MEASURING NET ENERGY (EROI) AND BREAK EVEN PRICE (LCOE)

FOR AN WHOLE ENERGY BUSINESS

AS A COMPLEX ENVIRONMENTAL SYSTEM

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ABSTRACT

Not having a well defined scientific measure relating money with the physical resources used by the economy has made it hard to access its environmental impacts. The critical difference in the method used here is the assumption that if other information is not available the impacts associated with money are treated as “average” rather than as “zero”. That allows measurement of the physical energy costs of whole business systems using a rigorous, repeatable and improvable method. Businesses rely on a whole system of complementary parts: technologies, field and office operations, management, land, financing and a network of other commercial and environmental services. Our first assumption would be that each dollar of economic services required would need about average amounts of energy. A typical life cycle impact assessment (LCA) totals the accountable resource inputs for the primary technologies used and their production chains. What that omits are the various unaccountable physical inputs required for the other costs of business and operations. Paying for the know-how and labor of human services, the commerce and the other technology employed in business, all have impacts as much a part of the costs of producing a product as the principle technologies, and with this method can now be included in a physical measure of the business choices involved. To define the boundary of the system for energy input/output analysis we use the same financial costs and returns used to define the economic boundary of a business, and show how to begin a comparison of the energy and financial budgets for the business as a whole system interacting with a changing environment.

A "system energy assessment" (SEA) method was developed to calibrate hybrid measures and define a standard measure of energy required for business choices, including corrections for combining direct and hybrid measures that somewhat overlap. The example of a wind farm is used to illustrate. The analysis charts the sensitivity of energy return on energy invested (EROI) and the levelized price of energy (LCOE) to uncertainty in input values and environmental factors. How the business decisions, market pricing of products and government planning and policy might be guided by the information is briefly discussed.

Keywords: energy return, internal rate of return, net energy, energy economics, system boundaries

1. INTRODUCTION

The basic scientific problem of how to define complex environmental systems, like businesses, and construct comprehensive and comparable measures of them as individual entities, is approached here from a new direction, illustrated by the example of the development of a wind farm. Complex environmental systems are treated as consisting of everything needed to develop and operate them as an individual whole, i.e. as a 'cell' of organization and independent "working unit" in the environment, such as a business making its own choices on how to operate. The operational method for assessing such "whole systems" is to devise an "exhaustive search strategy" for its parts and features, such as to identify it's total energy or financial budgets. For this case study we consider the life cycle of a single model business, using all the business costs and revenue during the life cycle of its wind turbines as the boundary of the system.

"Energy return on energy investment" (EROI) is equal to total energy output divided by total energy input for an energy system [1, 2]. Having measures for the energy costs and returns of whole business systems would allow both government and business to better understand the resource development opportunities as well as risk exposures to resource use penalties such as embodied carbon and potential use conflicts with others in the present environment of rapid change in energy potentials, demands and technology. There is a large and diverse literature linking energy resources and technology to economic growth and economic returns [1, 3-6]. However, the existing literature does not use standardized methods for making direct measures for whole business systems except for their finances. EROI is often calculated using process life cycle assessment (LCA) data, limited to measures of the physical inputs and outputs of the primary working technology (e.g. wind turbines) of a business.

The first task here is to describe the method of "system energy assessment" (SEA) for measuring total energy use for a model business system and the EROI for the business life cycle. As we developed it, that calibrated measure of whole system energy use could be widely employed as a standard for measuring the energy costs of economic processes or choices. Then to better understand the whole business as an environmental system we relate the energy use model with financial models one would customarily expect for a large scale investment project. How the combined view of total physical and financial system behavior and impacts might result in more informed choices about environmental risks and opportunities is briefly discussed.

The financial boundary of a business choice is not the only way to define the natural boundary of the physical working system it identifies. It is the common one people use, though, and a good reference point for inquiring about what things not being paid for are being left out. In studying natural systems one always starts with one way of identifying the parts, and then looking for what's left out, and finding ways to account for it. Things that might be left out of system boundary drawn by finances include free environmental services such as sun, wind and soil, or the free resource of community supports and knowledge from social or industry networks. Also often left out are the costs of beginning and shutting down a business as needed for investments and disposal or developing its resources and replacing its resources or structures when exhausted, the seed and life-cycling costs. The end of every search defines a boundary of what was found with the strategy and resources available for the search, and is then taken to represent the natural boundary if the effort when it leads to persistently diminishing returns.

The project we study is a conceptual Texas Wind Farm, a fairly simple business comparable to many others. Other classic energy and economy studies have used somewhat similar methods of combining direct and indirect energy uses for informative insight into the range of energy intensities of the major industrial sectors of the economy, such as performed by Costanza *[4, 5]*. There are also EROI and energy intensity calculations of oil, gas, and coal industries, there exist sector-wide economic and energy data from various federal agencies [4, 5, 7]. However, these methodologies do not entirely match and they provide no guidance for assessing individual businesses or business models. For renewable energy systems (e.g. wind power) there also does not appear to be economic sector enabling data to be separated from the rest of the economy. Wind energy EROI data using LCA energy cost estimates was surveyed by Kubiszewski et al. (2009) (see figure 3 and §2.1 below) is partly comparable to our results.

Figure 1 shows results from Costanza and Herendeen (1984) [5] regraphed in relation to the average economic energy intensity found for the US economy in 1963 and for industries by share of GDP for each sector [5]. The results are presented here to illustrate the range of diversity to be expected. From Figure 1, the most consistent patterns appear to be that 1) producer sectors tend to have quite varied btu/$ of product, 2) energy sectors generally earned income using less energy than others and 3) consumer sectors are close to average.

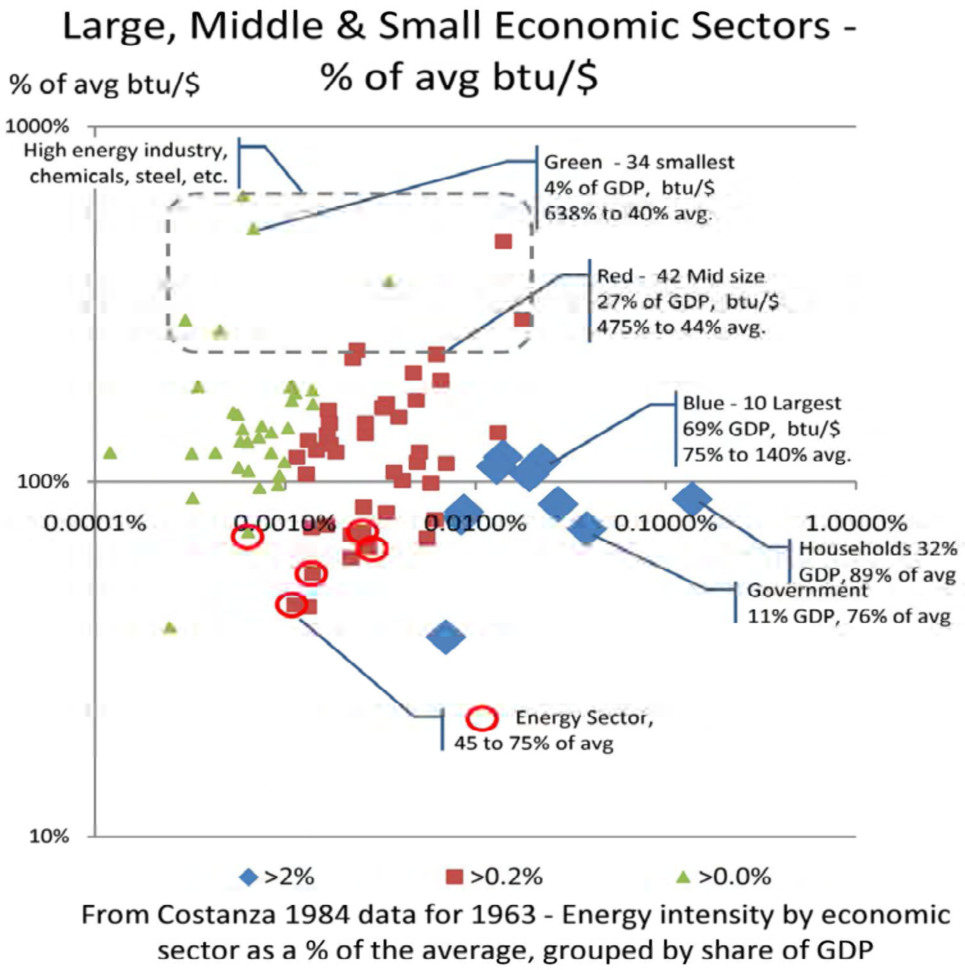

Figure 1. A comparison of the energy intensity (btu/$) and scale of industry sectors of the 1963 US economy shows consumers are near average and energy sectors are below average (data from [5]).

Thus, the Costanza and Herendeen (1984) data support the logical conclusion that consumers actually pay for and consume all producer products such that it is reasonable to count consumer spending as having average energy intensity. As producer inputs are more likely to be far from average they warrant more careful study (possibly using the Costanza findings as a reference). In the absence of study, however, it remains a better 'null hypothesis' to consider producer inputs as having average intensity rather than zero. Consequently, the general assumption for the SEA method is to treat all costs as having average impact intensity unless a more accurate figure is available (see Section 2). When estimates cannot be made then the omission is indicated, as consistent with a methodology of identifying everything within the system that cannot be directly accounted for.

To both test the completeness of the SEA model against financial standards and show it's use along side conventional financial analysis, a net present value assessment is done. From the wind project financial life cycle a breakeven price (levelized cost of electricity. or LCOE) and internal rate of return (IRR) are estimated. For simplicity, at this point no direct connection between the energy analysis and market variables, such as an event analysis for resource price changes, was hypothesized. Because the energy model used here is derived importantly from the financial assumptions, the apparent implications of energy returns (EROI) on financial parameters (LCOE) would simply reflect the assumptions being made. Future studies of operating wind energy businesses and others of related types (e.g. coal power, photovoltaics, biofuels, etc.) will provide better measures of market value of EROI. Still, just learning to study a whole business in relation to its physical and financial environments together, the main object of the study, provides rich insight into the nature of the business of providing energy.

1.1 Measurement Methods

System Energy Assessment (SEA) originates from a more general "total environmental assessment" (TEA) method [8], based on using exploratory assessment to investigate the development, boundaries and behaviors of complex environmental systems. SEA is reduced to measure only energy consumption and production. For SEA the LCA measure for mechanical energy use for technologies during their life cycle is used as a starting point, defining the smallest operating "whole working unit" of the business energy system (Figure 2). Then proxy measures are developed for accessing the energy used by the various whole working units of the business system not yet accounted for. The costs of those operations are initially assumed equal per dollar to the economy wide average. Larger circles of working relationships are considered until no more essential working parts can be found, as partly confirmed by finding that the effort of looking further has less and less effect on the total, diminishing returns. That is then considered to be the natural limit of accountability for the system.

It is not surprising that that natural boundary of accountability turns out to be to count everything the business spends money on, but it's nice to see it demonstrated. In this case the search process examines the whole nested hierarchy of independent working units of the business. Economies contain may kinds of nested systems as whole independent working parts of others, and awareness of how such whole systems work nested within the environment of larger scale systems is part of the task of interpreting the results too. Once the search to add up the energy used to bring the product to market is complete that defines the limits of the system with respect to the open market shared with others. The result is a scientific measure for energy use that directly corresponds to an independent individual working unit of both the business and natural environment.

Finding boundaries starting from accountable parts

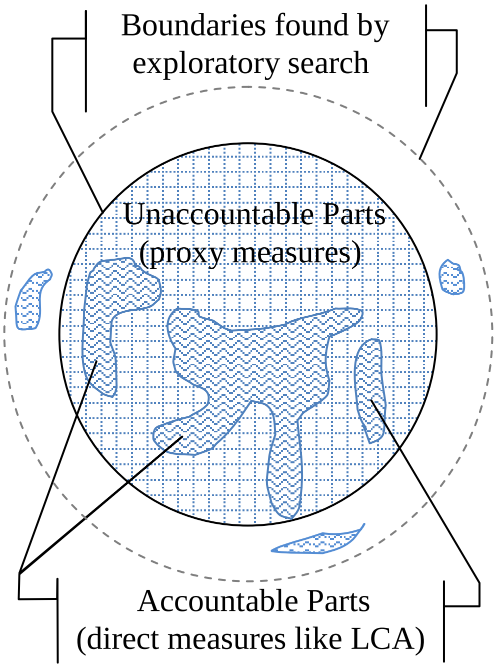

Figure 2. *Whole system measures*, Using exhaustive search to approximate an account for all working parts, and combine direct and proxy measures for parts for a physical measure and reference to individual whole complex systems.

What is uniquely different about physical measures of whole environmental systems is that they need to include both calibrated estimates of what is directly accountable and of what's left out, so to the limits of the search, no part of the system is left unaccounted for. For the economic fuel uses required to deliver business products the largest often overlooked category is the energy used by employees in spending their incomes earned by doing the work of the business. It's finding reasonable values for all identified missing information about the working physical system that having a search strategy for making measurements allows. What is then possible, when the assessment of the system includes values for both its directly and indirectly accountable parts, is for the physical measure to closely fit the natural boundary of the whole physical system, as a glove to a hand. Then it becomes possible to use the measure for pointing to physical system in all its natural complexity as the subject of discussion, as a whole and along with its organization, as greater than its parts. That leads to an understanding of its internal and external relationships quite different than found from treating measures as only data points to be related by rules of statistics. That is the step that then allows this study of complex systems to become physical science rather than statistical science.

Though LCA analysis uses quite well defined analytical boundaries for measuring the resources used by technology and their impacts, but there has previously been no standard way to define the analytical boundaries for business systems employing technologies. Absent a measures of the “totals” of energy use for making products, it has also not been possible to define measures of “net differences” or “net changes” between totals. That prevents completely meaningful comparison of energy costs for different technologies or industries or for personal or policy choices. The industry habit has been to the precise information available as the totals, like the indentified fuel uses counted by LCA, though they’re not the totals. Here we use that same data source, as a well defined starting point for looking for the other energy uses that need to be considered part of the same system, to capture all energy uses being left out.

LCAi is our term for the energy intensity identified for the principal technology (see Section 2). The SEA method then adds to that a series of estimates of energy use for everything else, the energy uses not individually accountable. That includes employing people, business services and other technologies. The procedure is to categorize each type of spending as above or below average energy intensity compared to the world average. So, in Table 2, the values of Ti and Ei are the energy intensity of technology and economic energy costs, respectively, relative to the world average. The data is then aggregated by the natural boundaries of the working units being studied. Thus, by combining accountable parts with implied shares of the whole for unaccountable ones, “bottom-up” LCA data is combined with “top-down” economic data, organized by the natural units of organization for the business system.

In looking for the correct boundary for measuring EROI the SEA assessment begins with the smallest whole operating unit needed to produce the product, the principle technology. It then proceeds up the organizational chain of the business to include the larger organizational scales of the business that operate the principle technology, the unaccountable economic costs of the technology itself, then adding the field operations, and the business and corporate levels of operation, as diagrammed in Figure 3, corresponding to:

LCAi: the direct energy consumed to deliver and operate a technology measured by LCA
SEA0: adding the indirect energy needed to deliver and operate the technology
SEA1: adding the total energy needed for field operations,
SEA2: adding the total energy needed for managing business, and
SEA3: adding the total energy needed for corporate management of the business.

Combining Technology & Economic energy use for Nested Scales of Business Operations

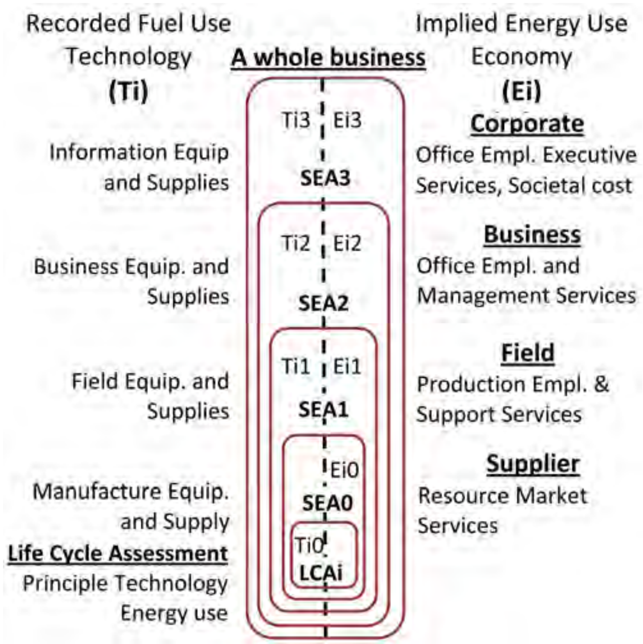

Figure 3 - *System Energy Assessment (SEA)* Directly accounted energy uses by technology and unaccountable energy for economic processes are aggregated by the nested scales of whole business operating units, to the market point of sale.

Combining direct and proxy measures & correcting for the overlap

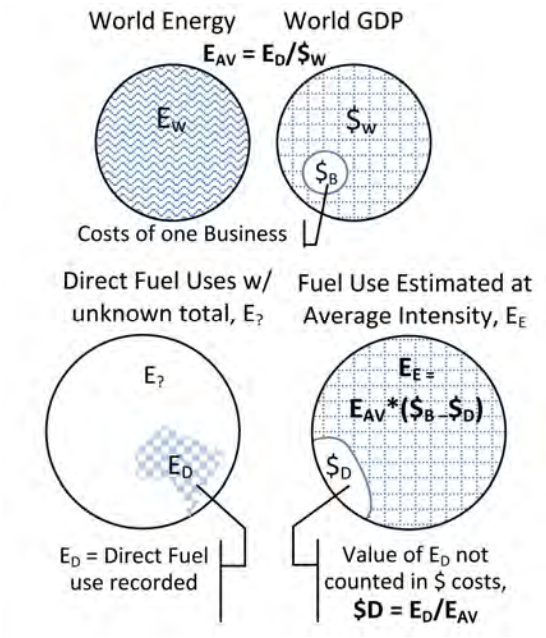

Figure 4 *Correcting for overlap* The economic costs of operations are converted to energy using the average energy use per dollar for the economy as a whole, after removing the average value-added for the directly accounted fuel uses.

2. ANALYSIS DESCRIPTION AND BACKGROUND ASSUMPTIONS

LCAi corresponds to the direct energy consumed in manufacturing, installing, operating and disposing the primary technology (e.g. wind turbine) an its necessary facilities. The important part of Figure 3 is how the information about the energy being used is divided between accountable technological and unaccountable economic processes. The one difficult concept is that economic energy it takes to deliver a purchase of fuels is not included in the energy value of the fuel itself, because the purchase price goes to people not to nature. The energy of the fuel itself comes from nature without a dollar cost, then used by technology and accounted for as a technology fuel use. Money, on the other hand, is paid only to people for either ownership rights or labor, and not to nature or technology. Maintaining a clear separation between those two to sources of information is what separates the physical energy accounts and economic energy accounts. It takes a little getting used to, but they need to remain separate because they somewhat overlap and a correction is needed.

The physical energy connection between people and technology is that people operate the technology, exerting a tiny amount of their physical energy to machines in providing "know how" and “control” for operating them. They will only agree do that if they are paid, and are free to use their earnings to consume products on the open market. What they use money for goes unrecorded generally, but their money will all be used for either spending or savings, and be received by someone else, in a closed system of accounts. In that way money and energy are similar, as conserved units accountable as being subtracted one place only if also added another place.

The recorded energy used for a technology, its energy intensity (Ti), can be added up in energy units, but the indirectly purchased energy used for business and human services, its energy intensity (Ei), needs to be converted to energy units. The simple means of doing that is to treat the energy value of all money spent as average for the whole economy or as average for its specific type of use. Employee spending may have one average and the purchasing of buildings or technology may have another average, for example, and estimates for them can be refined. The starting point is the global energy intensity of money E_{AV} (Equation 5), a ratio that has declined steadily over time at a fairly regular decay rate. A weighting factor Tii is used to adjust the average energy intensity E_{AV} to estimate technology fuel uses from its purchase prices.

$$\text{Ti} = \text{recorded energy} \quad \text{or} \quad \text{Ti} = \text{Tii}*E_{AV}*\$B \tag{1}$$

There would be a problem with simply adding the two measures, technology and economic energy use, though they seem like they derive from quite different activities. Combining them without adjustment would usually be more accurate than failing to count either one, but an economic estimate of the recorded fuel uses would be part of the economic energy use estimate. A simple explanation of the problem is that if you added up the economic energy use for all the money spent in GDP as average, and combined it with all the physical energy used by all the technology in the economy, you’d get two measures of exactly the same thing, and double the total actual energy use. So to correct for that “double count” an estimate needs to be made for the amount of money to subtract from the economic costs to remove the part representing the estimate of recorded technology energy use (Figure 4). It uses the average value-added of energy as the inverse of the average energy intensity of money. $VA_E = 1/E_{AV}$

Economic intensity corrected $Ei = Eii{*}E_{AV}{*}(\$_B - \$_D)$ (2)

Value-added for fuel use $\$D = Ti{*}VA_E = Ti/E_{AV}$ (2.1)

The economic value of the technological energy use is subtracted from the economic costs (Eqation 2), treated as proportional to the average use of energy by the weighting factor Eii. This simply subtracts the average value-added for the technology energy uses from the costs to be assigned adjusted average energy use. For average business costs, if you happened, by some chance, to have direct measures for 100% of the energy uses, then those would have a value-added equal to the total cost, and so a zero energy value would be assigned to the spending. Thus, statistically at least, that seems to perfectly eliminate the overlap from the two ways of measuring the same thing, while making up for the major omission from the directly recorded fuel uses of all the energy used in economic activity supporting them. As this approach is further studied other rules of thumb or databases of standard values may be developed, but at least this demonstrates the principle involved for this particular issue, as well as the general approach to assigning and adjusting proxy measure values for other things, as noted in the footnotes for Table 2, for example.

The total energy input (E_{in}) consumed by the whole system of the wind farm development is composed of the sum of the energy inputs for each business unit. The energy input requirements for each j^{th} business unit are calculated as shown, where Ti_i and Ei_i are the various recorded technology (kWh) and estimated economic energy use (kWh) inputs, respectively, using equations 1 and 2:

$$\boldsymbol{SEA_j = Ti_j \sum (Ti_i + Ei_i)} \tag{3}$$

SEA_j is the total energy input required to operate the j^{th} business unit and $dSEA_j$ is the incremental addition for that business unit from the prior one. The total energy used by the whole system, the wind farm and its energy using supports, is:

$$\boldsymbol{E_{in} = LCAi + \sum_{j=0}^{N} dSEA_j} \text{ - taking } \mathbf{N} \text{ to the natural limit} \tag{4}$$

2.1 Background on LCAi EROI for Wind Turbines

Kubiszewski et al. (2009) performed a meta-analysis to summarize the net energy of wind turbines based upon a suite of previous studies of 114 calculated values for EROI (see Figure 5) [9]. There is tremendous variation in the EROI values, over an order of magnitude with values reported at over 100. The average EROI for all studies was reported at 25.2 although the average for operational LCAs (those based upon actual performance of a turbine) was lower at 19.8.

Much of the variation in EROI is likely due to differences in the boundaries of the analyses. Kubiszewski et al. (2009) did distinguish the LCAs by indicating the parts of the life cycle (e.g. manufacturing, operation, business, decommissioning, etc.) considered. However, no pattern emerges to show what one would expect such as for LCAs including more parts of the life cycle having lower EROI. Lacking common standards for how to identify the boundaries of physical systems results in measures of their operation that are not comparable. The most common omission appears to be the impacts of the economic costs of business, including employee consumption and the use of many kinds of specialized business services for which no resource use accounting is possible [10, 11].

The data in Kubiszewski et al. (2009) show that 85% of the values for EROI for wind turbines are below 40, and this value may be considered an effective upper-bound to the estimates. There was also some pattern of differences between studies using the input–output analysis and those using process analysis. The former showed an average EROI of 12 while latter an average EROI of 24, attributed to how process analysis may involve a greater degree of subjective decisions[9]. Given accurate measures of the energy output (i.e. wind power generation) and successively more accurate measures of energy inputs as more costs are identified, the apparent conclusion from Kubiszewski et al. (2009) is that most methods of estimating EROI do not count most of the energy inputs

2.2 Initial Energy Flow Analysis of Wind – Nominal LCA

To supplement the EROI values discussed in the previous section, a nominal LCA for a Vestas onshore 2.0 MW wind turbine was used for this analysis [12]. The Vestas example provides some nominal characteristics upon which to base the analysis (e.g. the amount of each energy type used during manufacturing, capacity factor, etc.) [12]. In Section 2.3 this Vestas LCA information is combined with financial cost data using the Job and Economic Development Impact (JEDI) wind farm model [13] from the National Renewable Energy Laboratory (NREL) to calculate additional energy inputs required in a wind farm development. JEDI allows the user to choose a state for the wind development to indicate local taxes and impacts. Texas was chosen as the state.

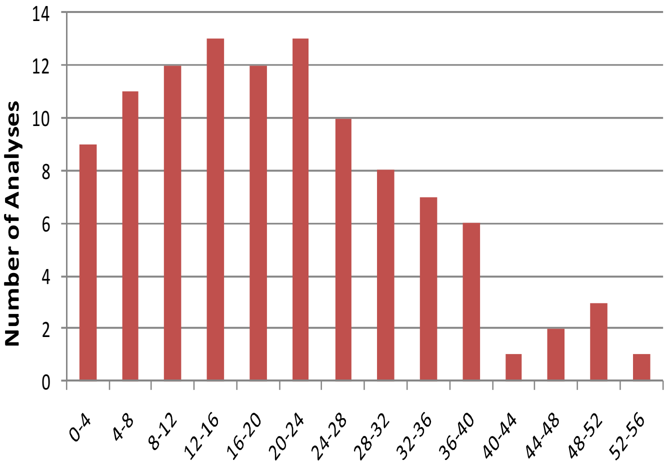

Figure 5. The frequency distribution of EROI for wind turbines as studied in [9] shows an unusually wide range, and may indicate the general lack of standards to follow.

Fuel/Resource	Energy Consumed (MJ)	Energy Consumed (kWh equiv.)	Fuel cost ($/GJ)
Hard coal	2,215,289	615,358	$2.34
Crude oil	6,036,268	1,676,741	$12.23
Lignite (brown coal)	445,086	123,635	$1.90
Natural Gas	1,618,085	449,468	$6.21
Nuclear Power	392,131	108,925	$21.65
Straw	0	0	$0.95
Wood	0	0	$0.95
Other Biomass	57,918	16,088	$0.95
Hydropower	2,286,277	635,077	$21.65
Wind	37,184	10,329	$0.95
		TOTAL Cost of fuels ($) =	**$147,960**
		Btu/$ of fuel purchase	83,777
Ratio of Btu/$ for fuel purchase to economy average Btu/$			11.0

Table 1. The quantity of fuel consumed for a Vestas 2.0MW turbine has an energy content of LCAi = 13,100,000 MJ costing approximately $150,000. Data on energy consumed are from reference [12].

The EROI estimate from the process analysis LCA for the Vestas 2.0 MW turbine is 31, with the turbine generating 5,634,000 kWh/yr at a capacity factor of just over 32% for 20 years. In total 13,100,000 MJ (3,640,000 kWh equivalent) of energy was calculated to be consumed for manufacturing and installing the turbine and transmission components (see Table 1). Thus, an EROI of 31 is used as the LCAi a starting value for incorporating the energy requirements of business operational units during a wind project.

In order to compare calculated EROI values with standard energy financial descriptors such as LCOE, a monetary cost value must be associated with each. Thus, the corresponding financial expenditure for the fuels is $147,960 as calculated by multiplying a market value of energy to each form of energy consumed during the wind turbine life cycle (see Table 1).

2.3 Energy Flow Analysis of Wind - SEA

Section 1.1 and Figure 3 discussed how the System Energy Assessment estimate starts with the least inclusive and most precisely calculated component: the LCAi measure of direct accountable energy used for producing and operating the primary technology. All the other costs are aggregated by the business unit to which they apply and assigned a technical and economic energy intensity for their costs as outlined by Equations 2-4 in Section 2.

Because no accurate data exist regarding the energy intensity of each input to the wind farm, the SEA calculation of this paper assumes the average energy intensity of the global economy to assign energy consumption to the monetary expenditures of the analyzed wind project. The average energy intensity of the economy, based upon power purchasing parity (PPP), was calculated using data from the United States Energy Information Administration (EIA) of the Department of Energy. The world gross domestic product (GDP-PPP) in 2006 was $59,939 billion ($2005) while consuming 472 quads of primary energy [14]. These values correspond to an energy intensity of 7,630 Btu/$ in 2006. Because the energy output of a wind turbine is electricity, we convert this value to equivalent units of electricity, or kWh (see Equation 5). There are well known differences in market value to different fuels for a given task (e.g. oil, coal, electricity, etc.), but the analysis of this paper is considered preliminary and does not make a distinction between energy inputs and outputs of different kinds [3, 6, 7].

$$\text{World Energy Intensity:} = \frac{\left({}^{472\text{e}15\ \text{Btu}}\!/_{59{,}939\text{e}9\ \$2006}\right)}{3{,}410\ \text{Btu/kWh}} \qquad (5.0)$$

$$= {}^{7{,}630\ \text{Btu}/\$2006}\!/_{3{,}410\ \text{Btu/kWh}} = 2.24\ \ \text{kWh}/\$2006 \qquad (5.1)$$

The historic decay rate of 1.24%/yr projected to 2020, the mid-point of the project, yields

$$2.24 * (1 - .0124)^{14} = 1883$$

Table 2, below presents the merging of recorded technology fuel uses and economic costs converted into energy units for each scale of working business unit by the SEA method. The starting point is the fuel use data from the VESTAS Onshore project taken from Table 1, converted to kWh per kW installed capacity. This value for LCAi is usually what is thought of as the total energy use of the business for the product produced. What we find here is it's about 25% of the total, resulting in a 400% difference in EROI. The various other energy use values are derived using the budget information from the NREL JEDI wind farm model. Contingency cost estimates for minor items omitted from the JEDI budget and an estimated of the share of the national tax burden attributable to profits in proportion to their share of GDP are added. Fuel use budget items are converted to energy based on the purchase price of oil, and other expenses are generally treated as consuming energy at the world average rate. We did not use the evidence from Costanza (Figure 1) that the products of different industries have different characteristic energy intensities. The footnotes to the table explain more of the details.

Monetary costs in Table 2 are expressed as annual costs per kW installed capacity too, with onetime costs distributed over the 20 year operating lifetime of the project. The weighting factors, Tii for mechanical energy and Eii for economic intensities are assigned, and the economic intensities adjusted for implied overlap with the technology energy use intensities using equations 1-3. A value of *Eii* = 1 means that the energy intensity of purchases are assumed to be average. The value of *Tii* = 12.7 (i.e. 12.7 times average) is derived from Table 1 for the mechanical energy used by purchased fuels for other uses by the wind developer, as for the fuel oil purchases. The mechanical energy intensity of technology purchases, Tii=.03 (i.e. 3% of average) is derived using Table 1 energy values and the JEDI capital costs, indicating that the purchase cost of fuels found by LCA is a very small part of the price of delivering and operating the technology. That indicates why there is more economic energy use implied by the cost than mechanical energy use.

Whole business system SEA Input/Output Table

Output per kW capacity	Value	LCOE	kWh	profit	Global Average Ei/$
Electricity Sales	$281.70[1]	$0.10	2,817	31.1%	1883[2]

	Inputs per kW installed capacity per year	Cost $B $	% Avg Tii	Fuels Ti kWh	LCA val $D	%Avg Eii	Econ Ei kWh	SEA Ei kWh	Range est.	Accum. EROI
LCA	Energy for principle technology		0.03[3]	90.89				90.89	0.2[5]	30.99
SEA0	Aannualized Tech & Equip. CostCost	$76.14	0.03	4.54	$2.41	1.0[4]	138.9	143.40	0.2	
	Annualized Phys Plant Cost	$25.48	0.03	0.00	$0.00	1.0	48.0	47.98	0.2	
	Subtot& Accum Range	101.62						191.38	0.200	14.72
SEA1	Field technology	$11.60	0.03	0.69	$0.37	1.0	21.2	21.85	0.2	
	Field fuels	$0.17	12.07[3]	3.93	$2.09	1.0	-3.6	0.33	0.2	
	Field Business Services	$0.20[6]	-			1.0	0.4	0.38	0.3	
	Field employees	$2.75	-			1.0	5.2	5.18	0.3	
	Subtot& Accum Range	14.72						27.73	0.220	12.86
SEA2	Business technology	$0.25[6]	0.03	0.01	$0.01	1.0	0.5	0.47	0.5	
	Biz Fuels	$0.35	12.07	7.87	$4.18	1.0	-7.2	0.65	0.5	
	Operating Business services	$1.50[6]	-			1.0	2.8	2.82	0.5	
	Business salaries	$1.54	-			1.0	2.9	2.90	0.5	
	Subtot& Accum Range	3.64						6.85	0.381	12.47
SEA3	Corporate technology	$0.10[6]	0.03	0.01	$0.00	1.0	0.2	0.19	0.5	
	Corporate Fuels	$0.05[6]	12.07	1.14	$0.60	1.0	-1.0	0.09	0.5	
	Corporate operations & services	$0.50[6]	-			1.0	0.9	0.94	0.3	
	Invest Land & Local Taxes	$13.99				1.0	26.3	26.34	0.2	
	Invest Fees & Insur	$3.41				1.0	6.4	6.43	0.2	
3.1	Finance cost estimate	$20.32				1.0	38.3	38.28	0.2	
3.2	Cost of Government estimate	$48.61[7]				1.0	91.5	91.5	0.2	
3.2	Production tax credit	-$0.21[8]				0.0	0.0	0.00	0	
	Subtot& Accum Range	75.79						143.13	0.201	7.63
Project Totals & accum. Ei and EROI		**$195.77**					**1885**[9]	**369.08**	**0.177**	**7.63**

Table 2. **Whole business system SEA I/O Table**. Recorded fuel uses from LCA studies are added to the economic fuel uses also required. Each SEA level, 0 to 3, represents a whole physical working unit on which to base a whole system accounting. The subtotals indicate what is likely, that the largest energy use levels are closer to the physical work, and that accumulative EROI's decline less as more of the hidden energy uses are found.

1. The value of the electricity sales is based on an assumed capacity factor of 32.16% and sales price
2. Average economic energy intensity from EIA data = 1.883kWh/$ declining at 1.24%/yr.
3. Tii is the weight factor for the technology fuel use per dollar, .03 for the ratio of LCA measured fuel use to technology costs, also used to estimate fuel use for other technology, 12.07 for purchased fuels based on cost of fuel oil.
4. A weight factor, Eii, to assign to spending on products or services with different intensities, such as found by Costanza ranging from 75% of average to 600% of average, see Figure 2, left equal the average, 100%, for lack of study here.
5. Range estimates here are conceptual, set as +/- 20% for most items and +/-50% for less clear ones, mostly to show that large measurement uncertainty is a small factor in the analysis.
6. Some business costs were given contingency estimates to include the categories here omitted from the JEDI model.
7. Taxes on net revenue are estimated to measure the energy costs of government for maintaining the business environment, at the rate of 39% for the ratio of total local, state and federal government costs to GDP.
8. The production tax credit considered in the financial model is assigned an Eii of zero, considered as a transfer payment from other tax payers and not contributing energy to the business.
9. The accumulative EROI of 7.63 implies an average economic intensity for the 20 year costs of 1885 Wh/$, virtually identical to the world average used of 1883 Wh/$.

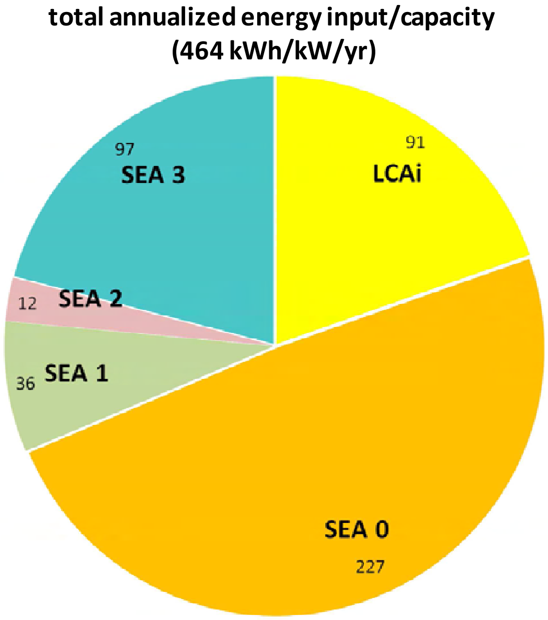

Figure 6. The annualized 20 yr whole system energy use by scale of business unit, LCAi to SEA3. The LCAi energy use (direct fuel use for making and recycling the primary technology) and the economic energy needed to do that, SEA0, account for 65% of the total.

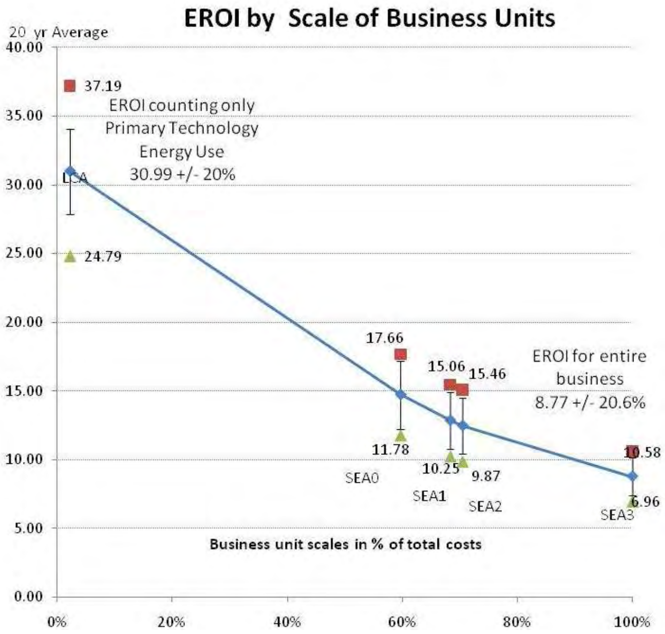

Figure 7. The EROI decreases as additional, business units are considered to the point of sale. The asymptotic trend helps confirm the accounting for all costs.

2.4 Cost and Energy Flow Analysis

The results of Section 2.3 discuss all energy inputs as annualized averages. However, the 2/3 of the energy inputs are required for the manufacturing, constructing and operating (LCAi and SEA0) the wind turbine. This section presents a comparison of monetary and energetic costs each year of the wind project.

The Wind Energy Finance Model of the National Renewable Energy Laboratory (NREL) [15] was used to estimate the annual cash flows and costs relating to the corresponding energy inputs discussed in Section 2.3. Capital and operating costs obtained from the NREL JEDI model, and used in the SEA analysis, were input to the Wind Energy Finance Model. A 3% inflation rate was assumed. A typical capital structure was adopted, with 20% equity (with a target IRR of 6% - equal to the assumed discount rate) and 80% debt (with a 6.8% interest rate on the debt financing). By constraining the IRR at each SEA level of analysis to be equal to the discount rate, a breakeven cash flow and LCOE is produced relating to profit for the wind farm. Because this present analysis is focused upon energy flows, this “no profit” scenario assures an equal comparison of EROI and LCOE for each business unit. The production tax credit of 2.1 cents per kWh for ten years (escalated at the assumed rate of inflation) was also included and the results categorized into the business units discussed in Section 1.1 and 2.3.

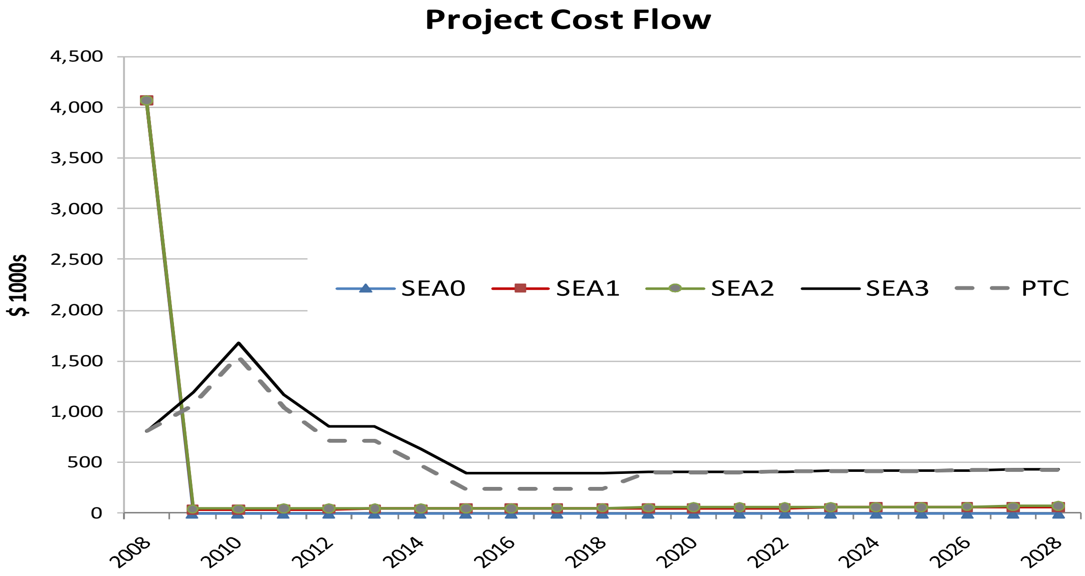

Figure 8. Except for SEA3 which uses financing, the project monetary costs for each scale of business organization are dominated in the first year with the high first costs of development.

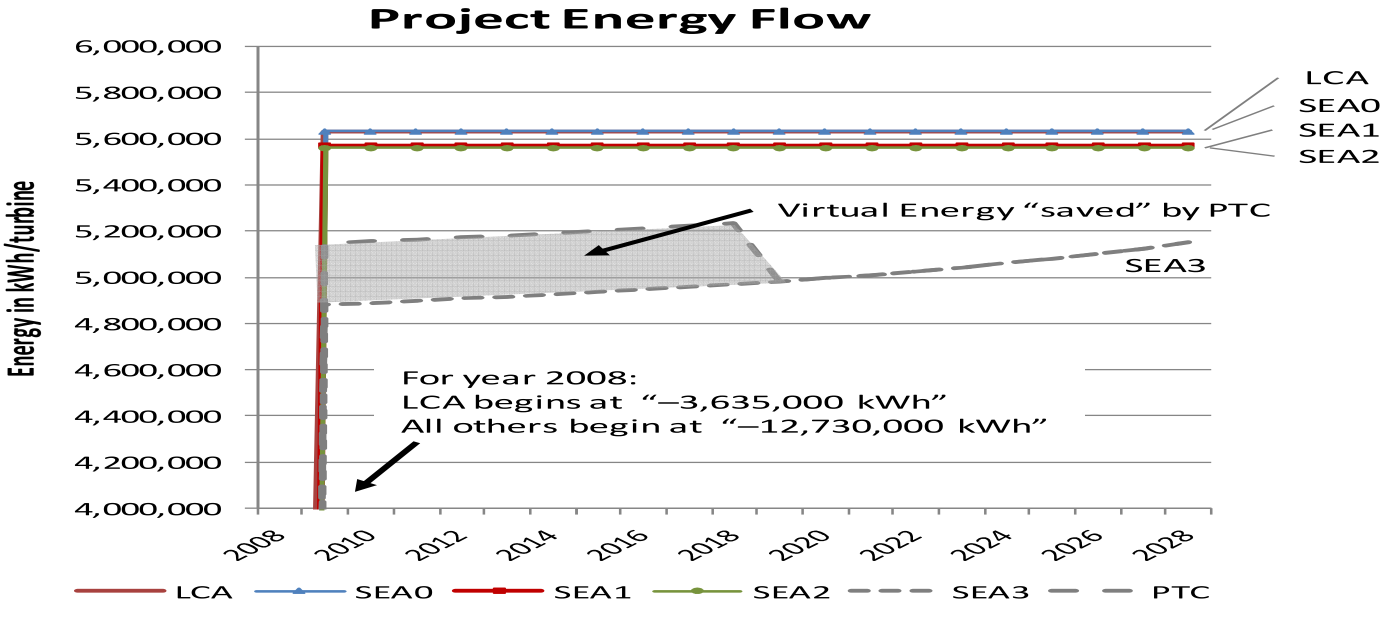

Figure 9. Energy flow (kWh/turbine) for the different business scales.

The majority of monetary costs (~65%) occur in the first year to pay for the turbine and construction (see Figure 8). The finance costs shown in SEA3 assume 80% debt financing with the initial cost in the first year at

20% of first costs of development. The effect of the wind Production Tax Credit (PTC) is shown as a dotted line reducing the financial costs for the first 10 years. Of course, the PTC does not change the wind turbine energy inputs or output (see Figure 9), nor consequently the EROI

For each nested level of the business units and monetary cost flows in Figure 8, Figure 9 shows the energy flow per year (in kWh equivalent per turbine per year) for the analyzed wind turbine. Positive values represent electricity output from the turbine. The vast majority of the energy expenditure occurs in the first year to manufacture and install the turbine, just as in the cost flow. The fuel consumption counted by LCA for the turbine manufacturing and construction are shown in Table 1 and total 13,100,000 MJ, or 3,635,000 kWh equivalent. The turbine then generates 5,634,000 kWh/yr. The field and business operations (SEA0 through SEA2) then consume less than 100,000 kWh/turbine/yr.. Once the energy associated with paying for the finance costs (interest on loan) and taxes (e.g. government services) are taken into account, another 400,000 – 700,000 kWh are consumed per year (SEA3).

The gray area shows the “virtual energy grant” of 265,000 kWh/yr that might be associated with the PTC. However, a reduction in business tax does not represent a decrease in energy use for the government or the wind project, but a shift of tax burdens to others. From a comparison of Figures 8 and 9 there are other questions raised about how financing costs should or should not be counted as actual real time energy uses. This comparison bears study, and a preliminary discussion now follows.

2.5 Cost and Energy Flow Analysis

Model Inputs with distributions:

1. *fuel costs energy intensity*. We used a ratio of about 11:1 (but Phil used 10.2:1) for Btu/$ for fuels : Btu/$ for overall economy. We could use a uniform range of 9:1 to 12:1.
2. *Installed turbine costs ($/kW):* this will come from NREL and LBNL publications. Our previous nominal value was $2000/kW installed.
3. *Fixed/variable O&M costs ($/kW):* Jay has suggested from the DOE report that a log-normal distribution is feasible
    a. *Labor costs ($/kW):* This I guess is a subset of O&M costs (see cell C72 in JEDI worksheet). Not sure if this is a different value or not. We could assume the mean value is that in the JEDI project spreadsheet. Maybe std. dev. of 10%. Any ideas Jay? Forget this?
        i. cell C72 for lumped labor
        ii. cells C69 for field (SEA 1)

        iii. cells C70 and C71 business (SEA 2)

4. *Capacity factor:* normal distribution as suggested by Jay form DOE documents
5. *Inflation (?)*: should we have different inflation rates? Or just a constant 0%, or 3%?
6. *Discount rate (?):* Jay – I say we keep the same discount rate for LCOE and NPV calculations. But, should we put in different rates?

Model Outputs we want to track:

1. *LCOE ($/MWh)*
    a. This is cell H30 on each of the cash flow worksheets when the NPV of the project is zero (or cell b48 is zero for a 20-yr project).
2. *EROI – 3 ways*
    a. Phil's simple EROI (by simple I mean without discounting). This is currently cells N22:R22 (I think) on "Project LCA & SEA" worksheet.
    b. Carey's EROI using discounting for 20-yr project for each SEA step.
        i. This is cells B10, B22, B34, B46, B58, B70, B82, and B94 on worksheet "EnergyFlows_ConstantEE"
        ii. This is cells B10, B22, B34, B46, B58, B70, B82, and B94 on worksheet "EnergyFlows_DecayingEE"
3. *Phil's % of business costs:* this is cells N15 to R 15 in "Project LCA & SEA" worksheet. – PHIL: I THINK YOU NEED TO UPDATE THIS TO YOUR 'NEW' SEA METHOD (AS OF 7/21/10).
4. *IRR for cash flows*
    a. This is cell B51 on each of the cash flow worksheets. By making NPV = 0, I guess we have by definition made this IRR = 0% until there are taxes factored in?
5. *IRR for 20-yr energy flows – 2 ways*
        i. This is cells B11, B23, B35, B47, B59, B71, B83, and B95 on worksheet "EnergyFlows_ConstantEE"
        ii. This is cells B11, B23, B35, B47, B59, B71, B83, and B95 on worksheet "EnergyFlows_DecayingEE"

Jay's comments on distributions for inputs from looking over DOE documents on wind:

For O&M, it looks like we are presently assuming $0 variable O&M and $19.8/kW. The 2008 EERE-DOE Annual Report (Fig. 26) provides a distribution for variable O&M, but not for fixed O&M. Glancing at the variable O&M distribution, it has a standard deviation of about $13/MWh for projects completed in 2006 and 2007. The mean is also about $13/MWh. The range is very big, since one value is about $40/MWh. We can't really use a normal distribution, or we'd get a lot of negative O&M costs in the simulation. I'd suggest using a lognormal distribution. It is truncated, so it won't provide values below $0/kW. Thus, in @RISK, you could use the function =RiskLognorm2(2.75,0.688)I just played around with the function until I got a distribution with a mean of 19.8, and 3 times the mean is around the upper limit of a 95% confidence interval around the mean.

For the capacity factor, the 2008 EERE-DOE Annual Report (Fig. 24) provides a distribution for projects completed in 2007 across the U.S. The standard deviation is about 0.12, or 12%. I think a normal distribution is a reasonable assumption. Thus, in @RISK, you could use the function (referring to the sheet in the spreadsheet with the capacity factor for the mean value) =RiskNormal('LCOE_SEA3.2-PTC'!B7,.12)

For installed costs, the 2008 EERE-DOE Annual Report (Fig. 21) provides a distribution for projects completed in 2008 across the U.S. The standard deviation is about $365/MW. I think a normal distribution is a reasonable assumption. Thus, in @RISK, you could use the function (referring to the sheet in the spreadsheet with the capacity factor for the mean value) =RiskNormal('LCOE_SEA3.2-PTC'!B13,730). The 730 would be for a 2 MW project (2MW*$365/MW).

3. RESULTS AND DISCUSSION

The main conclusion of the present analysis is that by calibrating the measure of energy use to the natural boundary of the working system being measured, that a variety of otherwise hidden energy costs are taken into account, using a well defined and repeatable procedure that can be improved upon. The most visible energy costs are the *single* largest ones, but the rather “fat tails” in the distribution of hidden energy costs is much larger in total, and few have much to do with the technology employed. The single largest of the energy costs of operating the business may be the easiest to account for, but using that figure to estimate EROI or other energy cost impacts will produce results not comparable to the EROIs or energy costs of other technologies, whole businesses, economic sectors or choices. The principle error seemingly found is that of giving great effort to the precision in measuring things that are obvious, and giving relatively little attention to other necessary things that can only be known appoximately.

Difficult issues for analysis can arise due to the need to use environmental thinking to estimate weighting factors, and care needs to be taken to use proxy measures without overlap and to account for all the working parts of the system being studied. For this added complexity of the method to be reproducible requires others to both match the accounting procedure used and the technique of identifying the natural boundary for the system being studied. The SEA method shows that lacking other clear understanding of energy inputs, assuming average energy intensity for monetary costs is more accurate than assuming zero energy intensity.

3.1 Relation of EROI to Project Costs

Table 3 shows how the EROI varies with the breakeven LCOE and internal rate of return for energy (IRRe) for both the linear annualized cash accounting model (Section 2.3 and Table 2) and when using yearly flows (Section 2.4 and Figures 8 and 9. The comparison allows one to investigate how EROI might be affected by cash flows that can change yearly due to financial constructs such as taxes and depreciation. Both methods show EROI starting at 31 taking into account only the LCAi measure of direct fuel uses. There is no significant difference in EROI results until SEA3 where the EROI is found to be 6.1 for the linear model and to 3.9 for the energy flow model. The break even LCOE costs are directly from the NREL wind finance model [15].

The results indicate that our assumptions result in a business without profits, needing to sell energy at an LCOE price of $99/MWh for wholesale power. The selling price would need to be higher for profit without the PTC, especially as there remain a variety of omissions from the cost accounting indicated in Table 2. For comparable financial parameters (capacity cost, target IRR, capacity factor, debt level, etc.) this appears similar to other analyses for wind farms [16].

From the linear model, the revenue-based energy intensity of the wind farm (energy cost per $ of revenue) is approximately 1.7 kWh/$ per KW installed, or about 0.74 times the world average energy intensity (see Equation 5). The monetary cost-based energy intensity for the wind farm (energy cost per $ of average costs) is 2.5 kW/$ or 1.1 times the world average intensity.

Table 3. EROI, LCOE, and IRRe per business unit scale.

	LCAi	SEA0	SEA1	SEA2	SEA3	PTC*
EROI (linear)	31.0	8.9	7.9	7.7	6.1	--

EROI (cash flow)	31.0	8.9	8.0	7.9	3.9	4.3
LCOE ($/MWh)	2.29	58.20	66.30	67.10	99.00	78.90
IRRe (%)	155	44	44	44	39	--

[*] The EROI of including the PTC subsidy is shown only to indicate the “virtual energy” gain in EROI derived from the tax subsidy.

Notice that though the PTC decreases the monetary costs of the wind farm business, it is not a source of real energy income, but only virtually “saves” energy inputs (see Figure 6).If subsidies were given that did represent another economic sector’s decreasing use of energy enabling a real gain in profits for the wind farm as a business, the saved energy would not be result from the wind farm itself. Thus, the PTC can’t be included in the EROI for wind generation. It is conceptually easy to treat every item on a financial budget as having average energy intensity, but circumstances such as subsidies are important to notice and often point to how to treat individual items differently. The EROI derived from the cash flow (Table 3) raises a variety of questions about showing financial effects that may save money but not energy. Also, the question remains as to what degree monetary inputs may present varying degrees of misinformation about the whole system energy of working parts that a business represents, or vice versa.

More helpful for understanding the importance of counting all the parts of a system is to consider the implied excellent EROI of 31 with a wonderful implied IRRe of 150% and an unbelievable break even wholesale price of energy of $2.3/MWh. Actual wholesale prices in Texas are nominally 20-60 $/MWh. A thinking person would see those relations as reason to ask if there might be a type III error involved, one of using the wrong model rather than just a type I or II errors of failing to get the right answer from a good model.

3.2 Pros and Cons of SEA methodology

Like any life cycle assessment or related information model, the results are only as good as the questions being asked and the completeness and accuracy of the data. The SEA methodology produces "soft information" in that it relies on combining high accuracy and low accuracy measures. One of the uncertainties is the accuracy of using average energy intensity for all costs. The Costanza data (Figure 1) does suggest that producer costs may have widely varying average intensity, but our business model only has one such large cost, that of the wind turbines. Both government and consumer costs in that study are shown as generally close to average.

This "average" impact approach was assumed for the bulk of the non-LCA accounted costs in this use of the SEA method. The benefit is that the SEA average approach certainly provides a better estimate than using a zero energy intensity, even if the improvement is at the expense of expected accuracy provided by the largest single use. The SEA approach, accounting by whole business unit, sets a standard for how physical measures of various distributed systems can be calibrated to empirically-located boundaries with similar degrees of uncertainty such that they are comparable and provide a basis for net energy estimates for different choices. Thus, SEA has distinct advantages relative to alternative methods of analyzing the energy inputs and outputs associated with complex systems.

3.3 Total Environment Issues

Life cycle assessment, whether LCA studies for the impacts of technologies or as TEA and SEA studies of whole environmental systems, is fundamentally a study of long term interactive change in complex economic and natural systems. Understanding environmental systems starts with studying how they grow, first without limits from small beginnings, to then enter competitive and collaborative relationships with others. Sometimes growth systems also then stabilize in a mature state and provide foundations for others to build on.

SEA studies provide some economically useful direct measures of business value, for current potential investors, but perhaps of more value is the important insight into how the business interacts with the physical environment it is or will become part of. Seeing the financial life-cycle model and the physical resource life-cycle model side by side stimulates thinking about the whole system and its changes. Today as the whole world struggles with increasingly stubborn harmful impacts of confronting our limits to growth, decision makers need all the accurate information and other help they can get for inventing the complex adaptations needed for us to fit in with the rapid physical environment changes in our future.

For example, EROI has not been a well calibrated physical measure before, and so whether or not a project was subsidized with a Performance Tax Credit has been based on political and financial considerations, not on how efficiently a new technology system provided energy to society. A similar measurement method could be devised to measure whole system carbon cost, call it SCA (system carbon assessment), and used together with EROI measured using SEA as a business system energy performance measure. The liability for future carbon cost assessments would appear to be a large risk of any investment today Using a whole system energy measure is really the only way at present to assess relative business risks and benefits to changing energy costs.

The fuels listed in Table 1 show the composition fossil fuels for the capital costs of the project, making it clear why there should be no illusion that wind energy is not produced by fossil fuels. Using such calibrated performance measures would also simplify government decisions for what innovative technology systems to support and would help direct limited tax resources to where they will have the most effect.

Another possible way to use the model to understand the environment is looking ways to raise the EROI by looking for a "better fit" with the environment. The availability of wind does not generally match peak power demand in urban areas where the energy is needed, and wind resources are often found in remote areas where the energy is not needed. It would be good to find a kind of energy use that could benefit from lower cost energy when and where it is generated. That is also not primarily a technology question but a economic environment question. Perhaps wind farms located where land is less expensive could avoid transmission, marketing and storage costs by co-developing industries with more automated operations that can use energy as available. Perhaps they could produce hydrogen fuel to balance their demand cycles or other process needing electrical power. If these plants were manufacturing wind turbines as well as other renewable technologies, it would close the loop on renewables as a whole system and test their sustainability [17].

The largest financial and energy costs for the wind farm come from the first costs of development for the 20 year project. Other large costs come from the added cost of financing for the first costs, and for the support of government in maintaining the economic environment in which the business operates. If short term financing of a long term project and government costs are the main energy uses for the business system, it prompts other questions than how to improve the technology. Perhaps some of those capital costs could be engineered to last longer, and the business benefit from generation energy from them for longer than 20 years. That could significantly raise the overall EROI. For the JEDI wind farm the working parts of the turbines are about 55% and the longer lived parts of the capital costs might not need to be replaced for the second or third 20 years of operation.

A question about basic methodology is raised by the large cost of government, 39% of the total. Should that be removed from the EROI analysis, and be put on the other side of the equation entirely, to represent part of the societal overhead cost that energy producing systems are needed to support? Removing government costs from the measure of EROI would serve to create an energy performance measure of government overhead and societal services. It would help establish how much physical energy resources are actually available for competing public interests to use. It would also remove that amount energy uses not really part of business operations themselves, and restrict the SEA accounting to what people normally think of as the business and its chains of supports and supplies. It would make business plans more comparable as business plans. In comparing EROI's for business plans in different societies, of course, one would need to add the societal costs back in to make them comparable.

Understanding government as environmental overhead costs should also contribute to the broader environmental systems ecology question of how to determine the level of EROI actually sustainable on earth and the kinds of business systems that are operable using it. Work needs to be done to formalize the methods used by Hall et al. (2009) [2] to estimate the EROI required to run a reasonably complex society. Well documented declines in EROI caused by resource depletion and increasing costs of extraction are but one factor. Combined with physically declining energy returns on investment the societal demand for ever more energy use as an economic overhead cost compounds the problem. Particularly at limits to growth, increases in surplus energy stop materializing. As plans to use future surpluses for necessary maintenance fail, added expenses for promised improvements need to be deferred, and unexpected costs due to conflicts arising over increasing demand for diminishing resources and escalating costs for both sustainable investment and environmental remediation emerge. The budgets for formerly assured necessities are then threatened, and the whole system put on a collision course with itself, absent carefully coordinate response. The ability to accurately measure the energy requirements for operating complex societal systems and their complexity would be quite valuable for making informed choices for sustainability, and the world needs better understanding in this regard [18].

3.4 Future Work

By accounting for only the average electricity output from the wind turbine, and not the particular intermittent pattern of its output, the calculated EROI for wind may not be comparable to energy from other sources. EROI is a generic measure of energy, and not a general measure of the utility of an energy source to its use. Future work is left to use the SEA methodology to compare multiple types of electricity generation (e.g. natural gas combined cycle, pulverized coal, photovoltaic solar, etc.). In that comparison a common descriptor of the electricity output may be required. An example is comparing the costs to produce a constant electricity output over time (e.g. day, year) or the costs to match the diurnal patterns in electricity demand in average markets. It is known that fossil, nuclear, and hydropower are generally dispatchable and can follow the demand pattern. It's also known that fossil fuels are highly portable, and marketable overseas for example, and wind resources are more tied to the land where they are generated. The portability of seemingly unlimited energy resources has greatly influenced the patterns of world economic development, and understanding the value of renewable resources that are less portable is needed.

In some regions with high wind integration, scheduling protocols have provided the necessary system coordination. For example, Denmark uses pumped hydropower within Scandinavia for storage of excess electricity and exports to other markets. In the Texas grid (Electric Reliability Council of Texas), 4.9% of the electricity in 2008 was from wind power, and the large capacity of natural gas generators on the grid has thus far enabled relatively easy integration of wind. However transmission constraints have restricted wind power flow at many times to lower the capacity factor by up to 10%.

Eventually at very high penetrations of wind (over 20% of total electricity) newer chemical or thermal battery systems may need to be employed. However, installation of natural gas combined cycle systems may serve the need to mitigate the intermittency of wind at the cheapest cost. Thus, if the energy inputs and/or EROI of each component added to the electric grid is know, one can estimate the EROI of the supply system as a whole for matching the demand.

The most fundamental question for this method needing further study, of course, is the real meaning of "average". If in a month a person gives money to 500 different businesses, and each business receiving the income then spends on 500 different people, then in three months there are 500^3*500^3 partial recipients of any dollar a person receives in their monthly pay. That's 1.5*10^16 end recipients per quarter, or if you assume there are 5 billion economically active people on earth then that means each one might receive part of that single dollar by about 3 million different paths, on average. It suggests the remarkably large network of connections of the world economy are much more fluidly interactive than we perceive. What's not so clear is whether there is a texture discernable making one person or community's spending more or less energy intensive per dollar of value [8]. There is evidence in contradictory studies, for differences between national and global accounts. It would appear that nations have distinctly different energy intensities and trends of efficiency change[19], but are also being smoothly allocated by a unified and smoothly changing global economy that consumes energy quite efficiently as a whole[20]. This whole subject needs much more careful study, even if at this point it is quite clear that absent other information the energy represented by any expense is more accurately estimated as "average" than as "zero".

Another area of research needing attention is the basic relation between financial information and physical economic processes. Information systems are prone to accumulating spirals of misinformation about physical things, such as the various kinds of market pricing bubbles. Financing schemes, taxes, subsidies, returns to investors, and discounting cash flows could all introduce immaterial speculative information if used as measures of energy. How money in financial markets so easily generates enormous misinformation about material values and resource uses needs to be better understood. That makes devising a reliable way to measure physical flows in a world where so many of them seem unreliably accounted that much more important. It’s important to be selective in what measures to use as proxies for other things. There is a noticeable difference between the remarkably smooth curves of world energy use and constant proportional measures of GDP[20] and large scale movements of the stock market over the decades which follow no corresponding course[21 Figure 2].

4. CONCLUSIONS

Prior attempts to determine the EROI associated with specific industries or projects has suffered from a number of limitations. The common LCA approach accounts for directly measurable fuel use and production by the primary technologies. It neglects energy uses that are not individually accountable or that are not part of the primary technology used. A “top down” approach using econometric measures of probable energy use does gloss over some unique attributes of particular inputs. When calibrated to a natural system boundary it is so much more inclusive, though, that when combined with a "bottom up" approach such as LCA, the combined accuracy is greatly improved. Financial cash flows and rates of return in particular, are understood to not occur “by magic”, but do not directly mirror the physical energy flows or degree of environmental impacts they physically rely on. Those take place through a complex physical economic system, and are not recorded.

The hybrid SEA approach outlined here seeks to combine the bottom up LCA approach’s strength in recognizing the unique energy flows associated with specific technologies with the ability of a top down approach to recognize the full scope of a project’s impact on energy flows within a global ecosystem. In finding a way to use the financial accounting boundaries for business systems to construct a physical measure based on the physical environmental boundaries of the system and identify it as an unit of organization in its environment, this approach is consistent with the view that a business is a component of a complex natural system, and the general desire to better understand both.

NOMENCLATURE

Ei_j: economic energy of j^{th} business unit

Ti_j: technical energy of j^{th} business unit

WtTi: technology energy intensity relative to world average energy intensity

WtEi: economic energy intensity relative to world average energy intensity

EROI: energy return on energy invested

IRR: internal rate of return on money or cash flow

IRRe: internal rate of return on energy or energy flow

LCA: life cycle assessment

LCOE: levelized cost of electricity

NPV: net present value

SEA: system energy assessment

TEA: total environmental assessment

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