Applying Time to Energy Analysis

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Is a BTU today worth more or less than a BTU ten years from now? It's seemingly an easy question. A BTU will heat one pound of water one degree whether its 2010, 2020, or 2100. And, in a world of entropy where the easiest and best quality energy sources (generally) get used up first, one unit of energy should increase in value over time, as its ability to accomplish work becomes more valuable to society as time progresses. However this is solely a physical perspective, one that ignores biology of time preference. Once humans with finite lifespans and cultures with sunk costs enter the picture, a BTU today, *behaviorally*, becomes worth more than one in the future. This fact has pretty big implications for biophysical analysis of energy alternatives, which will be explored below.

This post is an adaptation (first a shrinking, then an expansion) of Chapter 5 of my dissertation, which was co-authored with my colleague Hannes Kunz.

Executive Summary

Biological organisms, including human societies both with and without market systems, discount distant outputs over those available at the present time based on risks associated with an uncertain future. As the timing of inputs and outputs varies greatly depending on the type of energy, there is a strong case to incorporate time when assessing energy alternatives. For example, the energy output from solar panels or wind power engines, where most investment happens before they begin producing, may need to be assessed differently when compared to most fossil fuel extraction technologies, where a large portion of the energy output comes much sooner, and a larger (relative) portion of inputs is applied during the extraction process, and not upfront. Thus fossil fuels, particularly oil and natural gas, in addition to having energy quality advantages (cost, storability, transportability, etc.) over many renewable technologies, also have a 'temporal advantage' after accounting for human behavioral preference for current consumption/return.

ENERGY GAIN

The concept of 'energy gain' - how much energy remains for an organism or process after the energy to procure it has been accounted for - has been a popular topic on this website for many years. Here is a short list of essays/analyses previously on TOD explaining that biophysical concept:

A Net Energy Parable - Why EROI Is Important?
Ten Fundamental Principles of Net Energy Analysis
At $100 Oil What Can the Scientist Say to the Investor?

The Energy Efficiency of Energy Procurement Systems
The True Value of Energy is the Net Energy

Basically, over time, natural selection has optimized towards the most efficient methods for energy capture, transformation, and consumption. In order to survive, each organism needs to procure at least as much energy as it consumes (Lotka 1922pdf, Odum 1973). For example, lions that 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, a lion needs 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. Irrespective of dollar costs, which are often distorted due to inflation, subsidies, debt induced affordability, and myriad other economic distortions, 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 consists of transitions in energy quantity and quality. Generally, the value of any energy transformation process to society is proportional to the amount of surplus energy it can produce beyond what it needs for self-replication. (Hannon) 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).

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	19.8	Kubiszewski 2008
Solar Photovoltaic	6-8	Battisti 2005
Corn based ethanol	0.8-1.6	Farrel, 2005

Examples of EROI Values/Studies -Table from Murphy (2010)

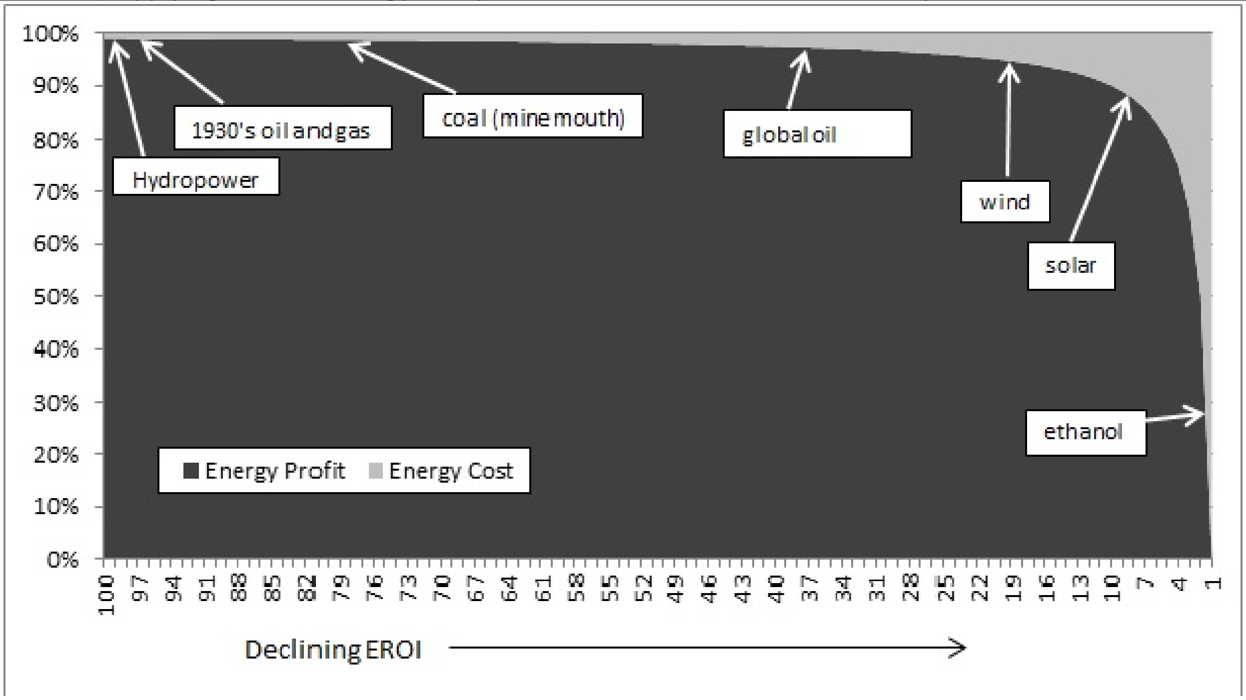

Figure 1 - Net Energy Cliff (based on Hagens, Mearns, Balogh etc. based on work of many before)

As fossil fuels become more difficult to extract and thus are more expensive, a move from higher to lower energy gain fuels may have important implications for both how our societies are powered, and structured. As illustrated in Figure 1, declines in aggregate EROI either mean more energy is required by the energy sector (light blue) leaving less energy available for other areas of an economy (the dark blue), or that energy is less affordable for aggregate society in general. Declines in amounts of surplus energy have been linked to collapses of animal societies and historical human civilizations. (Tainter)

ENERGY AND TIME

Energy gain, though prominent, is but one of several factors that defines the value of energy to an organism or utility of an energy system. Consider time for instance. Energy output occuring after the energy input can be disadvantageous to an organism. If the lion in the above example can't access the calories from the gazelle until 1 week after the kill, this would pose a problem. Similarly, energy that is accessed beyond ones lifetime wouldn't be benefial to an individual. Thus *time* beoomes an integral variable in the energy gain calculus. At the intersection of time and energy is power. In physics, power is defined as the rate at which energy is converted into work. Some have suggested that power (or energy transformed per unit time) has been a primary driver of both human and nonhuman biological systems (Hall, Lotka). 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)

As explained here, there is a tradeoff between the energy return on *energy* invested, and the energy return on *time* invested. We see this tradeoff between energy and time in many areas. Airplanes get us to our destination much faster than cars or trains, but are less energy efficient per unit distance travelled per passenger. Similarly, people speed at 70 mph so as to arrive faster while driving 55mph would use less energy. In an economic sense, 'power' is maximized in our current culture via digital wealth, as the instantaneous survival/status benefits of burning/using energy have physical limits whereas digital markers do not.

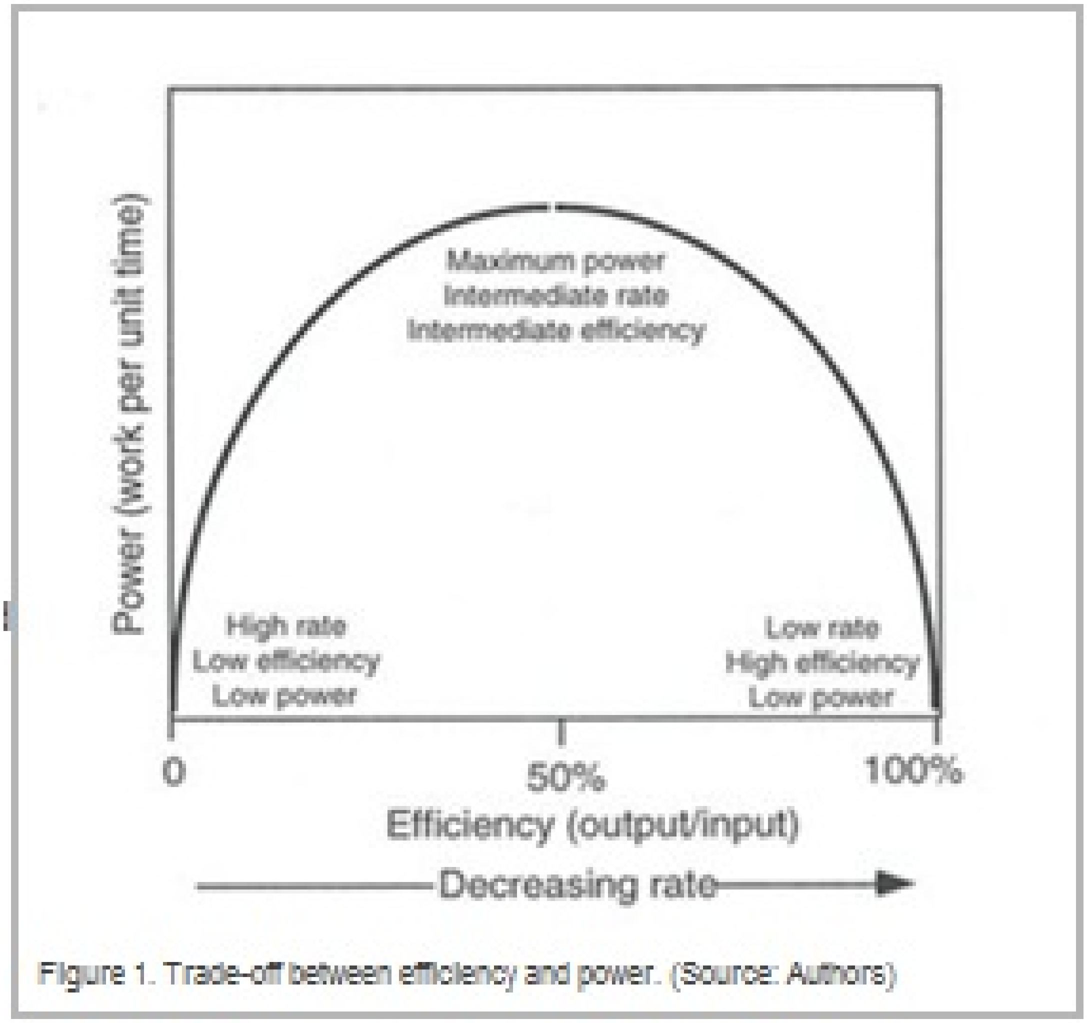

Figure 2 - Maximum Power schematic (source)

The above graphic depicts the Maximum Power Principle. At zero efficiency power is also zero because no work is being done. Also, at maximum efficiency, power again is zero because to achieve maximum efficiency one would have to run processes reversibly, which for thermodynamic systems means infinitely slowly. Therefore the rate of doing work goes to zero. It is at some intermediate efficiency (where one is “wasting” a large percentage of the energy) that power is maximized. (The implication that 'waste' has been evolutionarily selected for, is also referenced in the field of biology (Zhahavi)).

Discount Rates and Time

(*For a colorful overview on the evolutionary origins of steep discount rates, see Climate Change, Sabre Tooth Tooth Tigers, and Devaluing the Future*)

Humans prefer present over future consumption in most situations (Frederick). The extent of this preference is measured using a *discount rate* - the rate at which an 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). Most organisms in nature do not live as long as their biological potential. Thus in most animals, emotions and instincts drive behaviors with short-term goals, such as eating, drinking, resource acquisition and mating. These automatic behaviors, rooted in older brain regions like the limbic system, are inherently myopic - e.g. while they are active the future carries little weight (Berns]. 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, (other than for situations when the immediate needs of the test subjects have just been satisfied) (Bateson). However, humans differ from other animals in that we can worry about and/or experience immediate pleasure from considering delayed consequences. As such, our emotional systems also have the potential to motivate behaviors with long-term positive trade-offs. 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.

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), 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, require sufficient excess returns to justify the risks of waiting for the arrival of future benefits.

Decades of research in multiple disciplines have indicated that discounting of the future is also prevalent in human societies. In meta-analyses on individual discount rates, 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% (Frederick). Research on long term discount rates associated with durable goods purchases and energy saving devices show extremely high discounting (>100% annualized) (Hausman, Ruderman). Though some degree of time preference is present in all of us, certain cultures and demographics exhibit even 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 (Chabris). Unsurprisingly, people under stress exhibit higher preference for immediate versus delayed consumption. (Takahashi).

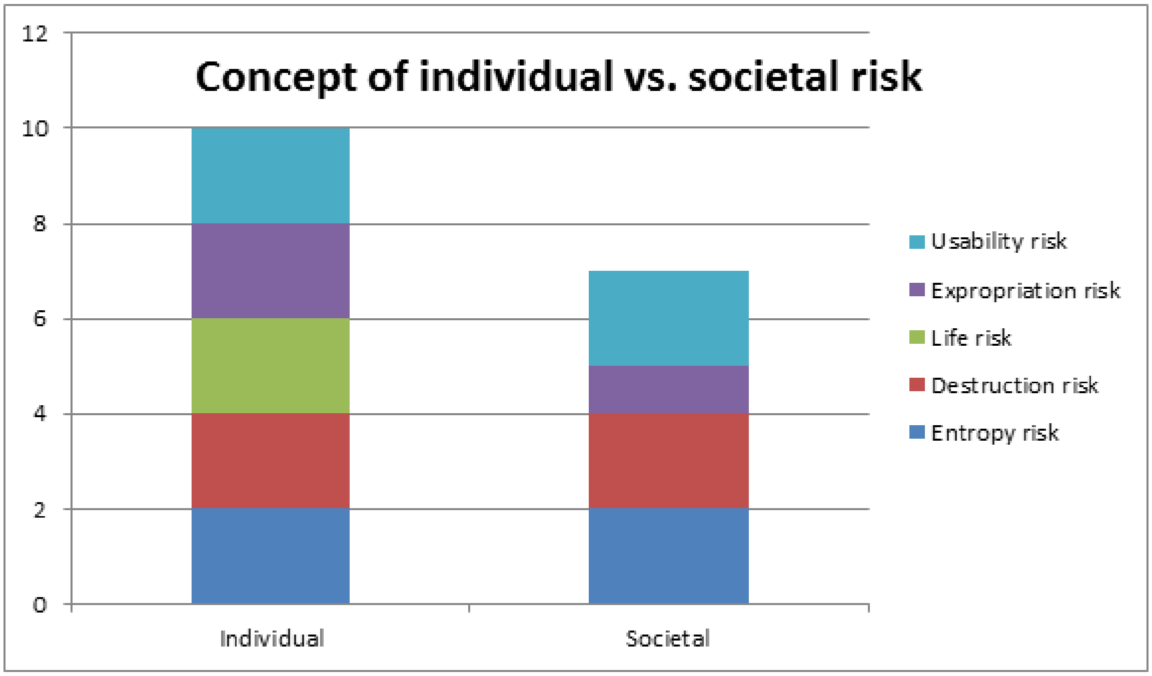

Figure 3 - Conceptual graphic of societal vs. individual risks

It is clear that human decision-making cannot be accurately predicted without reference to social context. 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. 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 considerable 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). Many environmentalists assert that social discount rates should be less than 3% 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). 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. 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). The United States Office of Management and Budget has applied a 7% discount rate towards civic projects in each year since 1992. This post 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.

Time and Financial Risk

Because a dollar received today is considered more valuable than one received in the future, time is also an important factor in financial and economic decisions. First, in a modern (and historical) leveraged banking systems where money supply increases over time without regard to underlying physical assets, 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.

Time Value of Energy

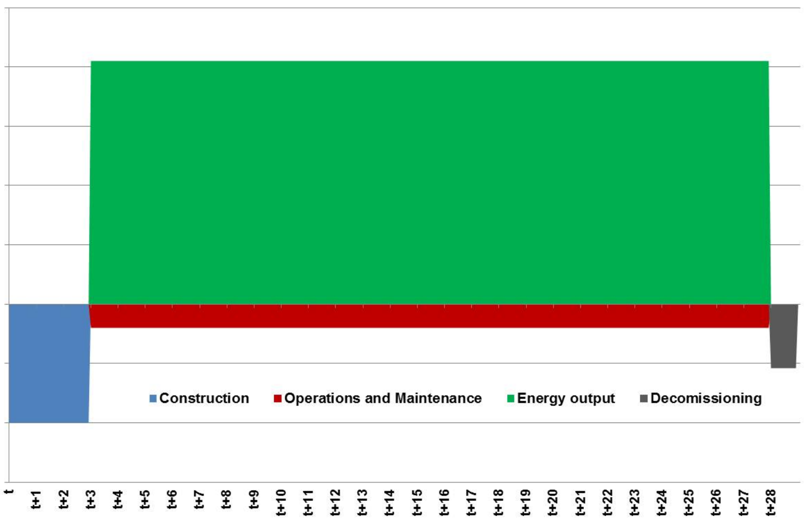

Figure 4 - Sample Input/Output Timeline for an Energy Technology

EROI is represented as a static integer representing the ratio of energy output to energy expense for the life of an energy technology, simply Eout/Ein. This can be represented graphically using an energy flow diagram such as in Figure 4. 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+n dealing with decommissioning and waste removal (the grey).

In traditional net energy analysis, an energy input or output is treated the same regardless 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 moment will change as a function of economic, institutional, and technological factors. In this equation, time becomes an important variable.

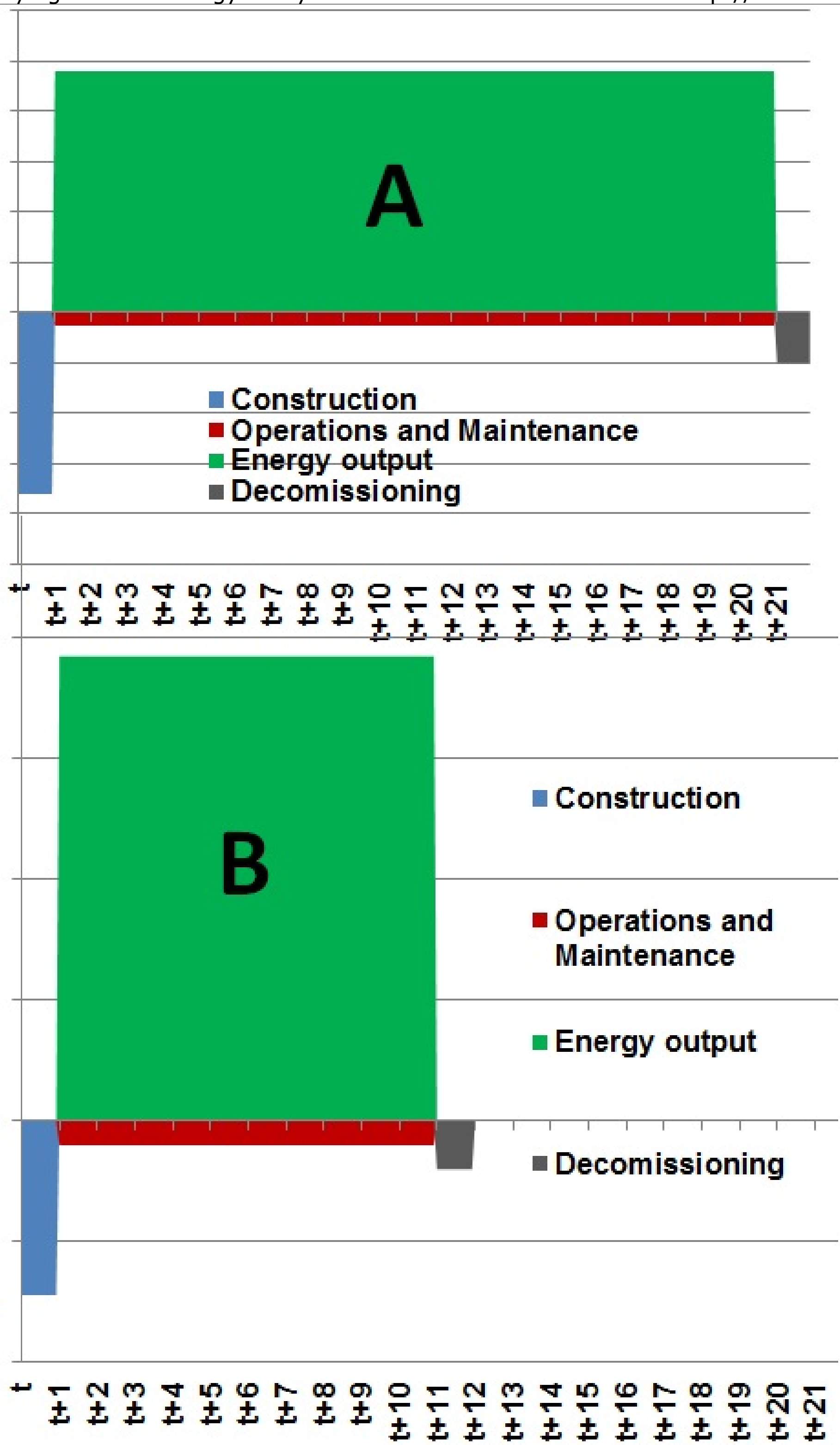

Figure 5 - Equivalent EROI over 10 years or 20 years

A comparison of two graphs for energy extraction might show the relevance of time. Both depictions in Figure 5 represent technologies that offer exactly the same energy return (EROI), but the first 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 is comparable, it is quite obvious that societies prefer the technology that delivers more faster (the graph on the bottom), though standard EROI analyses treats them the same.

Net energy statistics and Time

The following section applies the above theoretical framework to several real energy examples including 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.

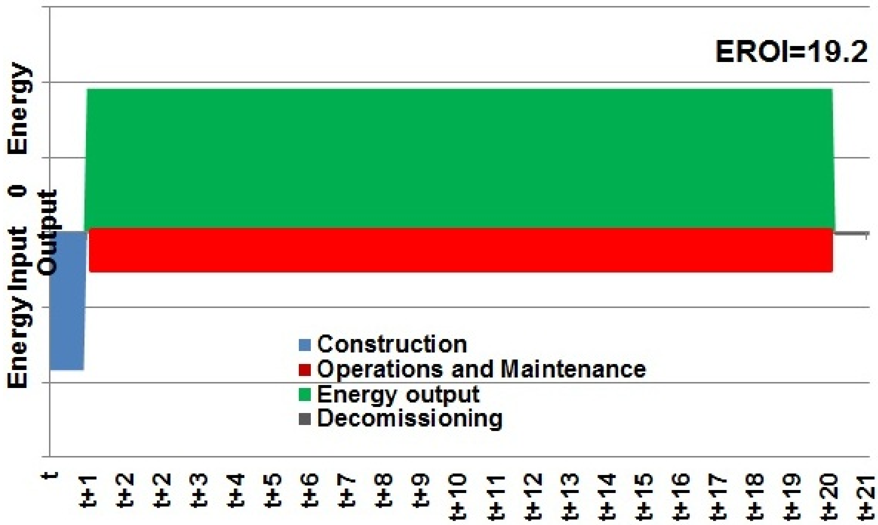

Figure 6 - Wind turbine energy input/output timeline - undiscounted

When introducing net present value to net energy gain or EROI calculations, both inputs and outputs are discounted more depending on how far in the future they occur. Figure 6 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. *(**The average EROI in a recent meta-analysis for operational turbines was 19.8:1 (Kubiszewski)(pdf). One of the wind farms studied was representative of age, size and EROI (19.2:1) from the meta-analysis, and we 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.)*

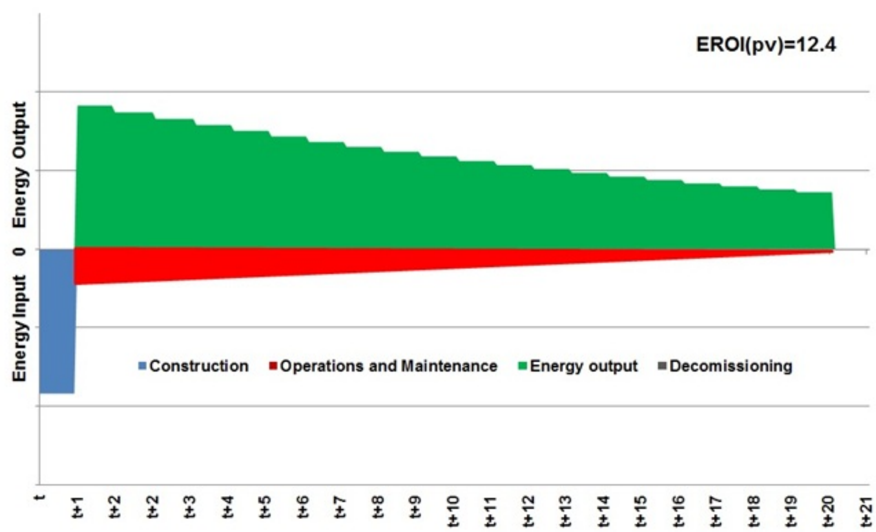

Figure 7 -Wind EROI discounted at 5%

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 high expectations for 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 and 'effective' EROI of 12.4 after discounting.

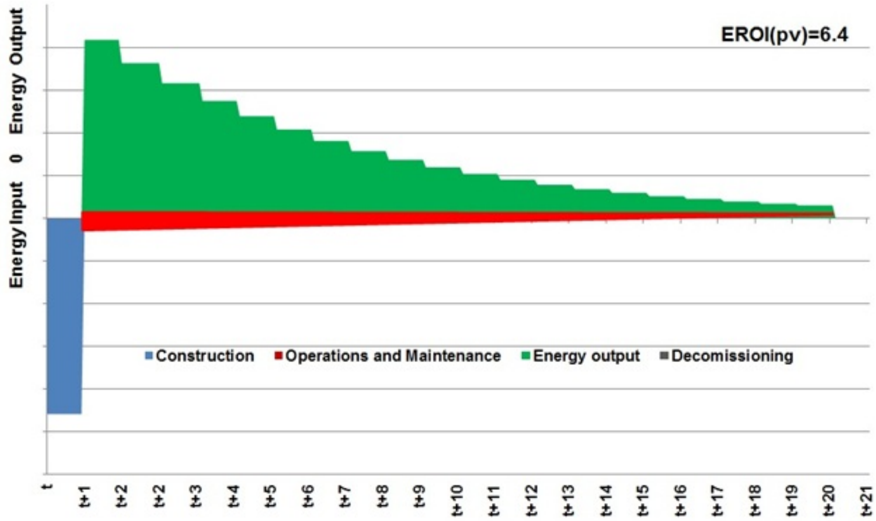

Figure 8 - Wind discounted at 15%

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.

The graphical depiction shown in figures 6-8 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 closely 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.

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

Figure 9 -Wind and Solar nominal EROI discounted at various rates

The above table shows the impact of discounting for typical wind and solar photovoltaic net energy. As most of the energy input required for wind turbines and solar panels is in the pre-production phase, the future (non-discounted) flow rates present an almost flat production profile as the ‘average’ energy return is modeled as a pro-forma. With such an energy input/output schematic, the future energy gain associated with the turbines has decreasing value to 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 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 because of the timing of energy inputs and the shape of the energy outputs. Though there are large upfront costs, a larger percentage of energy input occurs 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. Most shale gas wells are 90% depleted within 18 months (Wolff). 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).

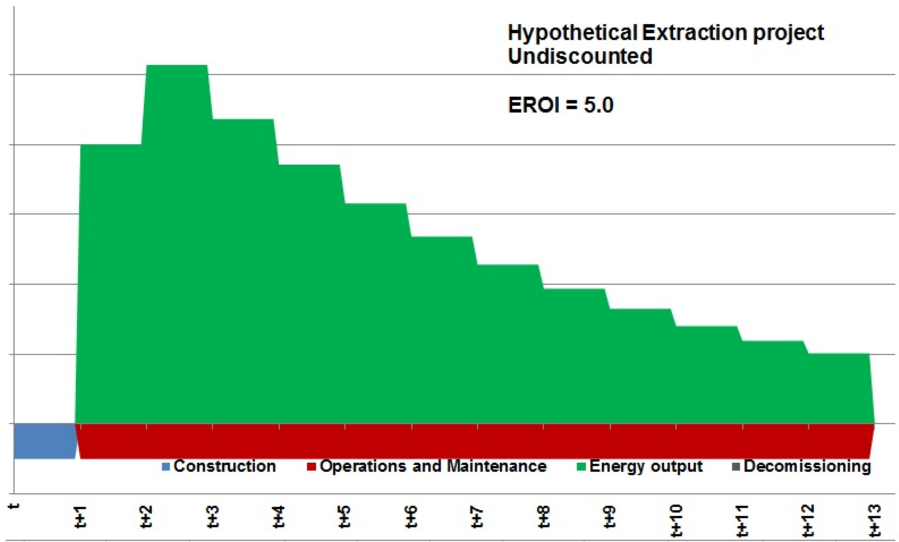

Figure 10a - Extraction technology - undiscounted

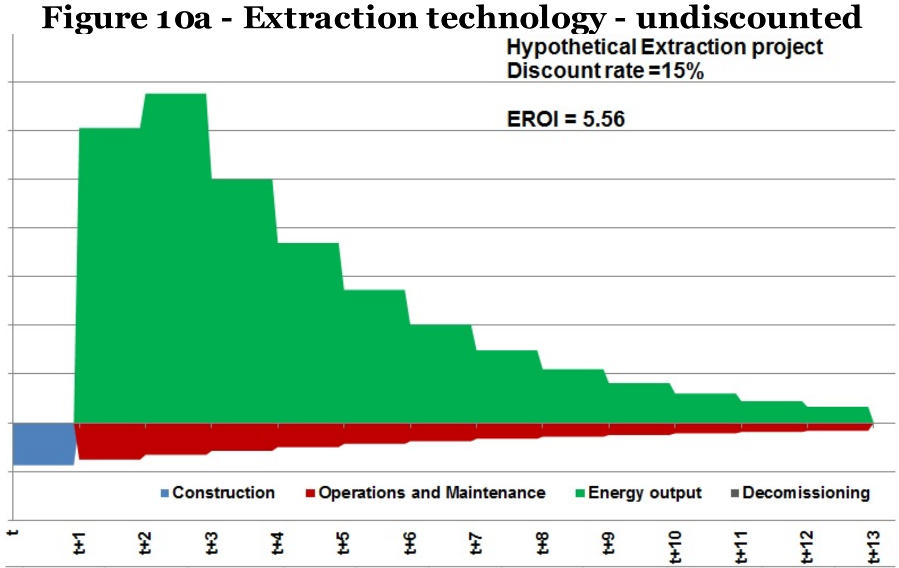

Figure 10b - Extraction technology - discounted at 15%

Figure 10a shows a hypothetical 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 (10b -lower half of graph), the discounted EROI is actually slightly higher than undiscounted EROI.

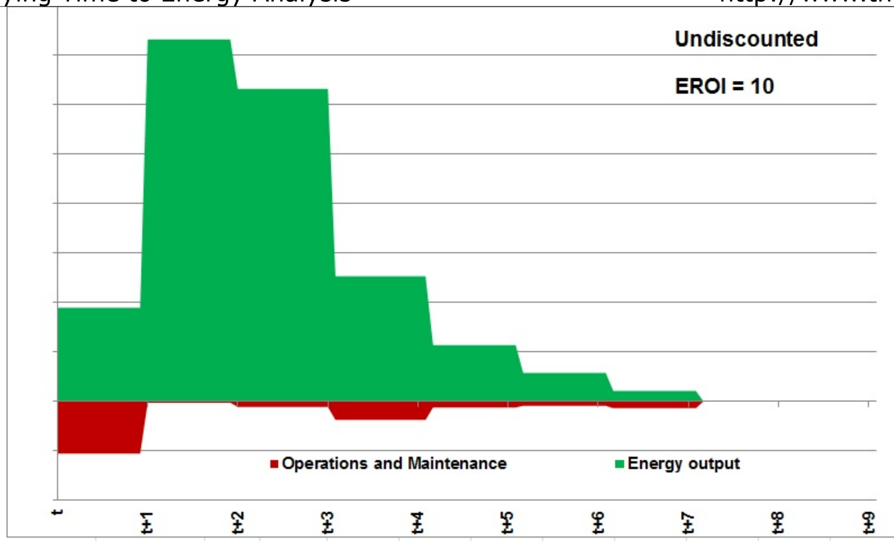

Figure 11a - Leon Herbert Field energy input/output - undiscounted

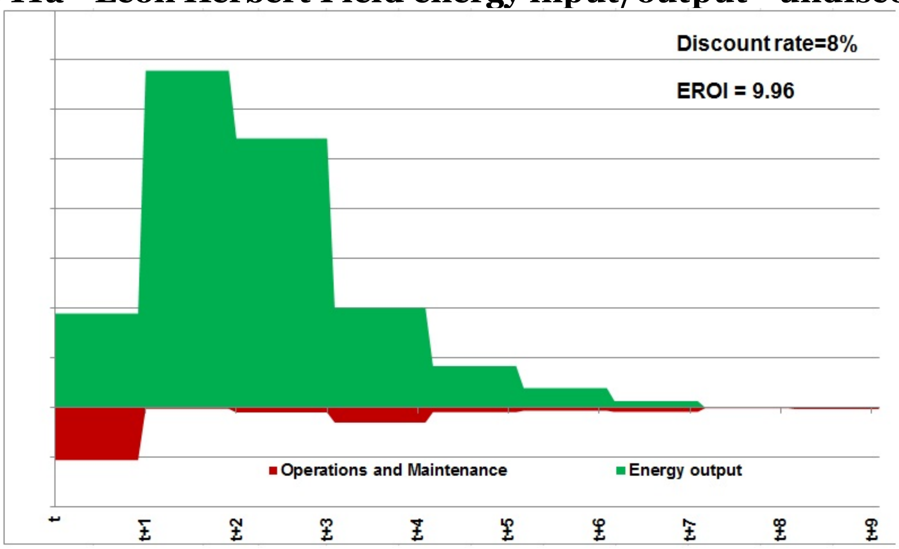

Figure 11b - Leon Herbert Field energy input/output - discounted at 8%

Figures 11a and 11b were modeled using an actual oil and gas field (Leon Herbert) in Louisiana which had completed its (seven year) production life cycle. We assumed it had an EROI of 10 which is the natural gas average based on the literature (Source. We took real dollar expenditures for the drilling, completion, work-over (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 - personal communications). We then discounted both the inputs (energy) and outputs (barrels of oil/mmbtu gas in dollar terms) to arrive at the temporal input/output diagrams shown. 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. Applying a discount rate to the energy flows changed the NPV only slightly (10 down to 9.96).

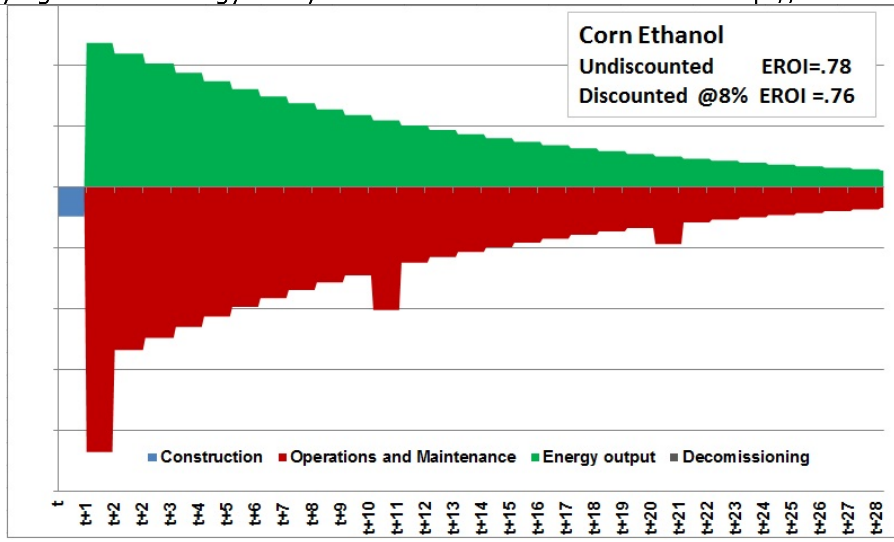

Figure 12 - Corn Ethanol energy input/output timeline

Similar to the wind and oil calculations, we used real data on corn production and ethanol processing to establish time horizons for energy inputs for each component in percentage terms of the total (Patzek, Pimentel). Since corn is grown and processed each year, most of the energy inputs, other than the capital equipment, (which we assumed needed replacement every 10 years), occur at roughly the same time as the energy output (the ethanol). Out of the many corn ethanol energy balance studies, the Patzek model showing sub-unity EROI was chosen because it had the widest boundaries. The above dynamic - that discounting doesn't really impact corn ethanol returns, is robust irrespective of the nominal EROI figure used.

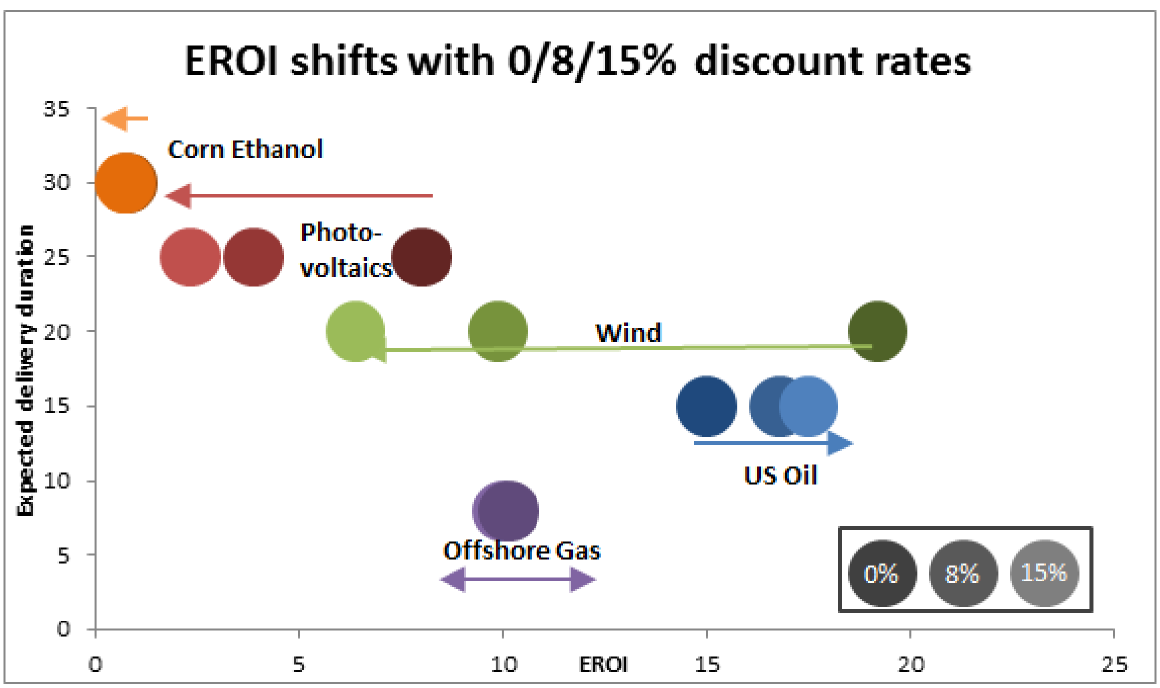

Figure 13 - EROI Time shifts after discounting

Figure 13 provides a clear indication that time discounting implies significant changes in present values of various energy technologies. The x-axis represents 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 typical timing of oil flows (a near term peak followed by long tail), discounting actually slightly increases the nominal EROI for oil.

Conclusion

In summary, this analysis has shown that regardless of financial incentives, people discount the future to varying degrees. The timing of energy inputs and outputs has an important impact on their 'time-adjusted EROI' - in effect a combination of future energy flows and human time preference. 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 may partially explain why many renewable energy technologies show a very slow adoption rate in situations that do not include subsidies.

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 with higher discount rates will likely handicap longer energy duration investments, as the cost of time will outweigh the value of delayed energy gains. It is interesting to note that the initial government/central bank response to the financial crisis - buying/guaranteeing sovereign debt has depressed what would normally have been an increase in interest rates - these artificially low rates make long duration energy assets (wind and solar) look better than fossil fuel generation options - something that would quickly reverse if rates went to market clearing levels sans government support.

Also in the context of general limits to growth, it is worth noting the evidence that stressed individuals 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 their immediate consumption. There is a tradeoff between energy costs and time costs that depending on the context will 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.

Final thoughts

Is a BTU today worth more or less than a BTU ten years from now?

The answer depends - on if you're a robot, or a human. As much as we'd like a biophysical statistic as an alternative to distortions in monetary analysis, it is clear that nominal EROI is not a strictly physical measure and its meaning changes when we introduce the biology of decisionmaking.

The above essay does not attempt to answer the longstanding debate on what discount rate is appropriate for energy projects and comparisons, but rather shows that some positive discount rate is inherently present in biological organisms, and therefore the net energy from human plans and projects will be affected, for better or worse, by the timing of the inputs and outputs. Like many aspects of sustainability /new paradigm discussions, there exists a dichotomy between the *prescriptive and the normative - what should be versus what is*. Ultimately, discount rates for future energy deliverables may differ between individuals or entire societies, but it seems important that the timing of energy flows is a variable that needs considering. As society potentially moves away from the maximization of money, the timing of energy flows may matter a great deal.

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