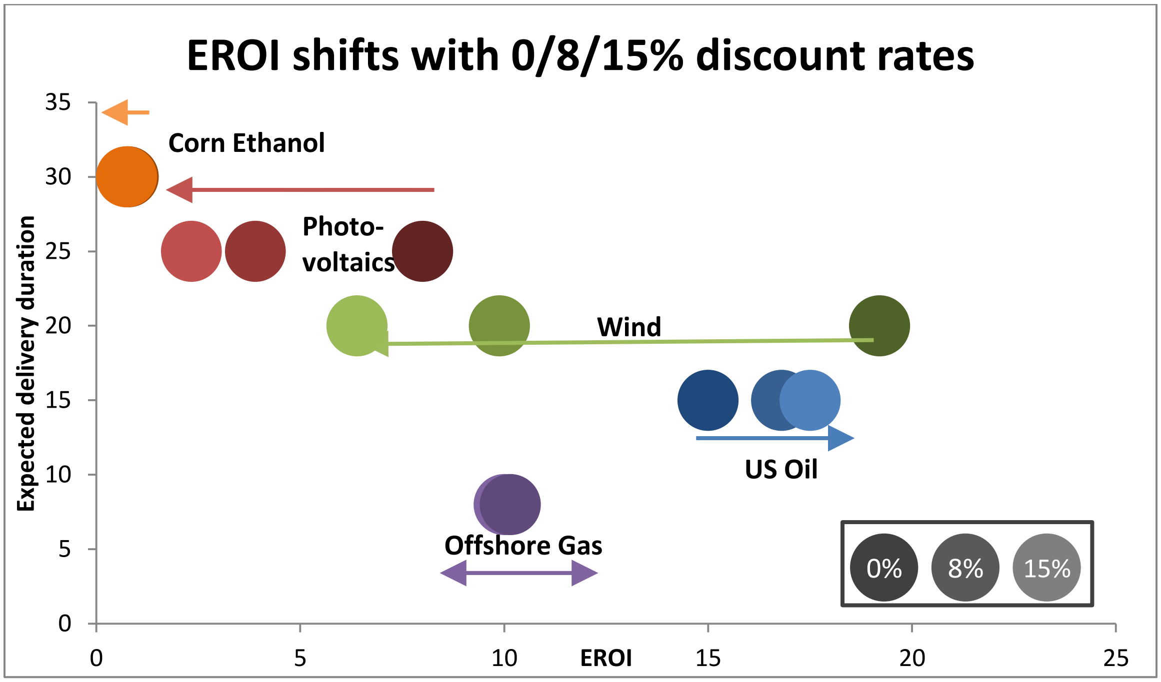

Figure 26 EROI Shifts for Various Energy Technologies at 0%, 8%, and 15% Discounting

5.6 Conclusion

This analysis has shown that irrespective of financial incentives, humans discount the future to varying degrees. When applied to net energy analysis the implications of discounting are non-trivial. Using a static discount rate, those technologies that require the majority of energy investment upfront provide less 'time-handicapped' net energy to society than do technologies with ongoing energy and material inputs during their life cycles. With the typical production profile for oil and gas, one can, find discount rate levels that will actually cause a preference for those fuels. In social circumstances where lower discount rates prevail, such as under government mandates and/or in generally more stable societies, longer term energy output becomes more valuable. Less stable societies that exhibit higher discount rates will likely handicap longer energy duration investments, as the cost of time will outweigh the value of delayed energy gains. Also in the context of general limits to growth, it is worth noting the evidence suggesting that stressed individuals also exhibit higher discount rates.

Thus, the discount rate may be viewed as the rate at which societies implicitly signal their desire to turn a present energy surplus into an energy transformation process so that greater energy services can be consumed in the future, in lieu of the immediate consumption. There exists a tradeoff between energy costs and time costs that depending on the context will meaningfully alter energy investments. Decisions made by energy modelers and policymakers are quite sensitive to the discount rate used. A big question is whether the social discount rate should be the same as the market return required by private investors. Given energy's primary role in the production (and survival) function, one can infer that energy producing projects may use lower discount rates than other competing projects. In our paper, we do not answer the longstanding debate on what discount rate is appropriate for energy projects and comparisons, but rather show that *some* positive discount rate is inherently present in biological species, and therefore the net energy from human plans and projects will be impacted, for better or worse, by the timing of the inputs and outputs. Ultimately, it is a decision either of individuals or entire societies, as to which discount rates they apply to energy related investments, but it seems important that energy technologies get reviewed with this concept in mind.

References

Denbury Resources, personal data communication (G.Roberts), April, 2010).

Energy Information Agency. (2008). *Analysis of crude oil production for arctic national wildlife refuge.* (Report #: SR-OIAF/2008-03). Retrieved from http://www.eia.doe.gov/oiaf/servicerpt/anwr/methodology.html.

National Energy Board. (2010, march). Short term Canadian natural gas deliverability 2010-2012 – an energy market assessment. Retrieved August 10, 2010 from http://www.neb.gc.ca/clf-ns/rnrgynfmtn/nrgyrprt/ntrlgs/ntrlgsdlvrvlty20102012/trlgsdlvrblty20102012-eng.pdf.

Office of Management and Budget. (1992). Circular No.A-94. Retrieved from http://www.whitehouse.gov/omb/circulars_ao94/ Retrieved on July 27, 2010

Social Security Administration. (2006). *Period life table* http://www.ssa.gov/OACT/STATS/table4c6.html retrieved Apr 4, 2010

Ardente, F., Beccali, M., Cellura, M., & Lo Brano, V. (2008). Energy performances and life cycle assessment of an Italian wind farm. *Renewable and Sustainable Energy*, *12*, 200-217.

Arrow, K.J., et al. (1995). "Intertemporal Equity, Discounting, and Economic Efficiency. In: Climate Change 1995: Economic and Social Dimensions of Climate Change". Cambridge University Press.

Bateson, M. (2002). Recent advances in our understanding of risk sensitive foraging [references, *Proceedings of the Nutrition Society*, *61*, 1–8.

Berns, G., Laibson, D., & Loewenstein, G. (2010). Intertemporal choice – toward an integrative framework. *TRENDS in Cognitive Sciences* *11*(11) 482-488.

Chabris C., Laibson, D., Morris, C., Schuldt, J.,& Taubinsky, D. (2009).The allocation of time on decisionmaking, J *Eur Econ Assoc.*, 7(2), 628–637.

Cleveland, C. J. , (1992). Energy surplus and energy quality in the extraction of fossil fuels in the U.S. *Ecological Economics, 6* , 139-162.

Cleveland, C.J., Costanza, R., Hall, C.A.S., & Kaufmann, R. (1983). Energy and the United States economy: a biophysical perspective. *Science*, *225*, 890-897.

Costanza, R. (1987). Social traps and environmental policy. *Bioscience*, *37*(6), 407-412.

Cottrell, F. (1955). *Energy and society - the relation between energy, social change, and economic development*. Greenwood Press.

Frederick, S., Loewenstein, G., & O'Donahue, T. (2009). Time discounting and time preferences: a critical review. *J Eur Econ Assoc*, *7*(2), 628-637.

Hall, C.A. (2004). The continuing importance of maximum power. *Ecological modelling, 178*(1-2, 15), 107-113.

Hannon, B. (1982). Energy discounting. *Technological forecasting and social change*, *21*, 281-300.

Hausman, J. (1979). Individual discount rates and the purchase of energy-using durables. *Bell Journal of Economics*, *10*(1), 33-54.

Howarth, R.B., & Norgaard, R. (1993). Intergenerational transfers and the social discount rate. *Environmental and Resource Economics*, *3*(4), 337-358.

Howarth, R.B. (2009). Policy brief no. 3: discounting, uncertainty, and climate change. *Economics for Equity and the Environment*, Retrieved 4/15/2010 from http://realclimateeconomics.org/briefs/Howarth_Discounting.pdf.

Hubbert, . (1931). Hours - a declining quantity in *Technocracy*, Series A, No.8

Kirby, K.N., Petry, N.M., & Bickel, W.K,. (1999). Heroin addicts have higher discount rates for delayed rewards than non-drug-using controls. *Journal of Experimental Psychology: General*, *128*, 78-87.

Kubiszewski, I., Cleveland, C.J., & Endres, P.K. (2010). Meta-analysis of net energy return for wind power systems. *Renewable energy*, *35*(1), 218-225.

Lind, R., Ruskin, F. (1982). Discounting for time and risk in energy policy. *Resources for the Future, Inc.*, Washington D.C.

Lotka, A.J. (1922). Contribution to the energetics of evolution. *Proc Natl Acad Sci*, *8*, 147-151.

Mazur, J. (2005). Effects of reinforcer probability, delay, and response requirements on the choice of rats and pigeons: possible species differences. *J Exp Anal Behav*, *83*(3), 263-279.

McClure, S., Laibson, D., Loewenstein, G., Cohen, J., (2004). Separate neural systems value immediate and delayed monetary rewards. *Science*, *306/*5695 503-507

Millar, J., & Zammuto, R. (1983). Life histories of mammals: an analysis of life tables. *Ecology*, *64*(4), 631-635.

Nordhaus, W.D. (2007). A review of the Stern review on the economics of climate. *Journal of Economic Literature*, *45*(3), 686-702.

Odum, H.T. (1963). Limits of remote ecosystems containing man. *The American Biology Teacher*, *25*(6), 429-443.

Pearce, D., Markandia, A., & Barbier, E. (1989). *Blueprint for a new economy.* London, UK: Earthscan Publications.

Robson, A. (2002). Evolution and human nature, *The journal of economic perspectives, 16*(2), 89-106.

Ruderman, H., Levine, M.D., & McMahon, J.E. (1987). The behavior of the market for energy efficiency in residential appliances including heating and cooling equipment. *Energy Journal*, *8*(1), 101-124.

Schneider, E.D., & Kay, J.J. (1985). Order from disorder: the thermodynamics of complexity in biology. In Michael P. Murphy, Luke A.J. O'Neill (editors) *What is Life: The next fifty years. Reflections on the future of biology*. Cambridge University Press, 161-172.

Sozou, P. (2009) Individual and social discounting in a viscous population, Proc. R. Soc. B 22 ***276*** **(1669)** 2955-2962.

Stern, N. (2007). The economics of climate change – the Stern review. Cambridge, England: Cambridge University Press.

Takahashi, T., (2004). Cortisol levels and time discounting of monetary gains in humans. *Neuroreport*, *15*(13), 2145-2147.

Takahashi, T., Ikeda, K., Hasegawa, T., (2007). A hyperbolic decay of subjective probability of obtaining delayed rewards. *Behavior and Brain Function*, *3*, 52.

Van Gool, W. (1985). *Energy and time in the economic and physical sciences*. Elsevier.

Wilson, M., & Daly, M. (2004). Do pretty women inspire men to devalue the future? *Proc Biol Sci.* 2004 May 7; 271(Suppl 4): S177–S179.

Zhuang, J., Liang, Z., Lin, T., & de Guzman, F. (2007). *Theory and practice in the choice of social discount rate for cost-benefit analysis: a survey*. Asian Development Bank, Manila, Phillipines.

CHAPTER 6: NET ENERGY AND VARIABILITY

6.1 Introduction

One key approach to analyzing the feasibility of energy extraction and generation technologies is to understand the net energy they contribute to society. These analyses most commonly focus on a simple comparison of a sources expected energy outputs to the required energy inputs, measured in the form of net energy, energy payback time, or energy return on investment (EROI).

What is not typically factored into net energy analysis is the influence of output variability. This omission ignores a key attribute of biological organisms and societies alike: the preference for stable returns with low dispersion versus equivalent returns that are intermittent or variable. This biologic predilection for stability, observed and refined in academic financial literature, has a direct relationship to many new energy technologies whose outputs are much more variable than traditional energy sources. Additionally, many of these flow based energy outputs are often uncontrollable or only partially controllable.

This paper will investigate the impact of variability on net energy metrics and develop a theoretical framework that applies financial and biological risk models to energy systems. We then illustrate the impact of variability on energy return using a number of representative technologies in electricity generation, with a more detailed analysis on wind power, where intermittence and stochastic availability of hard-to-store electricity will be factored into theoretical returns. Ultimately, this paper is aimed at developing a broader conceptual framework that assesses energy technologies against their specific variability risks in generation and application. Finally, the research here will be integrated with the results with the findings from Chapter 5 on timing of energy flows.

6.1 Background

In traditional net energy analysis, an energy input or output is treated the same irrespective of the volatility stream of the underlying energy technology. However, the operational requirements for electrical grids have considerable influence on our energy preferences and planning decisions. Even though 100 continuous kilowatt hours of electricity has the same BTU content as 100 sporadically generated kilowatt hours, their usefulness and value is proportionate to their fit with human demand systems. As such, volatility[5] and intermittency[6] become important variables.

The comparison of two hypothetical graphs for energy retrieval in Figure 27 shows the relevance of variability. Both of the above technologies offer the same EROI but the first one returns the energy steadily over 20 periods while the second returns double the energy and zero energy in random periods. The energy costs are identical at the start and during the life of the asset. Provided the quality of the energy retrieved is comparable, societies would prefer the technology that delivers the more stable returns (the graph on the left). However, nominal EROI analyses treat these two sources as equal.

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[5] *Variability* will refer to a measure of statistical dispersion, either referring to the variance (describing how far measured values lie from the mean) or standard deviation (the square root of the variance). . In finance, variability is usually termed volatility'

[6] . *Intermittency* refers to the non-continuous, stochastic nature of electricity generation by some sources. A *stochastic* process is one that is random, or non-deterministic

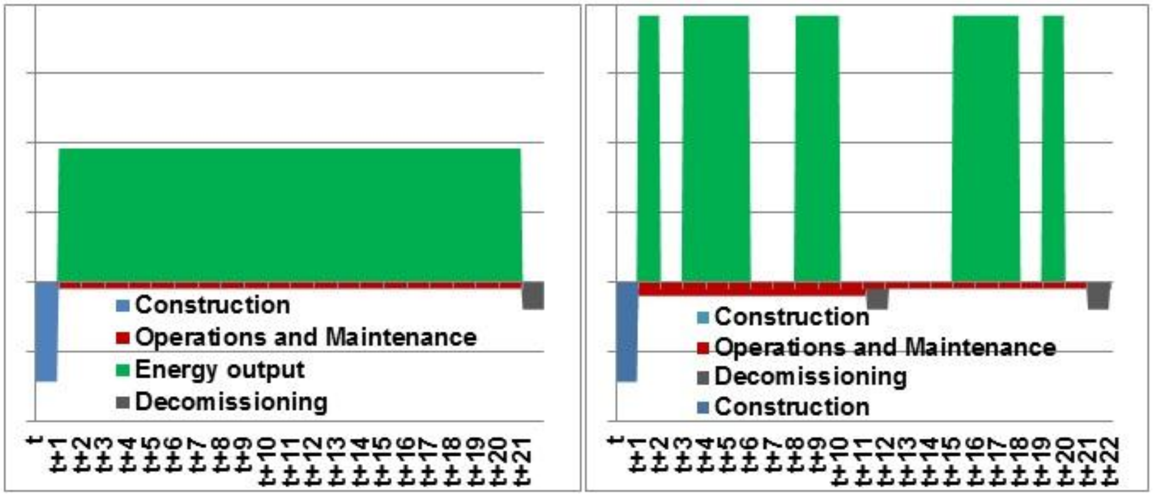

Figure 27 Sample Input/Output Timeline for a) an energy technology with steady states of return and b) variable rates of return

Risk, a fundamental feature of our natural environment, is typically defined as variance around a mean, although other definitions include the coefficient of variation, and unanticipated volatility. (Kahneman & Tversky, 1979; Weber, Shafir, & Blais, 2004). Risk is generally considered as different from uncertainty, as variability in risk is quantifiable while with uncertainty the variability is unknown (Knight 1921). Variability risk is a significant aspect of decision-making in both the animal and human world. (Caraco 1980, Bateson 2002). Using a simple example may illustrate the problem with variability from a biological perspective. A pride of lions travels a large distance to a water hole where they for years have found gazelles to feed on. At one point, however, they find the water hole dried up, with no prey (and no water) available. Despite the fact that this location has supported the growth of the pride for years, this single event might decimate the group. In contrast, another pride that regularly travels a smaller distance to a place offering less abundant but steadier hunting opportunities, though averaging a smaller return on its efforts, does not experience a similar setback. The genes would survive in the offspring of this second pride, who behaviorally were disposed towards the lower output, lower variability option. This phenomenon is formalized in the ecology literature as ‘risk sensitive foraging theory’ –a body of empirical research observing risk preferences in a variety of situations in the animal world. Whether animals behave as if they were risk-averse or risk-prone depends on the energetic status of the forager (e.g. whether they are starving or sated), the type of variance associated with the feeding options and the number of feeding options among which the animal has to choose (Bateson 2002). As a general rule, when variability is in the amount of reward animals almost always exhibit risk-averse behavior. When variability is in delay to reward, animals behave risk-prone universally. (Kacelnik 1996). In effect, animals “prefer” stable rewards and immediate results.

Similar preferences exist for human efforts. A farming approach that secures constant average annual returns of 80% to 90% of a possible maximum will be preferred over one averaging 100% but having widely varying returns between 0% and 250%. This is because any shortfalls are a significant threat to food security and survival. In the below example (Figure 28), people requiring food to survive would prefer the food producing output Method 1 over the higher yielding but more volatile output Method 2 due to the possibility of shortfall (i.e. periods 2,4 and 5 fall below the minimum survival requirements, assuming no storage).

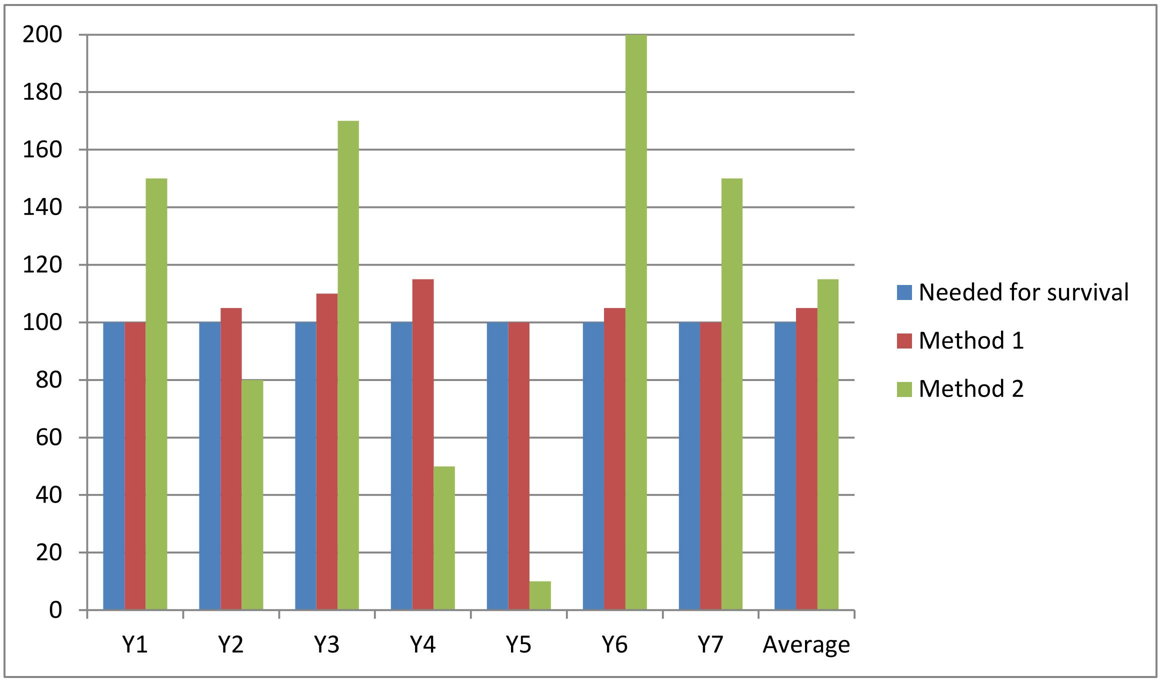

Figure 28 Hypothetical Comparison of Annual Returns from Farms that Exhibit Low Variability (Method 1) and High Variability (Method 2)

6.2 Variability Risk in Finance

Over time, risk and its measurement have become core parts of both economic and financial theory. The behavioral or physical aspect that is optimized for risk varies widely by species (and among academic disciplines) and includes territory, time, caloric value, energy, mating opportunities, reputation effects, fairness, certainty, emotion and mood effects, and property. In economics, the optimized currency is typically described as 'utility'. (e.g., MacArthur & Pianka, 1966; Nowak & Sigmund 2005). Bernoulli (1738) noted that "expected utility" (expected return modified by risk preferences) differed from "expected value" (the strict payout multiplied by its probability). Von-Neuman and Morgenstern further advanced the concept that rational individuals are risk averse and act as though they are "maximizing expected utility. More recently, Prospect

Theory advanced economists understanding of how people make choices involving risk by making the theory more psychologically realistic (Kahneman 1979). In essence, they posit that agents facing gains become more risk averse and those facing losses become more risk prone, consistent with the risk-sensitive foraging literature (Kacelnik 2003).

Finance has developed practical applications of these economic theories. In our financial system, investors can be thought of as optimal foragers; those with consistently high returns have more 'energy' with which to buy goods and services as well as confer this advantage to their offspring. Interestingly, functional magnetic resonance scans of stock traders brains show the activation of the same prefrontal regions after successful trades as when primates find food likes nuts and berries (Wise, 2006, Lehrer 2009). Like any ecosystem, finance is about achieving high rewards with as little risk (and variability) as possible, and has developed multiple methods of risk assessment. Over the past several decades, researchers in academia and private industry tested and refined measurements of how investors respond to various financial problems and scenarios (see, for example, Lo 2001).

In financial markets, risk is commonly measured by volatility, a statistical measure of the dispersion of returns for a given security or market index. Volatility is either measured by using the standard deviation or variance between returns from that same security or a market index. Essentially, the higher the volatility, relative to itself or to a benchmark, the riskier an investment becomes. (Sharpe 1966, Biglova 2004). Modern portfolio theory has formalized investor's preferences for lower volatility (given returns of equal expected value) with a measure termed "risk adjusted return", or the return per unit of standard deviation. In evaluating investment alternatives risk aversion lies at the core of risk-return models, such as mean-variance portfolio theory. Markowitz (1959) formalized the observation that investors are risk averse, and given two assets offering the same expected return, investors will prefer the less risky one. Thus, an investor will take on increased risk only if compensated by higher expected returns. Though there are many ways to measure risk adjusted performance, one popular portfolio metric called "Sharpe Ratio", takes this concept one step further and measures the amount of outsized return relative to a "risk free rate" for each unit of risk (Sharpe 1994). The Sharpe Ratio (real or ex ante) is thus the return of a given strategy minus the risk free rate of return (usually U.S. treasury bills) divided by the standard deviation of the return. Specifically,

$$S = \frac{\bar{r}_p - r_f}{\sigma_p}$$

Where:

S = Sharpe Ratio

$\bar{r}_p$ = Expected portfolio return

r_f = Risk free rate

σ_p = Portfolio Standard Deviation

Let's consider an example with four potential investments (A, B, C and, D). The assumed risk free rate is 3% (Table 8). The portfolio objective is an annual return of 5% reflected by the many pensions and endowments that have minimum return thresholds to pay out to their beneficiaries. As can be seen in Table 9, two dimensional (mean and volatility) return measures give a much more complete picture of investment success, though other nuances, such as maximum drawdown and relationship to a minimum accepted return are also important.

Table 8 Hypothetical Assets and Accompanying Annual Returns over 10 Years

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Mean
Minimum	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5.0%
Risk Free rate	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3.0%
Investment A	8%	10%	8%	10%	8%	10%	8%	10%	8%	10%	9.0%
Investment B	15%	5%	15%	5%	15%	5%	15%	5%	15%	5%	9.9%
Investment C	-9%	15%	39%	20%	-4%	-14%	28%	-12%	26%	15%	8.9%
Investment D	3%	2%	8%	-4%	10%	8%	-6%	4%	-8%	14%	3.1%

Table 9 Sample of Returns Metrics for Risk vs. Return

Asset	Geometric Mean Return	Standard Deviation	Risk Adj. Return	Sharpe Ratio
Risk Free	3.0%	0%	n/a	n/a
A	9.0%	1%	9.0	6.0
B	9.9%	5%	2.0	1.4
C	8.9%	17.9%	.50	0.3
D	3.0%	6.9%	.43	0.0

The advantage of risk metrics like the Sharpe Ratio is that one statistic generated from return histories (or expectations) gives the investor a meaningful way to compare very different investments.. Given the above options an investor would likely choose option A as its risk adjusted expected return as far superior to the other 3 assets. Asset B, while having an overall higher return, has much more volatility, especially when compared to the minimum portfolio return of 5%. This higher volatility suggests a greater chance that future returns could fall short of the minimum required return. The return streams from assets C and D are considerably more volatile, including periods of losses. Their low risk adjusted returns drawdowns suggest they do not provide much return adjusted for risk. When an investor has a number of low risk investments that meet his minimum return target, those metrics identified above drive the decisions, e.g. he will select the investments with the highest Sharpe Ratio or similar statistic. Only in situations where the investor, in order to meet a minimum return target, has no choice but to accept investments with high risk (and thus relatively low Sharpe ratio), will he employ additional selection criteria. For example, he will try to create a portfolio mix of those lower quality investments that are least correlated in their fluctuations to eliminate part of the risk in the portfolio.

6.3 Applying Financial Risk Concepts to Net Energy Analysis

In energy systems, for example in electricity production, similar needs to reflect risk adjusted returns are apparent. For example, to develop an index of electricity availability take the percent of a country's population with access to electricity and multiply it by the percentage of hours in a year that there is uninterrupted electrical service. Figure 29 plots such an "availability index" compared against GDP/capita (purchasing power parity adjusted) for 99 countries. It shows that stable electricity is key to producing economic activity significantly above 10’000 US$/capita. The fact that no country with electricity availability below 98% exceeds a per capita GDP of US$ 20’000 suggests that electricity seems to be the prerequisite for high output, and not the inverse. The value of steadily available electricity at all times far exceeds the value of situations that experience regular blackouts, irrespective of the total amount of energy available. As we will show later, the electricity grid is a particularly fragile system, which is susceptible to deviations as small as 0.5% between demand and supply at any given point in time.

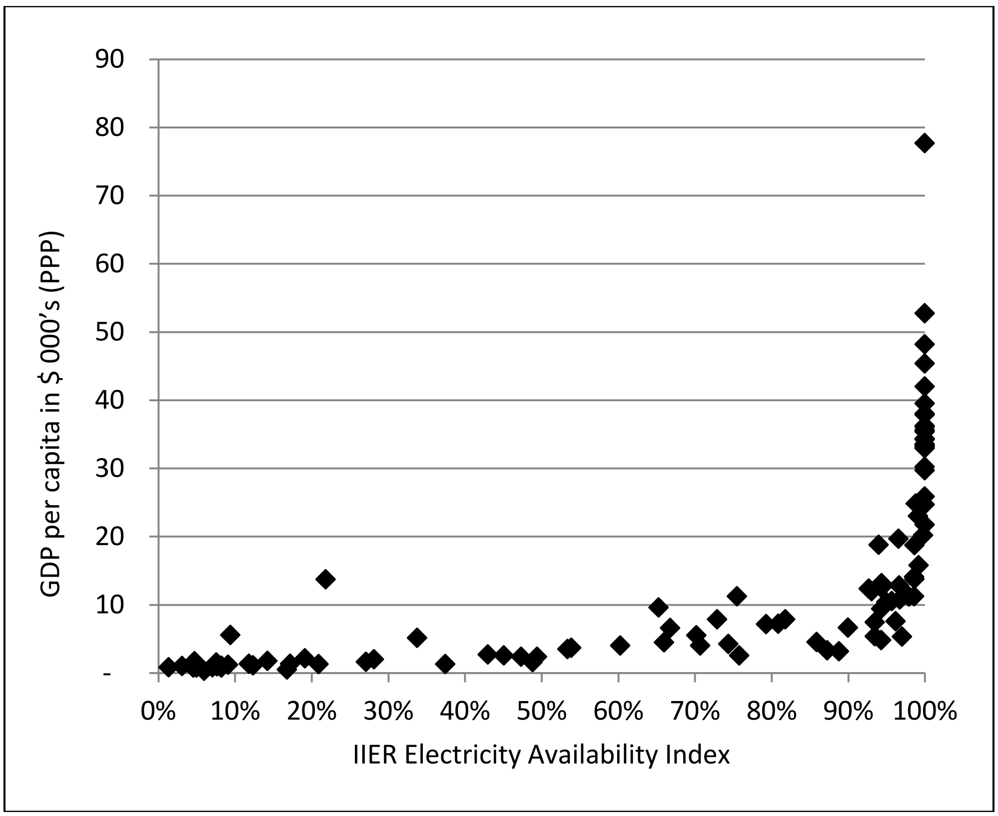

Figure 29 IIER Electricity Availability Index vs GDP/Capita (PPP) for 99 Countries

(Source: World Bank, WRI, EBRD 2010)

In general, energy supply technologies offer very different value to societies depending on how controllable they are. However, the importance of variability depends on the type of energy demand system. Storage-based energy sources such as oil, natural gas, or coal, (and to some extent hydropower), which are not subject to meaningful degradation, allow suppliers to maintain flows according to demand. They thus provide greater value and lower risk on the supply side. For example, oil exporting countries, in theory, can reduce oil production during periods of low demand and low prices (e.g. the British flooded the market with oil from the North Sea when the prices were depressed). This approach maximizes the value extraction on the supply side, as the stores can be accessed primarily in a discretionary way.

Flow based energy sources, such as run-of-river hydropower, solar power and wind energy, don’t allow for supply-side control without additional investments and storage losses. To a certain extent, the same is true for energy conversion technologies that produce flows from stocks, but require long lead times to switch on or off once they are operational. For example, nuclear power plants and some coal based power plants incur significant efficiency reductions when changing their load . Flows occur mostly independent of demand or prices. Deferral of supply of flow based energy is possible only with storage technologies, which typically involve a significant conversion or entropy loss, and additional upfront investment.

On the other hand, in electricity production systems, most stock-based conversion technologies (e.g. nuclear, coal, oil and gas generators) produce steady flows. In these situations, inflexibility of supply can be managed. Flow-based inputs with low (and mostly only short-time horizon) predictability like solar and wind power deliver output stochastically as a function of weather conditions. Once the infrastructure for these technologies has been installed (e.g. a photovoltaic panel, a wind turbine or a solar thermal concentrator) it can produce anything from 0% to 100% of nameplate capacity, completely independent of demand. This does not necessarily translate to complete (short term) unpredictability, as weather forecasts are able to provide some limited planning input, however, the overall delivery pattern is fully stochastic.

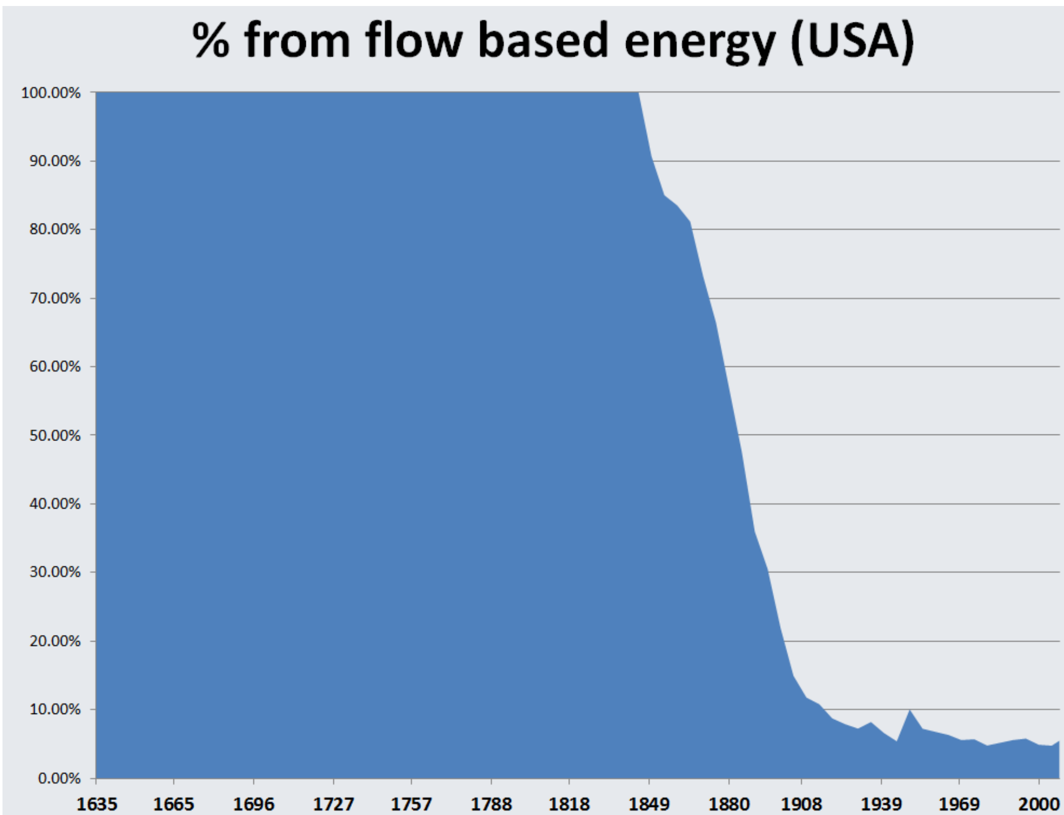

Figure 30 - Percent of Flow Based Energy 1635-2007 USA (Source IEA 2008)

Similar patterns exist when energy is used. Gas, coal or oil based fuels can be stored at a high energy density for significant periods of non-use with only limited (for natural gas) or no losses (for oil and coal), and then used as needed. Electricity however, once produced, does not have that feature – it is expensive to store, at a lower energy density, and always incurs losses. Electric power not used or stored at the time of its production is no longer usable even a few seconds later. In electricity systems, both over- and undersupply are equally detrimental, and if not managed, will lead to grid failures and blackouts. Figure 30 illustrates that the proportion of US energy derived from flow based sources has declined from 100% in the 1600s to around 7% currently (this assumes 50% of hydro-electric is storable and 50% run of river) (IEA 2008).

The largest human-made system that is fully based on short-term flows is our electrical grid, infrastructure delivering electricity on demand using complex and intensively managed combinations of inputs. For these reasons we have chosen to analyze electricity supplying technologies for this paper. In electricity delivery systems, demand varies significantly throughout the hours of the day, days of the week and seasons of the year. Different generation technologies (driven by different energy sources), meet this intermittent demand in different ways. Below, electricity generation technologies are categorized according to their flow risks.

6.3.1 Stable Output Technologies

Run-of-river hydropower delivers steady outputs that are not typically easy to alter. This is largely also the case for nuclear and most coal power plants that convert stocks into flows and cannot be modulated easily. Their outputs vary little and are predictable for extended periods of time when considered in aggregate (i.e. while one power plant might fail, the aggregate supply of multiple plants using one technology typically delivers stable returns to a grid system). However, these technologies cannot transition their output either up or down in a timeframe short enough to meet typical demand fluctuations. These output changes are typically associated with energetic (and thus financial) losses. In situations where they supply electricity grids (as opposed to individual industrial facilities), these technologies are not flexible enough to follow all the peaks and lows demanded by society and therefore are of lower overall value. If they are only used against the portion of demand that is stable, their contribution becomes 100% valuable and highly predictable in aggregate.

We begin with a hypothetical example in Figure 31, consistent with most demand curves for electricity for advanced economies of a day of operations of steady output sources in a network with a large proportion of stable outputs, for example – a country like France with a high share of nuclear power:

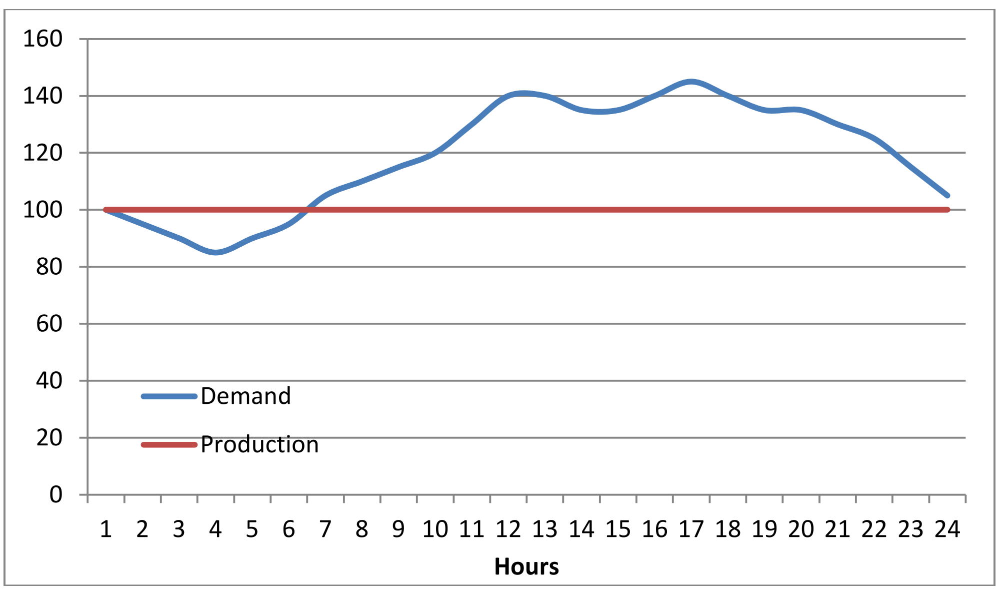

Figure 31 Hypothetical Electricity Demand Cure Plotted Against a Steady Source of Electricity

6.3.2 Flexible Technologies

Most stock-based technologies, like gas- or oil-fired power plants, or stored hydropower, can be modulated in a way that can directly follow demand patterns as they emerge. As such, they bear no demand shortfall risk in their application. However, in some cases, as these fuel types are the most valuable, they produce at relatively high costs (particularly true for oil-based generation, but similarly for natural gas).

The example in Figure 32 illustrates an electricity grid composed of a stable base of steady output technologies (such as nuclear, coal or any combination thereof), supplemented with flexible generation capacity (such as stored hydropower or natural gas). Together, these technologies are able to perfectly match human demand.

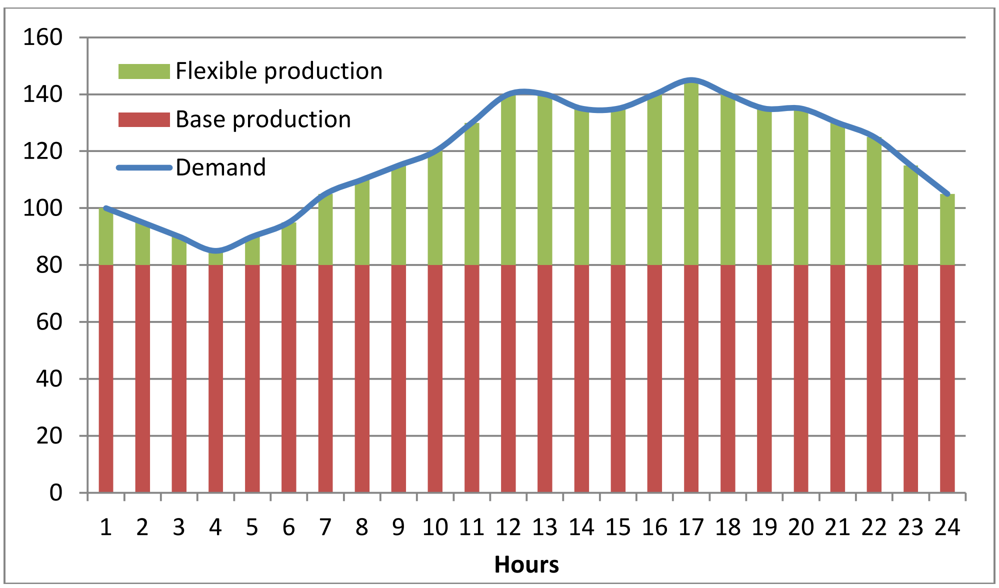

Figure 32 Hypothetical Electricity Demand Curve Plotted Against Base Load Power Generation Coupled with Flexible Generation Capacity

6.3.3 Stochastic Technologies

Stochastic flow-based power generation techniques often show no or very limited correlation with demand, and deliver their energy outputs based on mostly independent variables like sunshine or wind. These may partly coincide with demand, as with solar power, which is produced during day-time high demand phases, however users have no control over this phenomenon and (depending on weather) output may appear or disappear almost completely across large areas within short periods of time. Furthermore, solar panels also produce when daytime demand is already met by other sources, for example during weekends and holidays.

The example highlighted in Figure 33, shows a week of average wind power production and aggregate demand for Denmark from the summer of 2009. In this region, one of the best environments globally for wind power generation, wind supplies approximately 25% of total annual electricity demand. On an hourly basis, however, this coverage varies from 0% to 120% of total demand, across all hours of a typical year (Energinet 2010)

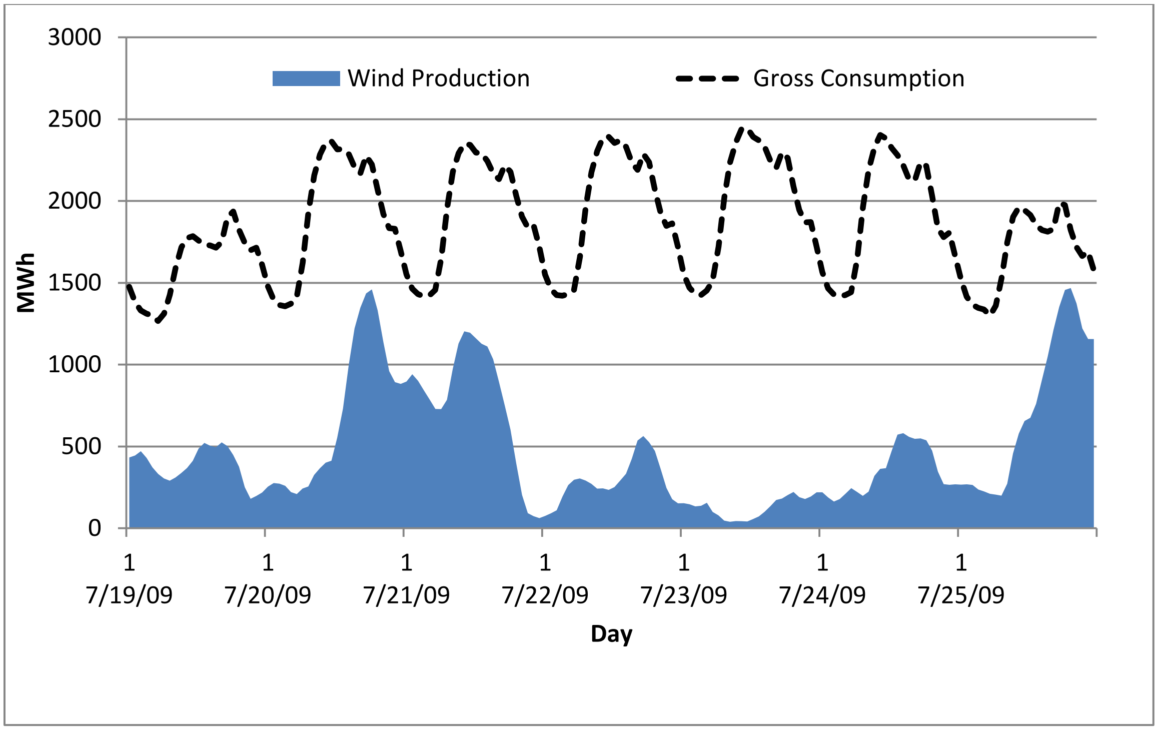

Figure 33 Aggregate Electricity Demand in Denmark (west) vs Total Hourly Wind Production

It's apparent from the above examples that two energy sources that have the exact same net energy output provide different values to society, once their different delivery patterns are considered. Sources that are fully manageable or contribute steadily to ongoing demand are definitely preferable to sources supplying their outputs mostly uncorrelated to demand, when all other parameters are equal. Though this is relatively well understood among energy analysts, it has heretofore not been incorporated into energy quality calculations in biophysical economics.

6.4 Applications of a Risk Adjusted Energy Analysis

As shown above, volatility in energy production causes problems, especially if the excess energy is not storable or requires costly investments to capture. To allow for a proper comparison of electricity generating technologies, negative influences to the overall energy system (e.g. the electricity grid) need to be factored into the net energy calculations.

For inputs derived from stocks, the aggregate delivery risk of multiple plants is very low, as long as no major supply chain disruptions affect fuel availability. This paper explicitly does not deal with these large supply-side risks, although they can be considerable, such as dependence on foreign oil from volatile regions of the world. Instead we focus on a framework for measuring the short-term risks that result from mismatches between supply and demand.

Stable flows, as long as they cannot easily be adjusted to demand, will provide less value to societies relative to sources with the ability to follow demand patterns. The relevant volatility risk for all sources is thus not the physical variability of the supply itself, but the standard deviation of supply relative to consumption. This applies only to flow-based supply systems. Stock-based supply systems, where the final energy carrier is stored without conversion or loss, are much more tolerant to supply fluctuations (i.e. supply deviation relative to demand), as long as no system-wide undersupply threatens overall stability.

In order to simplify the analysis we assume a closed system not factoring in transfers to and from other geographical areas. The relevant time interval for an analysis of risk adjusted net energy also largely depends on whether the final energy demand system is based on flows or stocks If the energy is used to feed a flow (such as an electricity grid), the variability at the shortest possible time interval should be measured. On resources that are able to be stored (e.g. biofuels produced from various crops) the interval of production (annually) is more appropriate. Said differently, if energy quality decays almost immediately after its production, a proper analysis would have to use the smallest possible time interval to assess its utility to its flow based human use.

In order to arrive at a meaningful valuation of energy input risk, we test several methodologies in order to estimate the impact on variability on EROI. Given limited data availability, we focus on three energy inputs into electricity grids: nuclear power, wind power, and natural gas (which is fully flexible, assuming sufficient generation capacity is available). This paper is not aimed at delivering new EROI numbers, but instead at introducing and conceptualizing the approach of risk adjustment in the review of energy in general. For this, we use both electricity demand and wind power data from West Denmark, because a solid data set is available, and Denmark is considered a very favorable location for large scale wind electricity production. For wind, we also combine the two independent regions of the Danish system (West and East), , as each integrates with different grid systems. We further analyze real production data from Spain (RED 2010), which operates with lower average wind outputs (e.g. a lower capacity factor) when compared to Denmark, but better temporal output distribution due to Spain's exposure to multiple, relatively independent weather systems.

In an attempt to quantify energy variability, we now introduce and compare three methodologies that can be applied to most available energy gathering or conversion technologies. The first method compares supply and demand, and penalizes an energy supply technology in proportion to the gaps between the two. The second and third methodologies quantify the energy cost of mitigation, e.g. the additional energy required either by adding flexible generation capacity (method 2) or storage (method 3) to handle the supply/demand mismatches.

6.4.1 Method 1: Supply-Demand Comparison

In the first methodology, we introduce a handicap for each unit of energy that deviates from total demand, based on a long enough time period (a year) where energy supply is scaled to meet energy demand. In this approach an energy system is modeled as if one technology alone would supply a fixed demand system. Here we assume that all deviations from demand incur a cost to the overall system to compensate for variability. This cost determines the handicap for a particular technology.

We compare three production scenarios, an inflexible system producing all power from nuclear power plants, a fully flexible grid only using gas powered turbines, and wind electricity production for West Denmark, combined Denmark (East and West), and Spain all scaled up to cover 100% of electricity demand over a year. These hypothetical supply patterns are compared with electricity consumption. All calculations are on an hourly basis. Over one year, the gaps between supply and demand for each technology are cumulated, and this sum relative to the total is considered a "handicap" to the nominal energy gain of a particular technology.

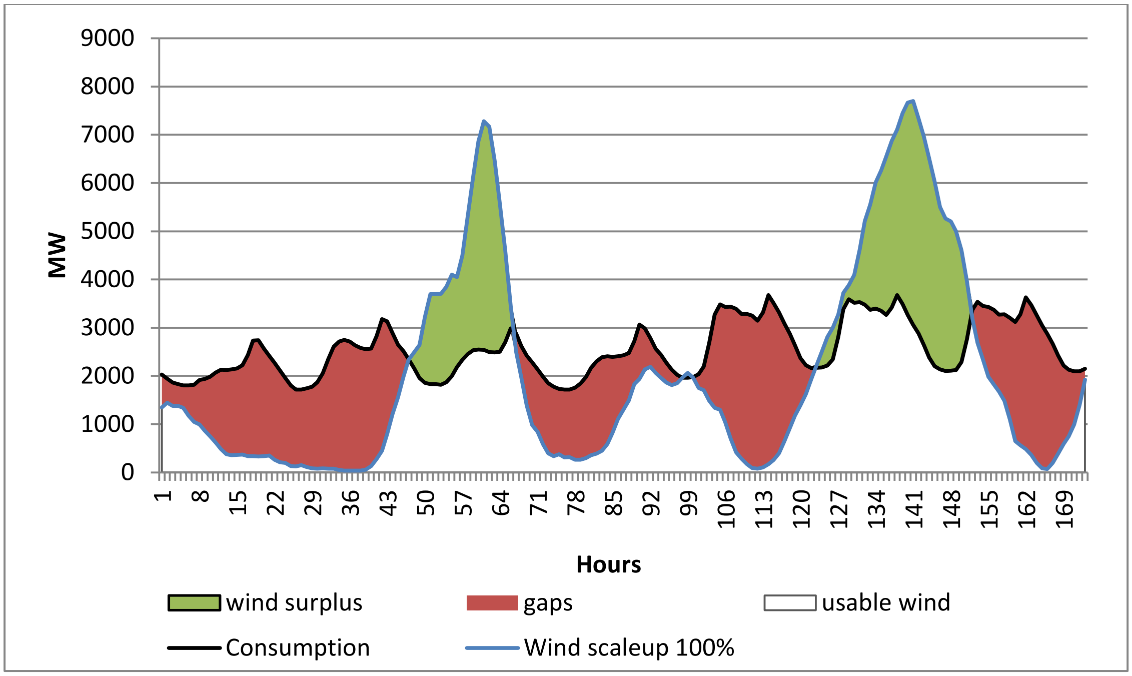

Figure 34 Wind Power Production (scaled to 100% annual electricity consumption) Plotted Against Actual Gross Consumption for Electricity in Denmark West for the week of July 25, 2009

Figure 34 illustrates this approach for wind power generation. The black line represents electricity demand, in hourly intervals, throughout a period of approximately one week. A flow-based source (in this case wind) produces energy in a pattern represented by the blue line, which on average produces energy matching demand for the entire year. However, this energy harvesting technology shows significant deviation from what is a regular demand pattern. Relative to the demand line, there are periods where it significantly over- (the green) and under-produces (the red). The risk-adjusted EROI thus has to account for lost energy due to waste (the green areas) and periods of shortfall requiring an energy subsidy from another source (the red areas). To obtain an accurate net energy statistic, the sum of all green areas during the technology's life cycle need to be subtracted from nominal EROI. Similarly, the sum of all the red areas, if another energy source was required to come online to meet human demand, would also be subtracted. All these periods of variability relative to demand are then cumulated to obtain a handicap to the nominal EROI metric.

Figure 35 depicts Denmark West electricity consumption during the first 14 days (336 hours) in January 2009. Overlaid are hypothetical supply curves for 100% coverage with nuclear power, and 100% coverage with scaled up wind power. Both the negative and positive supply gaps (indicated by the arrows) create problems for the grid system and thus need to be accounted for, which is quantified in the table below using data for the entire year 2009. For comparison, we also include 2007 and 2008 data for Denmark West, which shows only small deviations from 2009.

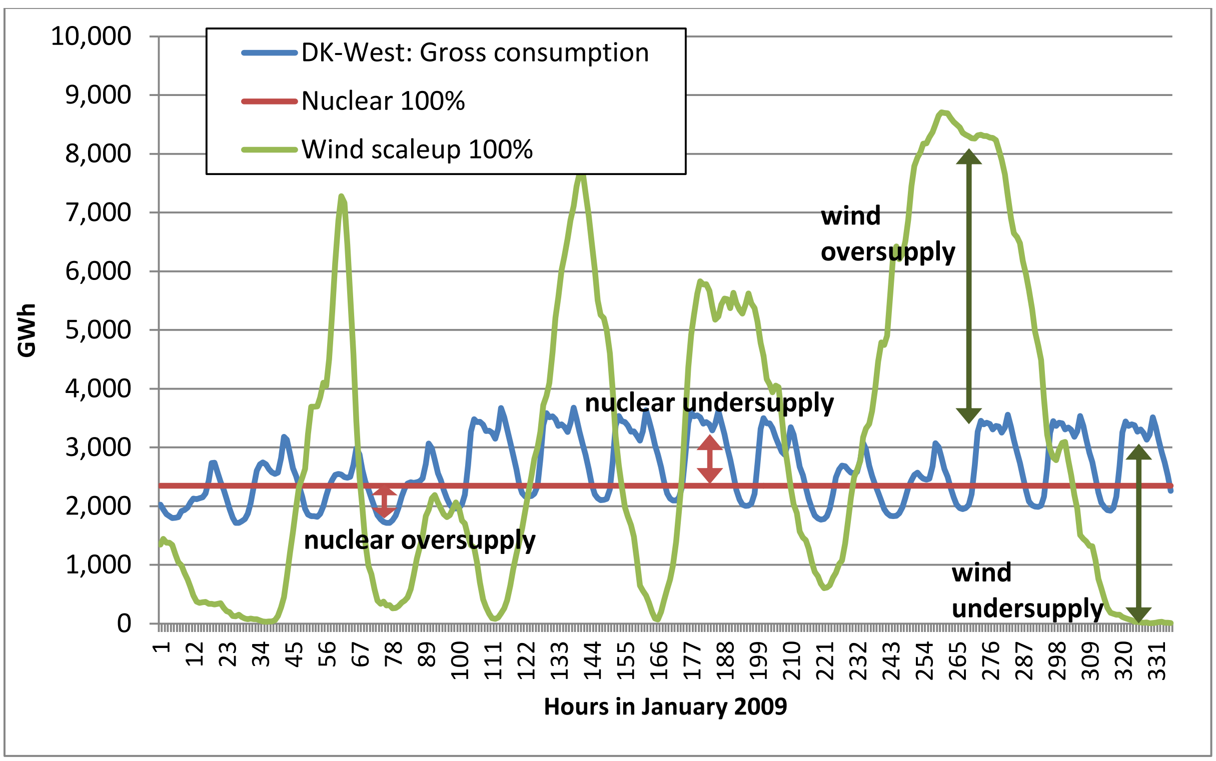

Figure 35 Gross Consumption for Denmark West Plotted against Wind and Nuclear Power (scaled to meet 100% of annual demand)

Table 10 Comparative Supply Gaps for Various Locations

	Total consumption GWh	Undersupply GWh	Oversupply GWh	Total Gap GWh	Handicap to EROI
Gas power DK West (2009)	20,550	0	0	0	0%
Hypothetical linear output source (Nuclear) in DK West (2009)	20,550	2,038	2,038	4,077	19.8%
Wind DK West (2009)	20,550	7,243	7,243	14,486	70.5%
Wind DK West (2008)	21,622	7,942	7,942	15,884	73.5%
Wind DK West (2007)	21,596	7,946	7,946	15,892	73.6%
Wind DK combined (2009)	34,591	11,875	11,875	23,749	68.7%
Wind Spain (2009)	251,630	61,102	61,102	124,204	49.4%

(Note that over- and undersupply are identical because sources are scaled up to 100%)

Under Method 1, the EROI for nuclear power would be discounted by 19.8%, whereas nominal wind EROI gets discounted by a factor of 49.4% (best case) to 70.5% (worst case). In other words – if wind has an undiscounted EROI of 19.2 (Kubiszewski 2010), the effective EROI after adjusting for intermittency risk would be reduced by an average of 60%, down to 7.7. Similarly, if nuclear power is rated with an EROI of 5-15 (Murphy et al 2010), a handicap of 20% would reduce its EROI to 4-12, while a flexible source like natural gas (only the generation component) would not face further handicaps based on variability.

This methodology can be represented using the following equation, where d is demand and s is supply:

$$EROI_{risk} = EROI \ X \ \frac{\sum_{t=1}^{n} |(d - s)|}{\sum_{t=1}^{n} s}$$

For energy systems which do not require a handicap for oversupply (e.g. producing a stock that can be stored easily and without losses), only the areas below the curve would need to be discounted. It may even be argued that discounting is unnecessary, so long as fluctuations don't exceed a certain level.

6.4.2 Method 2: Gap-Matching View

An alternative method for integrating variability risk with energy gain is to use existing technologies capable of filling the gaps left by the technology studied. While surpluses are still lost and need to be part of the technology handicap, supply shortfalls can be filled with a compensating technology. Such a buffer technology must be capable of filling the largest possible gap, even if this only occurs once. If this were not the case, the system (in this case the electricity grid) would fail at that moment (ENTSO-E 2009).

In this analysis, the handicap needs to be applied from the (energy) cost of providing the technology alternative, less its fuel cost. So if, in the example below, gas turbines need to be kept in reserve and ready to be operated permanently, in order to match the supply gaps from nuclear power or wind, the energy (or money) needed to provide this additional infrastructure must be accounted for.

For the same technologies analyzed in Method 1, we assume compensation of supply gaps with natural gas power for Method 2. As energy data for gas power are sparse, we use monetary production costs to approximate total handicaps from matching supply gaps.

The cost of providing the alternative technology is equal to the total cost of keeping the capacity available to match the largest gap in supply from the original source (in this case nuclear or wind power). Fuel costs are not included, as gas delivers additional energy to the grid.

For the gap-matching analysis, these calculations are based on total ex-power plant production cost (not including any grid connection). There are multiple, sometimes conflicting, sources of estimates for the levelized cost per kWh for natural gas, nuclear and wind power (IEA 2010, EIA 2010, UK ERC 2007). For this simulation, we assume a cost of 8 cents per kWh, and 8 cents for nuclear power. For natural gas, we calculate investment and operations cost based on normal operations estimates available from the IEA (2010) and EIA (2010) and assume a 2.2 cent per kWh operations and maintenance cost for normal use (35% utilization). In order to arrive at an appropriate cost, both investment and operations costs need to be attributed to each unit of power (kWh) produced from the source technology (e.g. wind or nuclear in this case). The underutilization of gas power plants when compared to normal operating modes needs to be factored in, resulting in a higher price, as is indicated in Table 11.

Table 11 Scenario Assumptions for Balancing Supply and Demand with Natural Gas

Natural gas compensating wind in West Denmark for 2009 (CBO 2003, adjusted to 2009 dollars)	Base cost of wind:	US$ .08/kWh
	Investment cost gas turbine:	1270 US$/kWe
	Operations cost (no fuels)	US$ .022 [7]
	Life expectancy of plant:	12.5 years
	Capacity requirement (largest gap):	3.5 GWe
	Total investment into capacity:	US$4,445 million
	Total annual consumption (2009):	20,550 GWh
	Gaps to cover:	7,243 GWh
	Utilization:	23.6%[8]
	Operations cost per kWh:	US$ .033 [9]
	Investment cost per annum:	US$ 355.6 million
	Operations cost per annum:	US$ 256.1 million
	Total cost per annum:	US$591.7 million
	Total cost per kWh of wind output:	US$ .029
	Handicap (over 8ct base cost/kWh):	36.0% (2.9 ct /8 ct)
	Capacity requirement (largest gap):	38.1 GWe
	Total investment into capacity:	4,445 million US$
	Total annual consumption (2009):	251,630 GWh
	Gaps to cover:	62,102 GWh
	Utilization:	18.6%[10]
	Operations cost per kWh:	4.1 ct [11]
	Investment cost per annum:	US$ 6,876 million
	Operations cost per annum:	US$ 2,574 million
	Total cost per annum:	US$ 6,460.7 million
	Total cost per kWh of wind output:	US$ .026
	Handicap (over 8ct base cost/kWh):	32.0%
Natural gas compensating nuclear power	Base cost of nuclear power:	US$ .08/ kWh
	Capacity requirement (largest gap):	1.33 GWe
	Total investment into capacity:	$US 1,689 million

[7] at 35% utilization
[8] used to correct operations cost
[9] adjusted for underuse
[10] used to correct operations cost
[11] adjusted for underuse

	Total annual consumption (2009): 20,550 GWh Gaps to cover: 2,038 GWh Utilization: 17.5%[12] Operations cost per kWh: US$ .044 [13] Investment cost per annum: 135.1 million US$ Operations cost per annum: 89.7 million US$ Total cost per annum: 224.8 million US$ Total cost per kWh of nuclear output: US$ .011 Handicap (over 8ct base cost/kWh):13.7%

Table 12 summarizes the resulting calculations. It is evident that the handicaps evaluated using Method 2 are very similar to the ones obtained using a strictly mathematical formulation as in Method 1. Wind would – based on Denmark West data, receive a handicap of 71.2% (vs. 70.5% in method 1), and nuclear a handicap of 23.6% (vs. 19.8 from Method 1)

Table 12 Demand/Supply Gap Calculations Based on Balancing With Natural Gas

Type of fuel and nameplate capacity	Total consumption GWh	Oversupply GWh	Oversupply handicap GWh	Largest supply gap GWh	Cost of supply gap in % of base technology cost	Total EROI Handicap
Nuclear (~2.35 GWe)	20,550	2,038 GWh	9.9%	1.33	13.7%	23.6%
Wind DK West (~10 GWe)	20,550	7,243 GWh	35.2%	3.5	36.0%	71.2%
Wind Spain (~145 GWe)	251,630	62,102 GWh	24.6%	38.1	32.0%	56.6%

[12] % (used to correct operations cost)

[13] adjusted for underuse

6.4.3 Method 3: Storage View

Method 3 examines an approach of storing surplus outputs during oversupply times, and using this stored power at times of low production. Storage incurs two costs; the direct provision of storage capacity for investment and operations, and the loss incurred during the transformation from flow into stock and back. Depending on the technology, the costs vary significantly. Power output is another property of energy storage that must be considered. Some technologies (e.g. ultracapacitors) are able to return power quickly to the grid, however have a limited storage capacity. Conversely, some storage options have a power output that is fixed or within a small range (e.g. fly wheels, compressed air storage), but can output their stored energy over a longer period of time.

In this approach, we will look at a broad range of technologies, despite certain limitations in scalability. Hydropower, for example won't be capable of providing large scale coverage in most areas, as total available and feasible capacity is unlikely to be increased sufficiently to meet the needs of the sizeable variability of stochastic renewable generation technology. However, for those nations or regions adjacent to large hydropower facilities (e.g. Denmark near Norway, New England Quebec near the Moses-Saunders Dam on the St. Lawrence) there is some potential for using pumped hydro storage or mitigation through delaying dam output (e.g. reducing water flows during times of high output from stochastic sources and increasing flows when the other energy outputs are lower).

Cost is certainly a factor in choosing an appropriate energy storage system. And is considered here as a proxy for the relative energy intensity of the various technologies (Costanza 1980). In this case, we assume that more expensive technologies require increased resources and advanced engineering which are a proxy for more energy use during construction and operations. An advantage of using storage technology is that it will not yield any losses related to unused capacity if it matches maximum cumulative output in oversupply situations.

To determine the required storage capacity, the largest possible cumulative gap between supply and demand needs to be identified. To optimize the model to predict the lowest total over-production to fill the largest gap, this requires multiple approximation iterations. More capacity is added to the system to account for the losses by the storage system, which makes some gaps smaller, which in turn allows re-sizing of production. This cycle is repeated until undersupply is equal to the smallest required surplus (minus conversion losses).

In a first approximation, we calculated the accumulation of gaps and surpluses over the course of a year (using 2006 to 2009 data for Denmark West and 2009 data for Spain to assess the soundness of the method used). This provides the information required to estimate the total need for storage. Table 13 summarizes the results of the first iteration, with estimates not yet corrected for storage losses.

Table 13 Annualized Storage Need for Wind and Nuclear

Location/Year	Maximum cumulative gap from wind power	Maximum cumulative oversupply from wind	Storage capacity requirem ent
DK West (2006) scaled up to 100%	2,771 (October 25, 2006)	70 (January 14, 2006)	2,771
DK West (2007) scaled up to 100%	363 (December 24, 2007)	2,426 (April 20, 2007)	2,426 (363*)
DK West (2008) scaled up to 100%	226 (October 3, 2008)	2973 (March 23, 2008)	2,973 (226*)
DK West (2009) scaled up to 100%	1,773 (Aug 11, 2009)	410 (Jan 21, 2009)	1,773
Spain (2009) scaled up to 100%	23,705 (October 11, 2009)	3,764 (May 5, 2009)	23,705
Hypothetical steady source (e.g. nuclear scaled up to 100%) DK West	540	304	540
Maximum gap per installed wind capacity	Approx. 160-200 kWh/kWe (installed capacity)		

* reduced values show only minimum gap, assuming oversupply is ignored

Results quantify that wind power is extremely volatile and unpredictable in its delivery pattern, and over long periods of time. While in 2008, the largest cumulative gap was only 226 GWh and occurred on October 3, the largest cumulative gap in 2009 is almost one order of magnitude larger and occurs on August 11, 2009. The same is true for oversupply. Other years (2006 and 2007) and regions (Spain 2009) showed different patterns for gaps and surpluses, but at similar levels, requiring approximately 160-200 kWh storage per installed kW of nameplate wind capacity..

For example, in order to provide ample storage using pumped hydro for a large offshore wind park with 150 MWe installed capacity, the total capacity of the storage basins would need to be able to provide 27 GWh of net power storage. Assuming a 30% loss for storage and re-generation, 38.6 GWh would be required. The theoretical power of 1000 liters of water (1 cubic meter) contains 0.272 kWh after a fall of 100 meters. So in order to support the 150MW wind park with stored hydro with an altitude difference of 100m, two basins of 142 million cubic meters would be required. Or, assuming two square basins with a depth of 40m, each square basin would be 1.88 x 1.88 km.

To complete those calculations the following data are needed: an approximation between total power requirements (i.e.. demand plus supply losses from storage) and the largest possible cumulative gap. This analysis can be done by scaling up the baseline capacity (e.g. wind, nuclear) so that the supply matches the loss from storage and release. The downside of this is that additional cost has to be incurred in base generation technology investments. The advantage is that storage gaps become significantly smaller due to larger surpluses at oversupply times. However, our data indicate that storage capacity requirements for all inflexible technologies are so enormous that they – even for small geographical areas and individual countries --, likely exceed all realistic possibilities. For reference – total generation capacity in the entire European UCTE area was 800 GWe in 2007. (RWE 2007). Given the above results, and a number of unsuccessful attempts at modeling outputs of much higher capacity expecting to eliminate those large gaps, Method 3 was abandoned as a valid energy handicap technique.

6.5 Discussion

When accounting for risks in delivering energy technologies, Methods 1 and 2 delivered highly comparable results despite the relative uncertainty regarding the cost model used in Method 2. It thus seems appropriate to introduce handicaps according the deviations between supply and demand in flow-based output systems such as electricity grids. As indicated in Table 14, the handicap range, depending on the Method and the location, are considerable relative to nominal EROI for wind and nuclear.

Table 14 EROI and Variability-Adjusted EROI for Wind and Nuclear Electricity Generation

Technology	EROI (undiscounted)	Method 1	Method 2
Wind	19.2	5.7 – 9.7 (location-dependent)	5.5 – 8.3 (location-dependent)
Nuclear	5 – 15	4 – 12	3.8 – 11.5

` As we have attempted to demonstrate here, developing a metric for risk-adjusting energy flows seems not only important but feasible. It remains an open question how to develop a similar methodology for application to stock based energy systems. Due to fungibility and transportability on global markets, the fluctuations and risk of individual coal, oil and natural gas wells, fields or mines, represents a different sort of risk, one that is less relevant to the aggregate energy gain of a specific technology, since all these energy types are storable once procured. Also, the availability of complete energy data is limited, posing another difficultly in establishing a similar metric. Ultimately however, the importance of variability matters most for societies' key flow-based energy system: the electricity grid. Applied to this, the initial approach appears to return valid results.

Table 15 applies the common financial risk metric, the Sharpe Ratio, to EROI analysis. Several energy sources were measured first obtaining EROI from the median reported numbers in recent literature (Murphy 2010). Then, the standard deviation of a source's energy delivery against human demand was computed on an hourly basis throughout one year using the datasets above. Given its ability to fill on demand electricity use, natural gas is viewed as 'risk free' energy asset from an intermittence perspective. Though able to switch on and off similar to gas, coal has – particularly for non-anthracite qualities - a lead time between 6 and 12 hours and therefore can only follow larger patterns (weekdays/weekends). The calculations assumed one daily load change. For solar, where no aggregate data is available due to the distributed nature of photovoltaic installations without central metering, a stochastic pattern was assumed comparable to wind, but with a higher correlation to human demand patterns due to the fact that sunshine is available throughout the day.

A 'Net Energy Sharpe Ratio" was then computed by taking the nominal EROI numbers, dividing by standard deviation and then subtracting out the risk free rate. Conceptually, this should rank fuels based on their intermittence/quality adjusted values to a human demand system. After natural gas, based on its high initial EROI, coal offers the highest "Sharpe EROI", followed by nuclear. Wind and solar power experience significant handicaps from high deviations compared to human demand patterns. Thus, from, the perspective of 'excess return versus a benchmark', coal and particularly natural gas exhibit high return for each unit of risk, while other sources come out significantly weaker.

Table 15 EROI, Net EROI (after conversion to electricity and "Sharpe" EROI

	Basic EROI	Elec. convers ion	Power plant	Net EROI		Stdev from demand	Return Deviat ion	<R>-Rf	"Sharpe" EROI
Gas	15	45%	5%	6		0.0%	-	0	-
Coal	60	35%	5%	18		20.9%	3.8	12.0	3.2
Nuclear	10	100%	-	10		23.0%	2.3	4.0	1.7
Wind	19.2	100%	-	19.2		86.8%	16.7	13.2	0.8
Solar	8	100%	-	8		75.0%	6.0	2.0	0.3

As within financial theory, a risk adjusted EROI will help sort energy inputs into a “portfolio” of technologies to contribute towards the final supply output. Societies can then select the technologies/sources with the highest risk-adjusted energy returns first. If the technologies delivering the best results are no longer available or feasible (for example due to external restrictions), alternatives will have to be evaluated based on a careful analysis of their correlations to one another. Low or even negatively correlated output methods might – in a portfolio of technologies – partly offset their risks.

In this paper we focused on variability risks. Other risks not covered here are also relevant when making decisions about future energy sources. One such risk, measuring the timing of flows in energy gathering and conversion risk, also bears further study (See Hagens, Kunz 2010 for overview). Integrating both time and variability risk gives a fuller sense of how a particular technology/source fits with human demand profile for energy services. Table 16 indicates, at various discount rates, the combined handicap

(Time + Variability) for Wind and Solar Photovoltaic. At a 20% discount rate, the adjusted EROI from a base case for solar of 8:1 drops to a sub-unity EROI of 0.9:1.

Table 16 - Applying Time and Variability Handicap to Wind and Solar

	Dis. Rate=>	5%	5%	10%	10%	15%	15%	20%	20%
	Nominal EROI	Time	Time +Var	Time	Time +Var	Time	Time +Var	Time	Time +Var
Wind [14]	19.2	12.4	**7.4**	8.6	**5.2**	6.4	**3.8**	5.0	**3.0**
Solar PV[15]	8.0	5.1	**2.5**	3.3	**1.7**	2.3	**1.2**	1.7	**0.9**

Ultimately, in a comprehensive framework on energy and risk, time and variability are key risks, but environmental externalities, natural disasters and weather related shortfalls, geopolitical risks, and other general systemic risks that are inherent in energy delivery systems would need to be integrated as well. The higher the impact of disruptions (in flow-based systems), the larger the problems with stochastic or unreliable inputs becomes, as it not only creates a direct gap, but also threatens systems stability. Energy intermittency of wind (and other stochastic sources') thus create systemic and structural risks. In this context, "systemic risk" defines risk that is tied to the hour-to-

[14] Conservatively assumes 60% variability handicap as per Method 1 applied to large areas
[15] Conservatively assumes 40% variability handicap as per Method 1 applied to large areas

hour operation of the energy grid. Renewable electricity generation technologies which directly deliver into the grid based on stochastic input flows (like sun or wind) are thus heavily challenging the entire system and need to be handicapped accordingly when their energy returns are assessed. Ultimately, their imbalances cause problems or additional cost in the system, even if this cost is disguised

6.6 Concluding Remarks

Risk versus reward is a central theme in nature, particularly with respect to energy capture. When introducing supply risk into a biophysical review of energy technologies, both reliability and manageability become very important, as they define the benefit of a technology to society. Though the physical volatility and intermittency of energy are themselves important variables, it is their relationship to societal demand that ultimately defines how relevant risk becomes. Finance suggests that the covariance of a project's return with the return to the economy as a whole is what matters, not the covariance with itself. Similarly, a nominally high EROI statistic may not be of high value as a policy tool if risk and intermittency of energy sources are not considered in its formulation. In summary, the costs associated with increased variance from renewable electricity generation technologies to our human demand system may be a larger drawback than their comparatively lower net energy gain. Further research incorporating risk as a factor into energy quality is warranted.

References

Congressional Budget Office (CBO). (2003). *Prospects for distributed electricity generation. Chapter 2: The current status of and prospects for distributed generation.* Washington, D.C. Retrieved August 21, 2010 from http://www.cbo.gov/doc.cfm?index=4552&type=0&sequence=3.

EIA. (2010). *2016 levelized cost of new generation resources from the annual energy outlook 2010*. Retrieved August 21, 2010 from http://www.eia.doe.gov/oiaf/aeo/pdf/2016levelized_costs_aeo2010.pdf .

Energinet.dk, Danish Electricity Market Data retrieved from http://www.energinet.dk/en/menu/Market/Download+of+Market+Data/Download+of+Market+Data.htm retrieved on Apr 10,2010

EBRD - European Bank for Reconstruction and Development Business Environment and Enterprise Performance Survey (BEEPS), http://www.ebrd.com/pages/research/analysis/surveys/beeps.shtml Retrieved on Mar 15,2010.

European Network of Transmission System Operators for Electricity (ENTSO-E). (2009). *Operations Handbook Policy 1 – Load Frequency Control.* Retrieved May 19, 2010 from http://www.entsoe.eu/fileadmin/user_upload/_library/publications/ce/oh/Policy1_final.pdf.

International Energy Agency (IEA) and Nuclear Energy Agency (NEA). (2010). *Projected costs of generating electricity – 2010 edition.* Organisation for Economic Coordination and Development. France: OECD/IEA.

Poyry. (2009). "Impact of Intermittency – How Wind Variability could Shape the Irish and British Electricity Markets", July 2009.

Red Electrica De Espana. (2010). *Energy Demand in Real Time*. Retrieved August 16, 2010 from https://demanda.ree.es/generacion_acumulada.html.

RWE. (2007). *Factbook Energy Generation Capacity in Europe*, July 2007. Retrieved May 14, 2010 from https://www.rwe.com/web/cms/contentblob/108844/data/1046/de-Factbook-juni-2007-2.pdf .

UK Energy Research Centre (UK ERC). (2007). *A review of electricity unit cost estimates – Working Paper, December 2006* (Updated May 2007). Retrieved

August 21, 2010 from http://www.ukerc.ac.uk/Downloads/PDF/07/0706_TPA_A_Review_of_Electricity.pdf

World Bank – Purchasing Power Parity GDP Data http://siteresources.worldbank.org/DATASTATISTICS/Resources/GDP_PPP.pdf retrieved on Mar 17, 2010.

World Resources Institute – Electricity – Access To Electricity Percent http://earthtrends.wri.org/searchable_db/index.php?theme=6&variable_ID=1379&action=select_countries retrieved on Feb 19, 2010.

Bernoulli, D. (1954). Exposition of a new theory on the measurement of risk. *Econometrica (The Econometric Society) 22* (1): 22–36. Originally published in 1738; translated by Dr. Lousie Sommer. (January 1954).

Biglova, A.,Ortobelli, S., Rachev, S.T., Stoyanov, S. (2004). Comparison among different approaches for risk estimation in portfolio theory. *Journal of Portfolio Management. 31*(1), 103-112.

Carney, B. (2009). *Impact of drought on U.S. steam electric power plant cooling water intakes and related water resource management issues*" National Renewable Energy Labs April 2009.

Cleveland, Cutler J. (1992). Energy surplus and energy quality in the extraction of fossil fuels in the U.S. *Ecological Economics*, 6: 139-162.

Cleveland, Cutler J., Robert Costanza, Charles A.S. Hall, and Robert Kaufmann, (1984). Energy and the U.S. economy: A biophysical perspective. *Science* 225: 890-897.

Costanza, R. (1980). Embodied energy and economic valuation. *Science* 210, 4475: 1219-1224.

Cottrell, F. (1955). *Energy and society - the relation between energy, social change, and economic development*. Greenwood Press.

George, S., George, H., & Nguyen, S. (2010). *Risk quantification associated with wind energy intermittency in California*. Retrieved from http://arxiv.org/ftp/arxiv/papers/1002/1002.2749.pdf.

Georgescu-Roegen, Nicholas. (1971). *The entropy law and the economic process* (10.4: From the Struggle for Entropy to Social Conflict, pgs. 306-15; exosomatic, pgs. 19, 307-08). Cambridge, Massachusetts: Harvard University Press.

Gilliland, M. (1975). Energy analysis and public policy: The energy unit measures environmental consequences, economic costs, material needs, and resource availability, *SCIENCE* 189, 1051-1056.

Hall C., Balogh, S., & Murphy, D. (2009). What is the minimum EROI that a sustainable society must have?”, *Energies* 2009, *2*(1), 25-47.

Ibrahim, H., Ilinca, A., & Perron, J. (2008). Energy storage systems—Characteristics and comparisons. *Renewable and Sustainable Energy Reviews,* 12(5), 1221-50.

Kacelnik, A., & Bateson, M. (1996). Risky theories – the effects of variance on foraging decisions, *American Zoologist 36*(4):402-434.

Kahneman, D., Slovic, P., & Tversky, A. (1982). *Judgment under Uncertainty: Heuristics and Biases*. New York: Cambridge University Press.

Kahneman, D., & Tversky, A. (1979). Prospect theory – an analysis of decision making under risk. *Econometrica 47*(2), 263-91.

Knight, F.H. (1921). *Risk, uncertainty, and profit*. Boston, MA: Hart, Schaffner & Marx; Houghton Mifflin Company.

Krebs, J.R., & Davies, N., (1997). Behavioral Ecology – An Evolutionary Approach – Blackwell Science 1997, New York.

Lehrer, J. (2009). *How we decide*, Boston, Houghton Mifflin Co.

Lind, R., & Ruskin, F. (1982). Discounting for time and risk in energy policy. *Resources for the Future, Inc.*, Washington D.C.

Lo, A. (2001). Risk management for hedge funds: introduction and overview. *Financial Analysts Journal*, *57*(6), pp. 16-33.

Lotka, A.J. (1922). Contribution to the energetics of evolution. *Proc Natl Acad Sci*, *8*, 147-151.

Markowitz, H. (1959). *Portfolio selection: Efficient diversification of investments*. New York: Wiley.

Millar, J., & Zammuto, R. (1983). Life histories of mammals: an analysis of life tables. *Ecology, 64*(4), 631-635.

Sharpe, W. F. (1966). Mutual fund performance. *Journal of Business 39* (S1), 119–138.

Sharpe, W.F. (1994). The Sharpe ratio, *Journal of Portfolio Management, 21* (1), 49–58.

Sortino, F. A., & van der MEER, R. (1991). Downside risk. *The Journal of Portfolio Management*, *17*(4), 27–31.

Tainter, J. A. (1990). *The Collapse of Complex Societie.s* Cambridge: Cambridge University Press.

Wise, R., Role of brain dopamine in food reward and reinforcement, *Phil. Trans. R. Soc. B* 29 July 2006, 361/1471 1149-1158.

BIBLIOGRAPHY

American Wind Energy Association. (2006). *Comparative air emissions of wind and other fuels*. Retrieved from http://www.awea.org/pubs/factsheets.htmlBritish Petroleum. (2005). *Quantifying energy: BP statistical review of world energy 2005.* London: Beacon Press.

Congressional Budget Office (CBO). (2003). *Prospects for distributed electricity generation. Chapter 2: The current status of and prospects for distributed generation.* Washington, D.C. Retrieved August 21, 2010 from http://www.cbo.gov/doc.cfm?index=4552&type=0&sequence=3.

Energy Information Agency. (2008). *Analysis of crude oil production for arctic national wildlife refuge.* (Report #: SR-OIAF/2008-03). Retrieved from http://www.eia.doe.gov/oiaf/servicerpt/anwr/methodology.html.

EIA. (2010). *2016 levelized cost of new generation resources from the annual energy outlook 2010*. Retrieved August 21, 2010 from http://www.eia.doe.gov/oiaf/aeo/pdf/2016levelized_costs_aeo2010.pdf .

Energy Watch Group. (2007, April). *Coal: resources and future production.* Retrieved Mar 15, 2010 from http://www.energywatchgroup.org/files/Coalreport.pdf

European Network of Transmission System Operators for Electricity (ENTSO-E). (2009). *Operations Handbook Policy 1 – Load Frequency Control.* Retrieved May 19, 2010 from http://www.entsoe.eu/fileadmin/user_upload/_library/publications/ce/oh/Policy1_final.pdf.

European Commission. (1997). *Externalities of Energy, Methodology Report, Volume 1.* Brussels: European Commission DG Research.

EPA. (2002). *A comprehensive analysis of biodiesel impacts on exhaust emissions.* US Environmental Protections Agency: Washington DC

Federal Reserve Bank. (2009, March 12). *Flow of funds of the United States fourth quarter 2008.*

International Energy Agency (IEA) and Nuclear Energy Agency (NEA). (2010). *Projected costs of generating electricity – 2010 edition.* Organisation for Economic Coordination and Development. France: OECD/IEA.

International Standard Organization. (1997). *Environmental Management – life cycle assessment – principles and framework.* (Ed. ISO 14040). Geneva: ISO.

McKinsey Global Institute. (2009, March). *Averting the next energy crisis: the demand challenge.* McKinsey & Company Southwide Energy Committee. (1980). *Petroleum product consumption and efficiency in systems used for energy wood harvesting.* American Pulpwood Association: Washington, D.C.

National Agriculture Statistics Service. (2007). US Department of Agriculture. Washington DC. http://www.nass.usda.gov/index.asp. Retrieved 4/14/2007

National Energy Board. (2010, march). Short term Canadian natural gas deliverability 2010-2012 – an energy market assessment. Retrieved August 10, 2010 from http://www.neb.gc.ca/clfns/rnrgynfmtn/nrgyrprt/ntrlgs/ntrlgsdlvrvlty20102012/trlgsdlvrblty20102012-eng.pdf.

National Resource Council - Committee on Water Implications of Biofuels Production in the US. (2008). *Water implications of biofuel production in the United States.* Washington D.C.

Office of Management and Budget. (1992). Circular No.A-94. Retrieved from http://www.whitehouse.gov/omb/circulars_ao94/ Retrieved on July 27, 2010

Office of Management and Budget. (2010). *Historical Tables – Budget of the* United States Government *2010.* Retrieved August 8, 2010 from http://www.gpoaccess.gov/usbudget/fy10/pdf/hist.pdf .

Poyry. (2009). "Impact of Intermittency – How Wind Variability could Shape the Irish and British Electricity Markets", July 2009.

Red Electrica De Espana. (2010). *Energy Demand in Real Time*. Retrieved August 16, 2010 from https://demanda.ree.es/generacion_acumulada.html.

RWE. (2007). *Factbook Energy Generation Capacity in Europe*, July 2007. Retrieved May 14, 2010 from https://www.rwe.com/web/cms/contentblob/108844/data/1046/de-Factbook-juni-2007-2.pdf .

Social Security Administration. (2006). *Period life table* http://www.ssa.gov/OACT/STATS/table4c6.html retrieved Apr 4, 2010

UK Energy Research Centre (UK ERC). (2007). *A review of electricity unit cost estimates – Working Paper, December 2006* (Updated May 2007). Retrieved August 21, 2010 from http://www.ukerc.ac.uk/Downloads/PDF/07/0706_TPA_A_Review_of_Electricity.pdf

US Department of Energy. (1989). *Energy systems emissions and material requirements.* Meridian Corporation: Washington, D.C.

World Bank – Purchasing Power Parity GDP Data http://siteresources.worldbank.org/DATASTATISTICS/Resources/GDP_PPP.pdf retrieved on Mar 17, 2010.

World Resources Institute – Electricity – Access To Electricity Percent http://earthtrends.wri.org/searchable_db/index.php?theme=6&variable_ID=1379&action=select_countries retrieved on Feb 19, 2010.

Alcamo, J., van Vuuren, D., Ringler, C., Cramer, W., Masui, T., Alder, J., & Schulze, K. (2005). Changes in nature's balance sheet: model-based estimates of future worldwide ecosystem services. *Ecology and Society*, *10*(2), 19.

Ardente, F., Beccali, M., Cellura, M., & Lo Brano, V. (2008). Energy performances and life cycle assessment of an Italian wind farm. *Renewable and Sustainable Energy*, *12*, 200-217.

Arrow, K.J., et al. (1995). "Intertemporal Equity, Discounting, and Economic Efficiency. In: Climate Change 1995: Economic and Social Dimensions of Climate Change". Cambridge University Press.

Ayres, R., & Martinas, K. (1995). Waste potential entropy: the ultimate ecotoxic?. *Economie Appliquees*, *48*, 95-120.

Ayers, R., Ayers, L., & Martinas, K. (1998). Exergy, waste accounting, and life-cycle analysis. *Energy*, *23*(5), 355-363.

Baines, J., & Peet, M. (1983). Assessing alternative liquid fuels using net energy criteria. *Energy*, *8*(12), 963-972.

Bannon, I. & Collier, P. (2003). *Natural Resources and Violent Conflict.* The International Bank for Construction and Redevelopment, Washington DC.

Barlow, M., & Clarke, T. (2002). *Blue gold: the fight to stop the corporate theft of the world's water*. New York: New Press.

Bateson, M. (2002). Recent advances in our understanding of risk sensitive foraging [references, *Proceedings of the Nutrition Society*, *61*, 1–8.

Bender, M. (1999). Economic feasibility review for community-scale farmer cooperatives for biodiesel. *Bioresource Technology*, *70*(1), 81-87.

Berglund, M., & Borjesson, P. (2006). Assessment of energy performance in the life-cycle of biogas production. *Biomass & Bioenergy*, *30*(3), 254-266.

Berndes, G., Azar, C., Kaberger, T., & Abrahamson, D. (2001). The Feasibility of large-scale lignocelluose-based bioenergy production. *Biomass & Bioenergy*, *20*, 371-383.

Berndes, G. (2002). Bioenergy and water - the implicaitons of large-scale bioenergy production for water use and supply. *Global Environmental Change*, *12*, 253-271.

Berndes, G. (2008). Bioenergy - A new large user of scarce water? In *Förare*, J. (ed.) Food and water. Forskningsrådet för miljö, areella näringar och samhällsbyggande, Formas

Berns, G., Laibson, D., & Loewenstein, G. (2010). Intertemporal choice – toward an integrative framework. *TRENDS in Cognitive Sciences* *11*(11) 482-488.

Berndt, E. (1983). From technocracy to net energy analysis: engineers, economists, and recurring energy theories of value. In A. Scott (Ed.), *Progress in Natural Resource Economics* p. 337-366. Clarendon: Oxford.

Bernoulli, D. (1954). Exposition of a new theory on the measurement of risk. *Econometrica (The Econometric Society) 22* (1): 22–36. Originally published in 1738; translated by Dr. Lousie Sommer. (January 1954).

Biglova, A.,Ortobelli, S., Rachev, S.T., Stoyanov, S. (2004). Comparison among different approaches for risk estimation in portfolio theory. *Journal of Portfolio Management. 31*(1), 103-112.

Borjesson, P. (2008). *Good or bad ethanol – what determines this?* (Report no. 65, Environmental and Energy Systems Studies). Department of Technology and Society. Sweden: Lund University.

Carney, B. (2009). *Impact of drought on U.S. steam electric power plant cooling water intakes and related water resource management issues*" NREL April 2009, Denver.

Chabris C., Laibson, D., Morris, C., Schuldt, J.,& Taubinsky, D. (2009).The allocation of time on decisionmaking, J *Eur Econ Assoc.*, *7*(2), 628–637.

Chui, F., Elkamel, A., & Fowler, M. (2006). An integrated decision support framework for the assessment and analysis of hydrogen production pathways. *Energy & Fuels*, *20*(1), 346-352.

Cleveland, C.J., Costanza, R., Hall, C.A.S., & Kaufmann, R. (1983). Energy and the United States economy: a biophysical perspective. *Science*, *225*, 890-897.

Cleveland, C., & Costanza, R. (1984). Net energy analysis of geopressurized gas-resources in the United States gulf coast region. *Energy*, *9*(1), 35-51.

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. (2005). Net energy from the extraction of oil and gas in the United States. *ENERGY*, *30*(5), 769-782.

Costanza, R. (1980). Embodied energy and economic valuation. *Science*, *210*(4475), 1219-1224.

Costanza, R. (1987). Social traps and environmental policy. *Bioscience*, *37*(6), 407-412.

Cottrell, F. (1955). *Energy and society - the relation between energy, social change, and economic development*. Greenwood Press.

de Boer, I. (2003). Environmental impact assessment of conventional and organic milk production. *Livestock Production Science*, *80*, 69-77.

DeNocker, L., Spirinckx, C., & 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.* Brussels: VITO.

Deffeyes, K. (2005). *Beyond oil: the view from Hubbert's peak*. Hill and Wang. New York.

Duncan, R. (2005-2006, winter). Energy, population and industrial civilization. *The Social Contract.*

Duncan, R. (2009, spring). Olduvai theory: toward re-equalizing the world standard of living. *The Social Contract.*

Erickson, J., & Gowdy, J. (2007). *Frontiers in ecological economics*. Williston, VT: Elgar Publishing.

Farrell, A., Plevin, R., Turner, B., Jones, A., O'Hare, M., & Kammen, D. (2006). Ethanol can contribute to energy and environmental goals. *Science*, *311*, 506-508.

Flynn, H., & Bradford, T. (2006). *Polysilicon: supply, demand, and implications for the PV industry*. Cambridge, MA: The Prometheus Institute for Sustainable Development.

Frederick, S., Loewenstein, G., & O'Donahue, T. (2009). Time discounting and time preferences: a critical review. *J Eur Econ Assoc*, *7*(2), 628-637.

George, S., George, H., & Nguyen, S. (2010). *Risk quantification associated with wind energy intermittency in California*. Retrieved from http://arxiv.org/ftp/arxiv/papers/1002/1002.2749.pdf.

Georgescu-Roegen, N. (1971). *The entropy law and the economic process* (10.4: From the Struggle for Entropy to Social Conflict, pgs. 306-15; exosomatic, pgs. 19, 307-08). Cambridge, Massachusetts: Harvard University Press.

Georgescu-Roegen, N. (1973). The entropy law and the economic problem. In H.E. Daly (editor), *Toward a steady state economy.* San Francisco: W.H. Freeman and Company.

Giampietro, M., Ulgiati, S., & Pimental, D. (1997). Feasibility of large-scale biofuel production. *Bioscience*, *47*(9), 587-600.

Gigerenzer, G. (2008). *Gut feelings, the intelligence of the unconscious*. New York: Penguin.

Gigerenzer, G. (2002). *Bounded rationality, the adaptive toolbox.* Boston: MIT Press.

Gilliland, M. (1975). Energy analysis and public policy: The energy unit measures environmental consequences, economic costs, material needs, and resource availability, *SCIENCE* 189, 1051-1056.

Gingerich, J., & Hendrickson, H. (1993). The Theory of energy return on investment - a case-study of whole tree chipping for biomass in Prince Edward Island. *Forestry Chronicle*, *69*(3), 300-306Gleick, H. (2000). *The world's water.* Washington, D.C.: Island Press.

Goldemberg, J. (2007). Ethanol for a sustainable energy future. *Science*, *315*, 808-810.

Hagens, N., Costanza, R., & Mulder, K. (2006). Energy returns on ethanol production. *Science*, *312*, 1746.

Hagens, N., & Mulder, K. (2008). A framework for energy alternatives: net energy, Liebig's law and multi-criteria analysis. In *Biofuels, solar and wind as renewable energy systems.* Netherlands: Springer.

Hall, C.A.S., Cleveland, C.J., & Kaufmann, R. (1986). *Energy and resource quality: the ecology of the economic process*. New York: Wiley.

Hall, C.A. (2004). The continuing importance of maximum power. *Ecological modelling*, *178*(1-2, 15), 107-113.

Hall, C.A.S., Balogh, S., & Murphy, D. (2009). What is the Minimum eroi necessary for civilization? *Energies*, *2*(1), 25-47.

Hammerschlag, R. (2006). Ethanol's energy return on investment: a survey of the literature 1990-present. *Environmental Science and Technology*, *40*(6), 1744-1750.

Hanegraaf, M.C., Biewinga, E.E., & Van der Bijl, G. (1998). Assessing the ecological and economic sustainability of energy crops. *Biomass & Bioenergy*, *15*(4-5), 345-355.

Hannon, B. (1982). Energy discounting. *Technological forecasting and social change*, *21*, 281-300.

Hardin, G.J. (1999). *The Ostrich factor: our population myopia*. New York: Oxford University Press.

Hausman, J. (1979). Individual discount rates and the purchase of energy-using durables. *Bell Journal of Economics*, *10*(1), 33-54.

Hill, J., Nelson, E., Tilman, D., Polasky, S., & Tiffany, D. (2006). Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the Academy of Natural Sciences*, *103*, 11206-11210.

Hirsch, R., Bezdek, R., & Wendling, R. (2005). *Peaking of world oil production: impacts, mitigation, and risk management.* Washington D.C.: Department of Energy.

Howarth, R.B., & Norgaard, R. (1993). Intergenerational transfers and the social discount rate. *Environmental and Resource Economics*, *3*(4), 337-358.

Howarth, R.B. (2009). Policy brief no. 3: discounting, uncertainty, and climate change. *Economics for Equity and the Environment*, Retrieved 4/15/2010 from http://realclimateeconomics.org/briefs/Howarth_Discounting.pdf.

Hubbert, M. (1931). Hours - a declining quantity in *Technocracy*, Series A, No.8.

Hubbert, M. (1949). The Energy from fossil fuels. *Science*, *109*, 103-109.

Hutson, S., Kenny, J., Barber, N., Linsey, K., Lovelace, J., & Maupin, M. (2004). *Estimated use of water in the United States in 2000*. US Geological Survey. Washington DC.

Ibrahim, H., Ilinca, A., & Perron, J. (2008). Energy storage systems—Characteristics and comparisons. *Renewable and Sustainable Energy Reviews*, 12(5), 1221-50.

Jaramillo, P., Griffin, M.W., & Matthews, H. (2008). Comparative analysis of the production costs and life-cycle ghg emissions of ft liquid fuels from coal and natural gas. *Environmental Science Technology*, *42*(20), 7559-7565.

Kacelnik, A., & Bateson, M. (1996). Risky theories - the effects of variance on foraging decisions. *American Zoologist*, *36*(4), 402-434.

Kahneman, D., & Tversky, A. (1979). Prospect theory – an analysis of decision making under risk. *Econometrica 47*(2), 263-91.

Kahneman, D., Slovic, P., & Tversky, A. (1982). *Judgment under Uncertainty: Heuristics and Biases*. New York: Cambridge University Press.

Kannan, R., Tso, C., Osman, R., & Ho, H. (2004). LCA-LCCA of oil fired steam turbine power. *Energy Con. and Mgmt*, *45*, 3093-3107.

Kaylen, M. (2005). An economic analysis of using alternative fuels in a mass burn boiler. *Bioresource Technology*, *96*(17), 1943-1949.

Keeley, L. (1997). *War before civilization: the myth of the peaceful savage*. New York: Oxford University Press.

Kennedy, D. (2007). The biofuels conundrum. *Science*, *316*, 515.

Keoleian, G. (1998). Application of life-cycle energy analysis to photovoltaic design. *Progress in Voltaics*, *5*(4),

Kidd, S. (2004). Nuclear: is there any net energy addition?. *Nuclear Engineering International*, *49*(603), 12-13.

Kim, S., & Dale, B. (2002). Allocation procedure in ethanol production system from corn grain - i. system expansion. *International Journal of Life Cycle Assessment, 7*(4), 237-243.

Kim, S., & Dale, B. (2005). Environmental aspects of ethanol derived from no-tilled corn grain: nonrenewable energy consumption and greenhouse gas emissions. *Biomass & Bioenergy, 28*(5), 475-489.

Kirby, K.N., Petry, N.M., & Bickel, W.K,. (1999). Heroin addicts have higher discount rates for delayed rewards than non-drug-using controls. *Journal of Experimental Psychology: General, 128*, 78-87.

Knight, F.H. (1921). *Risk, uncertainty, and profit*. Boston, MA: Hart, Schaffner & Marx; Houghton Mifflin Company.

Krebs, J.R., & Davies, N., (1997). Behavioral Ecology – An Evolutionary Approach – Blackwell Science New York.

Kubiszewski, I., Cleveland, C.J., & Endres, P.K. (2010). Meta-analysis of net energy return for wind power systems. *Renewable energy, 35*(1), 218-225.

Lehrer, J. (2009). *How we decide*, Houghton Mifflin Co.

Lincoln, S. (2005). Fossil fuels in the 21st century. *AMBIO, 34*(8), 621-627.

Lind, R., Ruskin, F. (1982). Discounting for time and risk in energy policy. *Resources for the Future, Inc.*, Washington D.C.

Lo, A. (2001). Risk management for hedge funds: introduction and overview. *Financial Analysts Journal, 57*(6), pp. 16-33.

Lotka, A.J. (1922). Natural selection as a physical principle. *Proc of National Academy of Science, 8*, 151-154.

Lotka, A.J. (1922). Contribution to the energetics of evolution. *Proc Natl Acad Sci, 8*, 147-151.

Lynd, L., & Wang, M.Q. (2004). A product-nonspecific framework for evaluating the potential of biomass-based products to displace fossil fuels. *J. Ind. Ecol., 7*, 17-32.

MacArthur, R.H., & Pianka, E.R. (1966). On the optimal use of a patchy environment. *American Naturalist, 100*(916), 603-609.

Macedo, I.C., Leal, M.R.L.V., & 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.

Mann, M.K., & Spath, P. (1997). Life cycle assessment of a biomass gasification combined-cycle system. (NREL/TP-430-23076). Golden, CO: National Renewable Energy Laboratory.

Markowitz, H. (1959). *Portfolio selection: Efficient diversification of investments*. New York: Wiley.

Mazur, J. (2005). Effects of reinforcer probability, delay, and response requirements on the choice of rats and pigeons: possible species differences. *J Exp Anal Behav*, *83*(3), 263-279.

McClure, S., Laibson, D., Loewenstein, G., Cohen, J., (2004). Separate neural systems value immediate and delayed monetary rewards. *Science*, *306/*5695 503-507.

Millar, J., & Zammuto, R. (1983). Life histories of mammals: an analysis of life tables. *Ecology*, *64*(4), 631-635.

Mortimer, N.D., Elsayed, M.A., & Matthews, R. (2003). *Carbon and energy balances for a range of biofuel options.* Resources Research Unit. Sheffield Hallam University: Sheffield, England.

Mulder, K., & Hagens, N. (2009). Energy return on investment - towards a consistent framework. *AMBIO*, *37*(2), 74-79.

Nordhaus, W.D. (2007). A review of the Stern review on the economics of climate. *Journal of Economic Literature*, *45*(3), 686-702.

Odling-Smee, L. (2007). Biofuels bandwagon hits a rut. *Nature*, *446*, 483.

Odum, H.T. (1963). Limits of remote ecosystems containing man. *The American Biology Teacher*, *25*(6), 429-443.

Odum, H.T. (1971). *Environment, power, and society*. New York: Wiley-Interscience.

Odum, H.T. (1973). Energy, ecology, and economics. *AMBIO*, *2*, 220-227.

Odum, H.T. (1983). *Systems ecology: an introduction*. New York: Wiley.

Odum, W.E., Odum, E.P., & Odum, H.T. (1995). Nature's pulsing paradigm. *Estuaries*, *18*, 547-555.

Oki, T., & Kanae, S. (2006). Global hydrological cycles and world water resources. *Science, 313*, 1068-1072.

O'Malley, C. (producer), & Creadon, P. (director). (2009). *IOUSA.* [motion picture]. USA: O'Malley Creadon Productions.

Patzek, T. (2004). Thermodynamics on the corn-ethanol biofuel cycle. *Critical Reviews in Plant Sciences*, *23*(6), 519-567.

Patzek, T., & Pimental, D. (2005). Thermodynamics of energy production from biomass. *Critical Review in Plant Sciences*, *24*(5-6), 327-364.

Pearce, D., Markandia, A., & Barbier, E. (1989). *Blueprint for a new economy.* London, UK: Earthscan Publications.

Pearce, J. & Lau, A. (2002). Net energy analysis for sustainable energy production from silicon based solar cells. In *Proceedings of Solar 2002.* Reno, NV.

Pimentel, D. (2003). Ethanol fuels: energy balance, economics, and environmental impacts are negative. *Natural Resources Research*, *12*(2), 127-134.

Pimentel, D., & Patzek, T.W. (2005). Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. *Natural Resources Research*, *14*(1), 65-76.

Pimentel, D.,Houser, J., Preiss, E., White, O., Fang, H., et al. (1997). Water resources, agriculture, the environment and society. *Bioscience, 47*, 97-106.

Price, D. (1995). Energy and human evolution. *Population and Environment: A Journal of Interdisciplinary Studies*, *16*(4), 301-319.

Ragauskas, A.J., Williams, C., Davison, B., Britovsek, G., Cairney, J., et. al. (2006). The path forward for biofuels and biomaterials. *Science, 311*, 484-489.

Rees, W. (1996). Revisiting carrying capacity: area-based indicators of sustainability. *Population and Environment*, *17*(3), 195-215.

Renault, D., & Wallender, W. (2006). Nutritional water productivity and diets. *Agricultural Water Management, 45*, 275-296.

Ricardo, D. (1819). *On the principles of political economy, and taxation*. Georgetown: J. Milligan.

Rijsberman, F.R. (2006). Water scarcity: fact or fiction. *Agricultural Water Management, 80*, 5-22.

Robson, A. (2002). Evolution and human nature, *The journal of economic perspectives, 16*(2), 89-106.

Ruderman, H., Levine, M.D., & McMahon, J.E. (1987). The behavior of the market for energy efficiency in residential appliances including heating and cooling equipment. *Energy Journal*, *8*(1), 101-124.

Sanderson, K. (2007). A field in ferment. *Nature*, *444*, 673-676.

Schleisner, L. (2000). Life cycle assessment of a wind farm and related externalities. *Renewable Energy, 20*(3), 279-288.

Schneider, E.D., & Kay, J.J. (1985). Order from disorder: the thermodynamics of complexity in biology. In Michael P. Murphy, Luke A.J. O'Neill (editors) *What is Life: The next fifty years. Reflections on the future of biology.* Cambridge University Press, 161-172.

Sharpe, W. F. (1966). Mutual fund performance. *Journal of Business 39* (S1), 119–138.

Sharpe, W.F. (1994). The Sharpe ratio, *Journal of Portfolio Management, 21* (1), 49–58.

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., & Shapouri, H. (1998). *An overview of biodiesel and petroleum diesel life cycles*. (NREL/TP-580-24772). Golden, CO: National Renewable Energy Laboratory.

Smil, V. (1991). *General energetics: energy in the biosphere and civilization*. New York: Wiley.

Smil, V. (2006). 21st century energy: some sobering thoughts. *OECD Observer.* Retrived from http://www.oecdobserver.org/news/fullstory.php/aid/2083/ September 15, 2008.

Soddy, F. (1926). *Wealth virtual wealth and debt*; *the solution of the economic paradox*. London: George Allen and Unwin LTD.

Sortino, F. A., & van der MEER, R. (1991). Downside risk. *The Journal of Portfolio Management*, *17*(4), 27–31.

Sozou, P. (2009) Individual and social discounting in a viscous population, Proc. R. Soc. B 22 ***276*** **(1669)** 2955-2962.

Spreng, D.T. (1988). *Net-energy analysis and the energy requirements of energy systems*. New York: Praeger.

Stern, N. (2007). The economics of climate change – the Stern review. Cambridge, England: Cambridge University Press.

Tainter, J. A. (1990). *The Collapse of Complex Societie.s* Cambridge: Cambridge University Press.

Tainter, J.A., Allen, T., & Hoekstra, T. (2006). Energy tranformations and post-normal science. *Energy*, *31*, 44-58.

Takahashi, T., (2004). Cortisol levels and time discounting of monetary gains in humans. *Neuroreport*, *15*(13), 2145-2147Tainter, J. (1988). *The Collapse of complex societies*. Cambridge, UK: Cambridge University Press.

Takahashi, T., Ikeda, K., Hasegawa, T., (2007). A hyperbolic decay of subjective probability of obtaining delayed rewards. *Behavior and Brain Function*, *3*, 52.

Tilman, D., Reich, P., & Knops, J.M.H. (2006). Biodiversity and ecosystem stability in a decade-long grassland experiment. *Nature*, *441*, 629-632.

Tyner, G., Constanza, R., & Fowler, R. (1988). The net energy yield of nuclear power. *Energy*, *13*(1), 73-81.

Ulgiati, S. (2001). A comprehensive energy and economic assessment of biofuels: when green is not enough. *Critical Reviews in Plant Sciences*, *20*(1), 71-106.

Van Gool, W. (1985). *Energy and time in the economic and physical sciences*. Elsevier.

Vorosmarty, C.J., Green, P., Salisbury, J., & Lammers, R.B. (2000). Global water resources: vulnerability from climate change and population growth. *Science*, *289*, 284-288.

Webber, M., & King, C. (2008). The Water intensity of the plugged-in automotive economy. *Environmental Science & Technology*, *42*(12), 4305-4311.

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*(2), 131-151.

Wilson, M., & Daly, M. (2004). Do pretty women inspire men to devalue the future? *Proc Biol Sci.* 2004 May 7; 271(Suppl 4): S177–S179.

Wise, R., Role of brain dopamine in food reward and reinforcement, *Phil. Trans. R. Soc. B*, 29 July 2006, 361/1471 1149-1158.

Wolff, J. (2008). Marginal cost for North American natural gas production. (2008). *Credit suisse equity research*.

Wolff, R. (2009, July 16). *Peak oil and peak capitalism*. Retrieved from http://www.theoildrum.com/node/5245

Zhuang, J., Liang, Z., Lin, T., & de Guzman, F. (2007). *Theory and practice in the choice of social discount rate for cost-benefit analysis: a survey*. Asian Development Bank, Manila, Phillipines.