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DEFINING A STANDARD MEASURE FOR WHOLE SYSTEM EROI COMBINING ECONOMIC "TOP-DOWN" AND LCA "BOTTOM-UP" ACCOUNTING

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ABSTRACT

Business investments rely on creating a whole system of different parts, technologies, field and business operations, management, land, financing and commerce using a network of other services. Using the example of a wind farm development, a typical life cycle assessment (LCA) focuses upon the primary technology inputs and their countable embodied direct impacts. What LCA omits are the direct and indirect impacts of the rest of the business system that operates the primary technology, the labor, commerce and other technology employed. A total environmental assessment (TEA) would include the physical costs to the environment of the labor, commerce and other technology too.

Here a simplified "system energy assessment" (SEA) is used to combine a "top-down" method of measuring implied indirect business impacts using econometric methods, with a "bottom-up" method of adding up the identifiable direct impact parts. The top-down technique gives an inclusive but rough measure. The bottom-up technique gives a precise accounting for the directly identifiable individual parts that is highly incomplete. SEA allows these two kinds of measures to be combined for a significantly improved understanding of the whole business system and its impacts, combining the high and low precision measures indentified by each method.

The key is exhaustively accounting for energy uses within the natural boundary of a whole business system as a way of calibrating the measure. That allows defining a standardized measure of complex distributed system energy flows and their energy returns on invested energy resources (EROI). The method is demonstrated for a generic business operation. Starting from the easily accountable inputs and outputs, SEA successively uses larger natural system boundaries to discover a way of finding the limiting value of EROI after all parts of the whole are included. Some business choices and a net present value model of cash flow for the 20 year project help illustrate the related financial issues. The business model used shows that the EROI of a generic "Texas Wind Farm" is 31 when accounting for direct and indirect fuels only, but decreases to 4-6 after accounting for the economic energy consumed by all necessary business units and services.

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

1. INTRODUCTION

This paper introduces a "system energy assessment" (SEA) method for measuring total energy use in distributed systems that could be used to model business systems or other economic processes. To do whole systems analysis for distributed systems, one must establish clear boundaries for what to measure. The act of locating and using the natural boundaries of the physical systems allows measures to correspond to the physical systems themselves, rather than to arbitrary definitions and units.

The main benefit of SEA is the ability to standardize and compare physical measures of parts of economic systems. The example used in this paper is a way to standardize the physical measure of energy return on energy invested (EROI). EROI is equal to total energy output divided by total energy input for an energy system [1, 2]. Having measures for the energy dependence and productivity of whole business systems also contributes to understanding both business opportunities and risk exposures in the present environment of rapid change in energy 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 accessing whole distributed physical 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 turbine) of a business. Here LCA measures for wind turbines are used as a starting point, defining the smallest operating "whole system" business unit boundary to start a process of assessing successively larger natural boundaries in the business system to find the limit of accountability for the whole business. These additional system boundaries are used to calculate energy requirements that are then related to a final system EROI.

Though LCA analysis uses quite well defined analytical boundaries for technologies and their impacts, there has been no standard way to define the analytical boundaries for the business systems applying the technologies. That prevents meaningful comparison of energy returns and financial returns for different technologies or industries. Because LCAs typically omit the impacts of using employees and business services to operate technology systems, they generally understate the energy used. Thus EROI realities and financial measures of a project need to be properly understood.

The present analysis addresses only one project, a Texas Wind Farm, to establish methodology for later comparison to other studies and generalization to other energy resources and technologies. With further study it may allow comparison with the results of classic energy and economy studies such as performed by Costanza [4, 5] that also use a method of combining direct and indirect energy uses, but applied to whole industry sectors of the economy. For 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 provide no guidance for individual businesses or means to evaluate new concepts. For renewable energy systems (e.g. wind power) there is also no defined economic sector enabling data to be separated from the rest of the economy.

An accurate understanding of EROI for individual businesses and small innovative business sectors is important to act as a guide for long-term value for sustainable systems. Using EROI in context of financial measures can also possibly replace short term measures for growth and profit that generally accelerate rather than alleviate resource depletion. Even if broad economic sectoral data for renewables were available, they would not provide the kind of individual system indicators that would guide adaptive development.

Figure 1 shows results from Costanza and Herendeen (1984) in relation to the average economic energy intensity found for the US economy in 1963 organized by shares of GDP for each sector [5]. The results are presented here to illustrate the general kind 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.

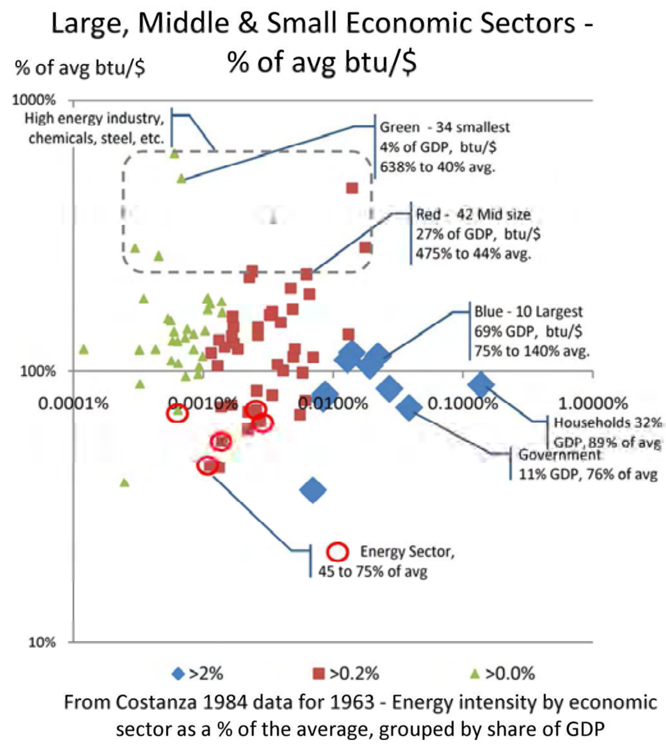

Figure 1. A comparison of the energy intensity (btu/$) and scale of industry sectors of the 1963 US economy shows consumers are near average and energy sectors are below average (data from [5]).

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 TEA (and SEA) method is to treat all costs as having average impact intensity unless a more accurate figure is available (see Section 2.3). The one exception has been to identify some inputs as "unstudied" and indicate their omission from the analysis.

To test the completeness of the SEA method, a net present value analysis of the wind project financial life cycle allows the breakeven price (levelized cost of electricity. or LCOE) and internal rate of return (IRR) to be developed. It also helps raise questions about the appropriateness of developing performance measures from only small parts of the business being considered and points to the benefit of having accurate totals. At this point no direct connection between the energy analysis and market variables was hypothesized, though. Because the energy model used here is derived importantly from the financial assumptions, the apparent implications of energy returns (EROI) on financial parameters (LCOE) simply reflect the assumptions being made. Future studies of actual operating businesses and business (e.g. coal power, photovoltaics, etc.) will provide real measures.

1.1 Measurement Methods

This analysis combines information from LCA life cycle assessment and methods of Total Environmental Assessment (TEA) [8]. Both are simplified here, reduced to measures of only energy consumption and production and called System Energy Assessment (SEA). LCAi is the measure the accountable direct fuel use for the principal technology (see Section 2.1). SEA adds to that estimates of energy uses for things that are not individually accountable. That includes employing people, business services and other technologies, and is done by categorizing different types of spending as above or below average energy intensity. The data are then aggregated by the natural boundaries of the system being studied (see Section 2.3). Thus, by combining "bottom-up" process LCA data with "top-down" economic data organized by the natural units of the business system, SEA provides physical measures of whole business systems

In looking for the correct boundary for measuring EROI the SEA assessment here begins with the smallest whole operating unit needed to produce the product, the principle technology. It then proceeds to press the limits to include other things operating the technology requires. The addition of the field operation costs, as a unit, and then the business operation costs, and then the corporate operating costs. At the point of including everything needed for the technology to work the progression of results is considered (Figure 4). EROI approaches an asymptotic limit, seeming to confirm that the inclusion of the whole system in the analysis is being approached. These whole working units of the business system are diagrammed in Figure 2. These business system units correspond to:

- LCAi: the "energy only" component of a process (e.g. "bottom-up") life cycle analysis
- SEA0: the supply network for the wind turbine technology (i.e. primary technology) itself,
- SEA1: field operations,
- SEA2: managing business, and
- SEA3: corporate levels of the business organization.

LCAi corresponds to the direct energy consumed by technology in manufacturing and installing the primary technology (e.g. wind turbine), its maintenance and disposal. The important part of Figure 2 is how the energy consumed is divided between technical energy and economic energy. These are actually two distinct and non-overlapping energy consumption streams, because people and technology have quite separate energy needs. The connection between people and technology is that the people operate the technology, providing "know how" and services, and will only do that if they are paid and can then consume energy and other products for their own needs. That is generally not individually traceable. The technical energy is consumed by machines and not suitable for powering people. Economic energy is consumed by the employees and service providers, and not suitable for running machines.

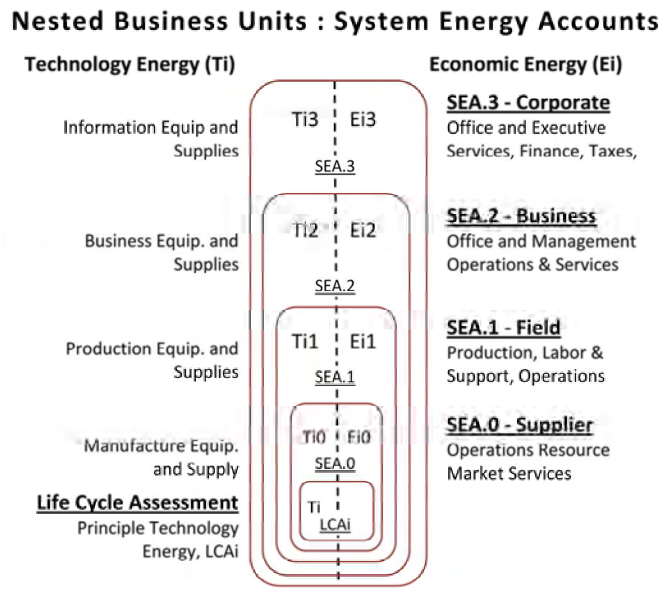

Figure 2. Whole System Energy Assessment (SEA) for a product adds the energy intensity of two streams (Technical Energy and Economic Energy) for each of the various operating systems needed during production and operation.

2. ANALYSIS DESCRIPTION AND BACKGROUND ASSUMPTIONS

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 in Equations 1-3:

$$\boldsymbol{SEA_j = Ti_j + Ei_j} \qquad (1)$$

$$\boldsymbol{Ti_j = cost_j \times WtTi_j \times \left(\frac{energy}{GDP}\right)_{world}} \qquad (2)$$

$$\boldsymbol{Ei_j = cost_j \times WtEi_j \times \left(\frac{energy}{GDP}\right)_{world}} \qquad (3)$$

where Ti_j and Ei_j are the technical energy (kWh) and economic energy (kWh) inputs, respectively, for the j^{th} business unit. Ti_j represents the use of fuels for physical work, and Ei_j is associated with purchasing goods and services in the economy. SEA_j is the total energy input required to operate the j^{th} business unit. The values for Ti_j and Ei_j are based upon their weighting ($WtTi_j$ and $WtEi_j$) in relation to the average energy intensity of the overall economy as described later in Section 2.3. Each $cost_j$ is the money spent by the j^{th} business unit.

The full energy input for the energy system (e.g. wind farm) is shown in Equation 4:

$$E_{in} = LCAi + \sum_{j=0}^{N} SEA_j \qquad (4)$$

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 3) [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: that with all other aspects equal, the LCAs including more parts of the life cycle should tend to have lower EROI. Lacking common standards for how to identify the boundaries of physical systems that need to work as a whole 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].

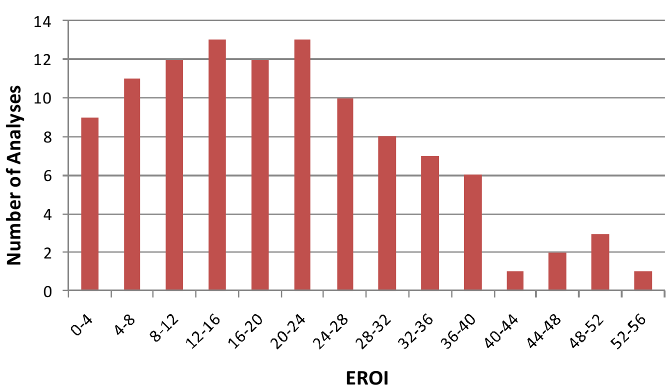

Figure 3. The frequency distribution of EROI for wind turbines as studied in [9] shows an unusually wide range, and may indicate the general lack of standards to follow.

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 that one (1) naturally has a very accurate measure of the energy output (i.e. wind power generation) and (2) gets a successively more accurate measure of energy input 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 costs.

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.

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.

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].

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

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 1 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 (other technology, wages, financing, land owner payments, etc.) are aggregated by the business unit to which they apply and assigned a technical and economic energy intensity for their cost as outlined by Equations 1-4 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). However, the authors are well aware of the different monetary values that the market applies to different forms of energy (e.g. oil, coal, electricity, etc.), but the analysis of this paper is considered preliminary and does not make a distinction in value for different energy inputs and outputs [3, 6, 7].

$$\text{World Energy Intensity:} = \frac{\left(472\text{e}15\ \text{Btu}/_{59{,}939\text{e}9\ \$2006}\right)}{3{,}410\ \text{Btu/kWh}} \quad (5)$$

$$= {}^{7{,}630\ \text{Btu}/\$2006}/_{3{,}410\ \text{Btu/kWh}} = 2.24\ \text{kWh}/\$2006$$

Table 2 presents the cost expenditures and their translations into energy using the SEA method. The LCA fuel use data is derived from Table 1. This LCAi value is the only data value that calculates energy consumption "bottom-up" and translates that energy to a dollar value. All other energy consumption values are derived using cost information from the NREL JEDI model as the baseline information. The translation of costs from the JEDI model into the business units of the SEA is not always a 1:1 relation.

The monetary costs in Table 2 are expressed on a dollar per kW per year ($/kW/yr) basis. Recall from Section 2.2 the operating lifetime is assumed from the Vestas LCA at 20 years. The energy consumption for the different business units is in units of annualized energy consumption (kWh/kW/yr).

The value of technical and economic energy weights, $WtTi_j$ and $WtEi_j$, are chosen in relation to information whether they should be above, below, or equal to the average energy intensity for the whole economy of Equation 5. For the analysis of the wind farm, $WtEi_j = 1$ is assumed for all costs, $WtTi_j = 11$ for fuel costs, and $WtTi_j = 0$ for salaries, taxes, insurance, and other services.

The value of $WtEi_j = 1$ means that the energy intensity of purchases by the wind developer are assumed at the average energy intensity of the overall economy. Hence the factor of 1. The value of $WtTi_j = 11$ is derived from Table 1 where the energy intensity of fuels purchased by the wind developer is assumed the same as during the manufacturing of the wind turbine. In other words, the energy intensity of purchasing fuels is eleven times more than purchasing items with the average energy intensity. Nominal values of fuels were assumed for Table 1 (e.g. $75/BBL of crude oil, $6.6/MMBtu for natural gas, and 7.8 cents/kWh for electricity).

Due to lack of data on the embodied fuel energy for the various technologies used in the business units (e.g. computers, buildings, etc.), no line items exist for technical energy, other than fuel and salaries. However, the weight $WtTi_j = 0$ is assumed for salaries paid to employees, who are assumed to be general consumers in the economy who spend their earnings at the average energy intensity (i.e. with $WtEi_j = 1$).

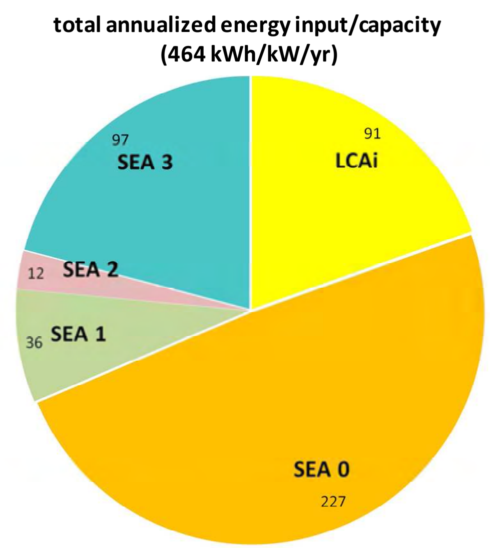

Figure 3. The annualized 20 yr whole system energy use by scale of business unit, LCAi to SEA3. The LCAi energy use (direct fuel use for making and recycling the primary technology) and the economic energy needed to do that, SEA0, account for 65% of the total.

Table 2. Technology and Economic fuel use (Ti and Ei) per KW per year of installed generating capacity. The fuel directly used by technology comes entirely from physical sources, but the money paid for it goes entirely to support the consumption of people providing other economic services, a separate energy use that is only statistically accountable. The direct and indirect energy uses for any purchase are accounted for separately for each whole operating unit. The columns for "Ti weight" and "Ei weight" indicate the ratio relative to average kWh/$ for each. In Figure 4 the totals for each operating unit are aggregated with the previous levels, starting with the LCAi direct energy estimate.

Income / kW capacity		$ Value		kWh		
	Electricity Sales	$281.7[1]		2,817		
		$	Rel Avg[2]	kWh	Rel Avg[2]	kWh
Energy & Money Cost / kW capacity		Cost	Ti Wt.	Ti	Ei Wt.	Ei
SEA0 - Supply & Construction costs	**Primary Technology**	$76.14	.4	91	1[3]	170.30
	Physical Plant Cost	$25.48			1	57.02
	subtot	$101.62		91		227.42
SEA1 - Field operation costs	**Field Technology costs**	$11.60	-[4]		1	25.96
	Field Business costs	-[5]	-[6]		1	
	Field Fuels	$0.17	10.2[7]	3.93	1	.39
	Field Employees	$2.75	0[5]		1	6.15
	subtot			3.93		32.48
SEA2 - Business operation costs	**Business Technology**	-[5]	-[4]		1	
	Business costs	-[5]	-[6]		1	
	Biz Fuels	$0.35	10.2[7]	7.87	1	0.77
	Business salaries	$1.54	0		1	3.44
	subtot			7.87		5.34
SEA3 - Corporate operation costs	**Corporate Technology**	-[4]	-[4]		1	
	Corp. Business Costs	-[4]	-[6]		1	
	Corp. Fuels	-[4]	10.2[7]		1	
	Land & Taxes	$13.99	-[6]		1	31.3
	Fees, Insurance, Finance	$23.73	-[6]		1	53.12
	Taxes and Credits	$5.63	-[6]		1	12.61
	subtot	43.36		0.0		97.04
Combined Total	**Totals**	$261.39		102.69		361.18
463.87	**Contingency**	-[4]		-[4]		-[4]

[1] Income at nominal market price of electricity 10 kWh/$,
[2] World avg. economic energy intensity from EIA data = 2.237 KWh/$ (declining at ~1.3%/yr.)
[3] The indirect fuel use rates of all expenses are treated as "average" so their weight factor is 1
[4] The direct fuel use rates for other business technology is not estimated, but might be near 40% of the cost as for the principle technology. Omitted estimates are shown as a missing values in the table for completeness
[5] Figures for some categories were not available or no direct fuel use rate was assigned
[6] The direct fuel use rates for other business operations is not estimated.
[7] The direct fuel use rates of other fuel costs is taken from the ratio of market prices and the fuel uses in Table 1

2.4 Cost and Energy Flow Analysis

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

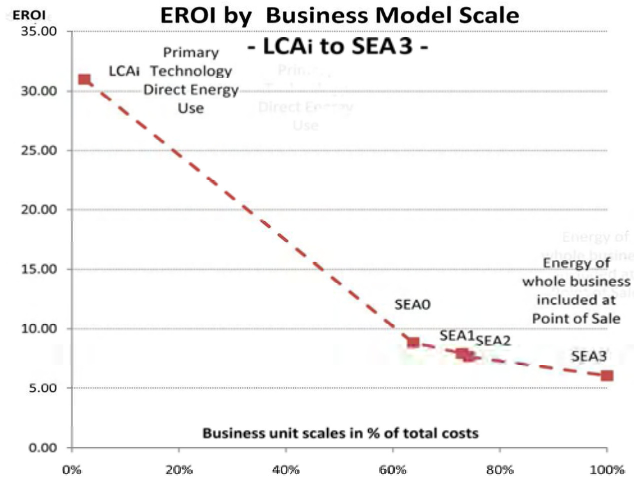

Figure 4. The EROI decreases as additional, business units are considered to the point of sale. The asymptotic trend helps confirm the accounting for all costs.

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.

The majority of monetary costs (~65%) occur in the first year to pay for the turbine and construction (see Figure 5). 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 6), nor consequently the EROI

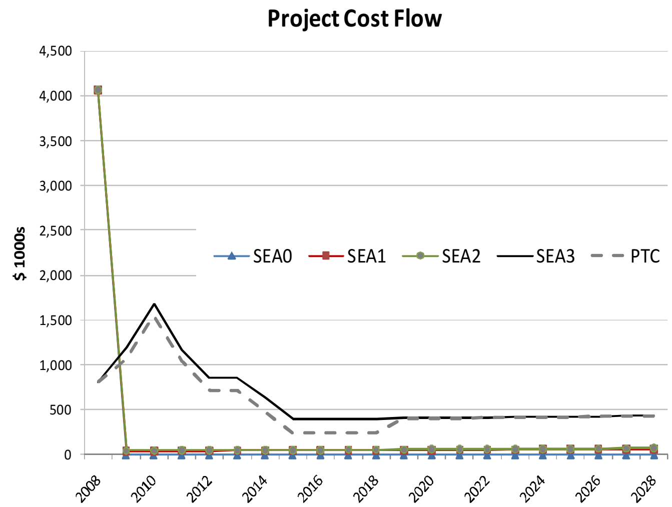

Figure 5. Except for SEA3 which uses financing, the project monetary costs for each scale of business organization are dominated in the first year with the high first costs of development.

For each nested level of the business units and monetary cost flows in Figure 5, Figure 6 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).

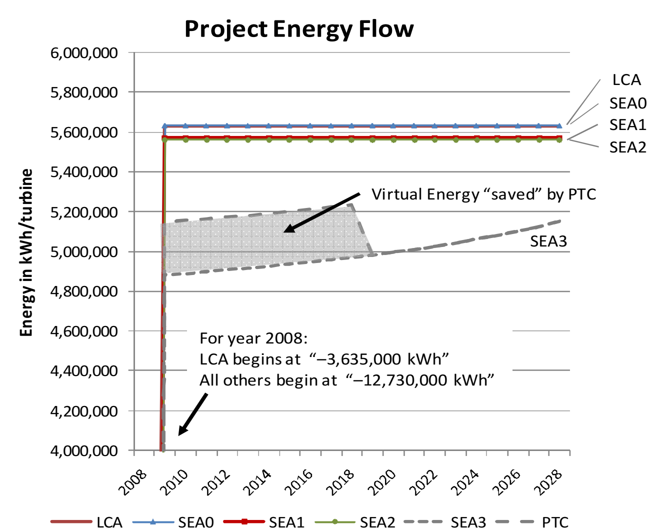

Figure 6. Energy flow (kWh/turbine) for the different business scales.

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 5 and 6 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.

3. RESULTS AND DISCUSSION

The main conclusion of the present analysis is that as more energy costs are taken into account, the apparent EROI of an energy system will decrease, and at a decreasing rate. The most important of the energy costs of operating the business may be the easiest to account for, but a final EROI comparable to the EROIs of other whole businesses and economic sectors will not be valid until the analysis extends to the point of sale. Difficult issues for analysis can arise due to some complex accounting strategies used in financial analysis that have no bearing on the amount of energy consumed by or produced for society. This complexity of translating financial accounting to energy accounting presents a hazard for the analytical method. The SEA method shows that lacking other clear understanding of energy inputs, the result of 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 5 and 6. 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 further uncertainties is the validity of using a default value of average energy intensity for costs purchased at unknown energy intensity. Some indications suggest that because of how money spreads to hundreds of different recipients with each step of transfer [8], that the real impact of spending is quite often very close to average. That and other issues have yet to be thoroughly studied.

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 provides a significantly better estimate than by assuming zero energy intensity, even if the estimate is largely at the expense of the unexpected inaccuracy of the method used before. The SEA approach by 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. Thus, SEA has distinct advantages relative to alternative methods of analyzing the energy inputs and outputs associated with complex systems.

3.3 Issues of Environmental Fit

Life cycle assessment, whether LCA studies of individual technology impacts or TEA studies of whole systems, is fundamentally a study of long term developments in economic and natural systems. It starts with how they grow from small beginnings to then study how they stabilize at maturity, to then eventually decline. It also provides some useful short term measures, but what is more important is the insight they provide into how systems can adapt to better fit our rapidly changing future. Used that way life cycle assessment assesses where the current state of affairs is located on a curve of long term developmental changes, identifying choices for a "better natural fit" with the changing environment.

As noted earlier, whether or not the project is subsidized with the PTC there is no effect on the EROI of the project. That is because all government subsidies are purely financial and usually offered on a political basis. Perhaps a performance-based subsidy, keyed to EROI, could be used to generate profits for reinvestment in proportion to proven whole system performance. In that case the PTC might be written to reward projects with better than usual energy performance, not just politically favored businesses.

The largest financial and energy costs for the wind farm are from the first costs of development and financing for the 20 year project. It makes one wonder if that implied strategy "is asking the right question". If some of those first costs could be engineered to last much longer than 20 years including using modular replacement of parts, the real EROI could go up significantly. Perhaps then the better long term strategy would be to take out longer term financing for the longer term parts of the investment.

Another way to boost EROI with a "better fit" is suggested by how the power availability for wind does not match the urban peak demand cycles. Combined with the high cost of land and long distance transmission of power, might suggest another strategy. It might be possible to locate wind farms where land is less expensive and avoid transmission and marketing costs by co-development with industry users that could automate plants to run with the availability of energy. Perhaps they could produce hydrogen fuel to balance their demand cycles and displace the need portable carbon fuels for wind turbine manufacture. 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].

A third way is to use this same model is to get better measures of the CO_2 risk exposure, such as to increasing taxes and hazards of long term sustainability for the rest of the economic system. The economic fuel use for the project is the lions share (80% of the project carbon impact), and the fuels listed in Table 1 show the composition. Thus, there should be no illusion that wind energy is not produced by fossil fuels.

This work should also contribute to the broader systems ecology task of determining what average level of EROI is actually sustainable on earth. It could also help 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, continually increasing costs of extraction, and the societal need for ever more energy to keep up with increasing economic overhead costs for maintenance and conflict resolution appear to be on a collision course. The ability to accurately measure the energy requirements for system complexity would be quite valuable for system 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. Future work is left to use the SEA methodology to compare electricity from 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.

In some regions with high wind integration system operation protocols have provided the necessary system operational buffers. 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 can is know, one can estimate the EROI of an entire electric grid.

4. CONCLUSIONS

Prior attempts to determine the EROI associated with specific industries or projects suffer from a number of limitations. The common LCA approach accounts for directly measurable fuel use and production for the primary technologies used. It neglects energy uses that are not individually accountable. A “top down” approach using econometric measures might gloss over unique attributes of particular inputs, by casting a wider net and being combined with a "bottom up" approach improves the accuracy of both. Financial cash flows and rates of return in particular, may not mirror physical energy flows or the degree of environmental impacts. Financing schemes, taxes, subsidies, returns to investors, and discounting cash flows could introduce speculative information into measures of material values. How money in financial markets so easily generates misinformation about physical flows needs to be better understood. That makes devising a reliable way to measure physical flows in a world where so many of them are not individually accountable that much more important.

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 identify the natural accounting boundaries within business systems and between it and its environment, this approach is consistent with the view that a business is 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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