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Article

Defining a Standard Measure of EROI for Energy Businesses as Whole Systems

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Abstract: This paper explores a new method for estimating the total embodied energy in business operations and calculation of energy return on energy investment (EROI). Instead of only counting evident energy uses we also assess the much larger category of all energy use needs of businesses, demonstrating a method of estimating of the energy required to run businesses that would otherwise go uncounted. That's analogous to both adding up the big trees and the acres of brush and grasses in estimating regional bio-mass. Current methods of business energy assessment such as LCA only count the recorded large energy uses of technology. Here we also include estimates of energy used by other business operations required for delivering the end product as shares of global energy use, defining a System Energy Assessment (SEA) method. By defining a physical measure of total energy required by a business system, ratios such as EROI of energy produced to energy consumed, for the first time, become true physical measures of energy provided to society by a business model. The key is to define the business as a whole system and locate its functional boundary, to include all parts needed for it to work as unit, acting on its own in the economic environment, like an organism. This largely corresponds to what a business pays for, and identifies the physical parts of the business system to be assessed for their energy requirements. To account for each energy use within that boundary we combine recorded energy uses with proxy measures of energy use, applying intensity factors to the financial costs. The use of costs as proxy measures of energy use begins with reasoning that the energy needed to deliver a dollar of economic services is better estimated as average than as zero, as other estimating methods generally assume. Thus, the SEA method provides a carefully regulated method of combining known energy information with implied shares of the energy used elsewhere in the economy. We demonstrate the SEA method via the case study of a wind energy business that shows EROI drops from nominally 31 to 6 for wholesale energy sales, after assessing the unrecorded energy needs, for a business that produces financial returns for the energy produced possibly a little below average for the economy.

Keywords: energy measurement, complex systems, net energy, energy economics, system boundaries, EROI, whole system assessment

1. Introduction

We approach the scientific problem of how to refer to and assess complex environmental systems by locating a system boundary containing all of its necessary working parts and then assessing the operation of everything within that boundary. It treats a businesse that works as a unit as if a cell or organism with a complete set of internal parts that works as a single unit. We use a model wind farm development to illustrate our approach, assessing the ratio of its energy return to energy invested (EROI) [1, 2]. We start with the traditional approach, using a life cycle assessment (LCA) energy costs of its wind turbines [16]. That core technology is considered as the smallest working unit of the system. We then increase the system boundary by including the operation of the businesses that provide the technology, then the business operations that run and manage the wind farm development. Assessing each scale of business organization as a "working unit" is part of an "exhaustive search" strategy to find the true boundary of the system and account for everything needed for it. The natural boundary is defined as the point of diminishing returns for the search. The strategy allows us to construct comprehensive and independently repeatable physical measures of otherwise undefined complex environmental systems, using their own natural boundaries

Having true measures for the total energy costs and returns of whole business systems has not been possible before. Knowing the totals would allow both government and business to better energy decisions. Without a way to measure the total energy required for any given choice there is also no way to tell the real difference any choice would make. That appears to be a basic deep problem with sustainability assessments to date. That problem is addressed by having a whole system accounting method. This yields a better understanding of the real resource development opportunities and risks. That includes better awareness of the lines of conflict with other resource users at environmental limits, of the unexpected costs of unplanned resource substitutions, and sustainability thresholds of industries built for earlier resource environments. The opportunities include a better ability to identify sustainable emerging technologies and having choices result in the intended effects. A large and diverse literature discussion links energy resources and technology to economic growth and economic returns [1, 3-6]. However, aside from financial information, the existing literature fails to break the information barrier on physical resource uses, and is missing standardized assessments for whole business system energy consumption. While LCAs calculate EROI using process bottom-up approaches, such analyses are generally limited to measures of the physical inputs and outputs of only the primary working technology (e.g. wind turbines in our case) around which the business centers, not the whole business operation itself.

We describe a whole "system energy assessment" (SEA) method for measuring total energy use for a model energy business and the EROI for its first capital investment life cycle, 20 years. This calibrated measure of whole system energy use can be employed as a standard measure of total energy costs of economic and business choices. It also somewhat represents a new way of thinking about energy, and will take some getting accustomed to. The individually identifiable energy uses turn out to be a small part of the total, so the effort turns to assessing the hidden energy uses. That is done by determining values of "economic energy intensity" (Ei) and "technological energy intensity" (Ti) to services a business pays for. We use the default assumption of "average" and qualify results accordingly rather than omit making estimates where other information is not available. .

A larger objective is to consider the whole energy system of the business and the whole financial system of the business as separate "dimensions" of the business as a whole environmental system, including the human cultures and other organizational aspects of the business that make it work as a unit. We look at how the whole system changes over time, considering changing energy costs and returns as well as financial costs and returns as they reach payback, as one normally would do only for finances. By comparing EROI and levelized cost of electricity (LCOE) we also see two whole system performance measures that change depending on how much of the whole business is considered. . We consider other applications, such as assessing the total monetary return for the energy invested (MREI). The total monetary value of the business compared to its total energy use appears possibly lower than the economy-wide average. These whole system views can be discussed in relation to how the business could better fit environmental conditions and demonstrate new ways economic and sustainability questions can be approached using the financial boundary of a business for whole system assessment.

The financial boundary of a business choice is not the only way to define the boundary of the physical working system it identifies. It is, however, commonly used and it presents a good reference point for inquiring about other things that may be taken for granted. In assessing natural systems, one always starts one view as a starting point and looking for what else is connected or being left out, and finding ways to account for it. Things that might be left out of a 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, and the social cultures making the human relations that businesses operate with day to day. Also often left out are the costs of launching and shutting down a business or developing or replacing resources, the life-cycling costs. The end of every search defines a boundary as what was found given the strategy and resources available for the search. It is then taken to represent the natural boundary for the search effort when it leads to persistently diminishing returns.

1.2 Background of energy economics and measurement strategy

Past energy and economic studies used various methods to combine direct and indirect energy consumption for informative insight into the range of energy inputs, outputs, and intensities (e.g. energy/dollar) of the major industrial sectors of the economy [4, 5, 7]. There are also EROI and energy intensity calculations (e.g. Btu consumed/$ of GDP) of oil, gas, and coal industries based upon sector-wide economic and energy data from various federal agencies such as the Bureau of Economic Accounting and US Census [8, 9]. However, these sector-wide and input-output methodologies are too large to relate to an individual business investment decisions, and generally make the strategic choice to sum the energy used by each subject rather than sum the energy needed each subject as we do.

For example, process-based LCAs do not account for the full costs of an energy business, but only the recorded energy uses of technologies. EROI calculations for wind energy using LCA energy cost estimates were surveyed by Kubiszewski et al. (2009) (see figure 3 and §2.1 below), and those data are partly comparable to our results yet show large inconsistency between results and the energy inputs which are included in the calculations. The methodological difference (lacking a standard boundary for what to count) results in LCA estimates that included energy inputs for turbine operations and maintenance as well as corporate operations, but without showing lower EROI than LCA estimates neglecting those energy inputs. Thus, neither existing process LCA estimates nor sector-wide input-output models provide guidance for assessing individual businesses or business models. For energy business systems (e.g. wind power, coal plants) in particular, studies of energy performance as industry groups are not available. Thus, the present work both fills the need for a rigorous method of defining energy use by whole systems in general and the particular need to provide a business-scale energy assessment method that links large scale analyses of the entire economy to the technology-specific scale of process LCA estimates.

Figure 1 graphs results from Costanza and Herendeen (1984) [5] as the energy intensity relative to an average derived from their 1963 US economy data versus the share of GDP for each sector [5]. We present these results largely to illustrate the characteristic range in energy intensities across sectors. From Figure 1, the most consistent patterns appear to be that 1) producer product sectors tend to have more varied btu/$ of economic energy intensity, 2) energy sectors generally themselves has below average energy intensities, and 3) consumer product and government sectors are mostly close to average. This very wide range of intensities, from 6 times average to about ½ of average, might decline when the intensities are estimated by the SEA method.

Still, because the ten largest sectors of the economy appear clustered closest to average energy intensity, the Costanza and Herendeen (1984) data supports the conclusion that unspecified expenditures are reasonable to count as having average energy intensity. That is also because that largest category of unspecified purchases necessary for businesses to operate occur through employee choices in how they use their compensation. As producer inputs are more likely to be far from average, they warrant more careful study, as the SEA method allows. In the absence of better information, a 'null hypothesis' of average energy intensity is clearly better than zero. The error one way is sure to be infinite and the error the other way likely to be equally positive and negative for a reasonable sample size. Energy is a costly and universal resource required for every product or service, and so used with competitive efficiency and allocated globally to its most valuable uses, and that implies that prices will reflect the scale of energy required, or else energy is not being efficiently allocated. Consequently, the general assumption for the SEA method is to treat costs as average intensity unless good information suggests otherwise. The basic intent is to study the services a business needs to work and estimate financial costs and energy intensities for them.

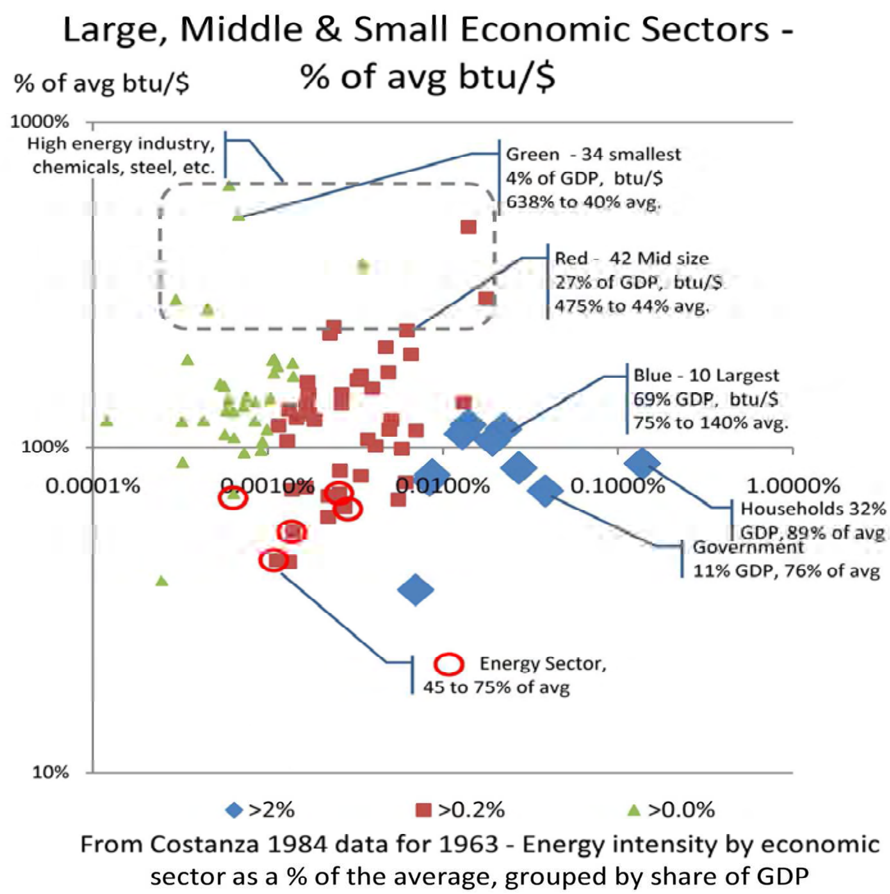

Figure 1. A comparison of the energy intensity (btu/$GDP) by scale of industry sectors of the 1963 US economy, shows consumers are near average and energy sectors are below average (data obtained from [5]).

To both test the completeness of the SEA model against financial standards and show its use in tandem with conventional financial analysis, we also conduct a cash flow model that serves as a basis for some inputs into SEA. From the wind project financial cash flow, we estimate a levelized cost of electricity (LCOE) defined as the sales price of electricity to obtain a net present value of zero. For simplicity, we hypothesize no direct connection between the energy analysis and market variables, such as the effect of energy price inflation, pending CO_2 pollution penalties or growing awareness of the opportunity costs of using depleting resources. In deriving the energy model from assessing itemized costs, we carefully consider what physical energy consuming processes the costs pay for, and that is what conforms the energy model to the physical system of energy uses, like shaping a glove to a hand. Most of the same costs are used for estimating LCOE but without considering what work is being paid for. Future studies of other operating energy businesses (e.g. coal power, photovoltaics, biofuels, etc.)

will provide better ways to assess the average intensity of producer products, and perhaps even consumer networks, and so better measure and reduce the uncertainties of the method.

2. Method Description and Background Assumptions[1]

2.1 Conceptual Background for SEA

System Energy Assessment (SEA) originates from a more general "total environmental assessment" (TEA) method [10] that investigates the development, boundaries, and behaviors of complex environmental systems. However, here we use SEA solely to measure energy consumption and production. The SEA method uses the process LCA measure for the primary energy consumption of a technology as a starting point, defining the smallest operating "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. We initially assume the costs of those operations to be equal to the economy wide average on a per-dollar basis. 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 yields diminishing returns, such as by running out of useful things to count. That is then considered to be the natural limit of accountability for the system.

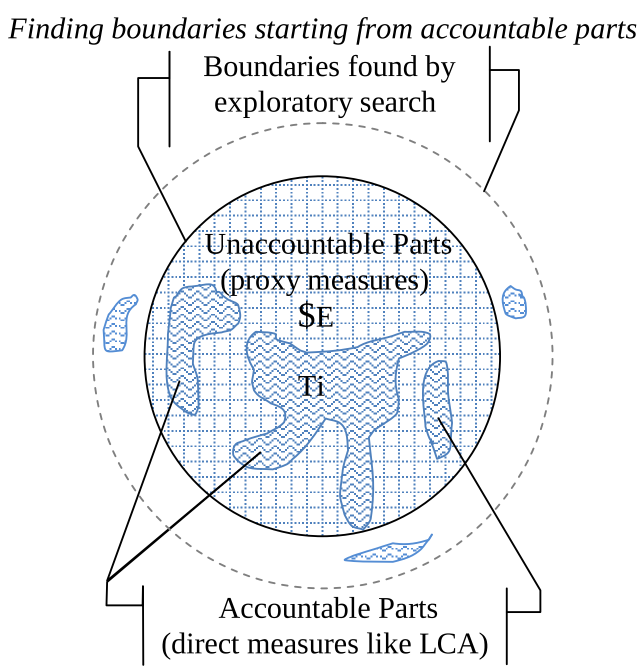

Figure 2. Whole system measure. Exhaustive search to a boundary finds the working parts to the limit of the search, assessed by different kinds of descriptive and metric information, e.g. money ($E) and energy (Ti).

[1] Note: see reference section at end for nomenclature, abbreviations

It is not surprising that one natural boundary of a business turns out to be the collection of working parts the business spends money on. The search process examines the several scales of working organization of the business, starting with the principal technology and then successive shells of operation and management up to the environmental services of finance and government. That proceeds up a nested hierarchy of larger scales of organization (figure 3). Economies contain many kinds of nested systems with various independent working parts that contain other systems of parts. An office work group is a community of independent individuals that work as an individual in an office department, which in turn operates as an individual within the business, for example. Learning how to identify systems by their working organization, to identify individual working units that then interact with others within larger scale organizations is physical system thinking. An awareness of that as an approach to systems ecology is needed interpreting the results of this method. Once a 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 the business and natural environment. It can then be studied from both inside the boundary and from outside, for understanding its role in its environment from either perspective.

Making physical measures of complex environmental systems is different from making measures of engineering systems in that you first need to search for the parts, and may need to invent ways to combine different kinds of measures. Assessing a complex system starts with some easily identified parts and expanding on what can be identified, but then switches to assessing how much information is being left out. In statistical terminology, you very much want to know if what you can't identify has a "fat tail" or a "thin tail.". Here it becomes a task of combining conventional physical measures of energy, watt hours of electric energy, with proxy measures of energy applied to money. What a business spends money on identifies a very large variety of unrecorded energy uses that were necessary for doing the work of the business. To the degree proxy measures can be defined and combined with the direct energy uses known, no part of the system remains left unaccounted.

For businesses the largest category of unrecorded energy uses needed to run the business is the energy used by employees when they spend the incomes earned in running the business, providing information technology to connect with the mechanical technology. That energy use is treated as embodied in the business products because, though not recorded, business products can't be delivered without it. Our assessment method is to assign a weighting factor, greater or less than 1, to reflect the probably intensity of any cost above or below the world average share per dollar. The next step is what makes it possible to combining economic with engineering measures (figure 4), correcting for the difference between how direct and proxy measures are defined.

When all the identifiable and evidently missing parts are included, the assessment has been shaped to fit the natural boundary of the whole physical system, as a glove to a hand. As a form fitting procedure, the physical system then also becomes a direct projection of the natural complex system as a whole. By analogy it is a "leaf print" or an "x-ray" projecting the natural features of the system, and changing the subject of the study from accounting to the otherwise undefined organization of the whole complex system itself. That is the step that allows this study approach to studying complex systems to become physical science rather than statistical science.

LCA analysis uses quite well defined analytical boundaries for measuring the resources used by mechanical technologies and their impacts [25,26]. There does not appear to have been a standard way to define analytical boundaries for assessing the resources used and impacts of business operations employing human technologies, however. Absent a way to define the "total" energy consumed in making products, it has actually then never been possible to define comparative measures of energy use for different businesses or of net change in energy use for particular business choices. That prevents rigorous comparison of individual or policy choices, a methodology defect that appears to have gone largely unnoticed. Here the problem is addressed using a method of mixing engineering measures with proxy economic measures and fitting the assessment to the natural boundaries of the system in question.

Nested Scales of Business Operations

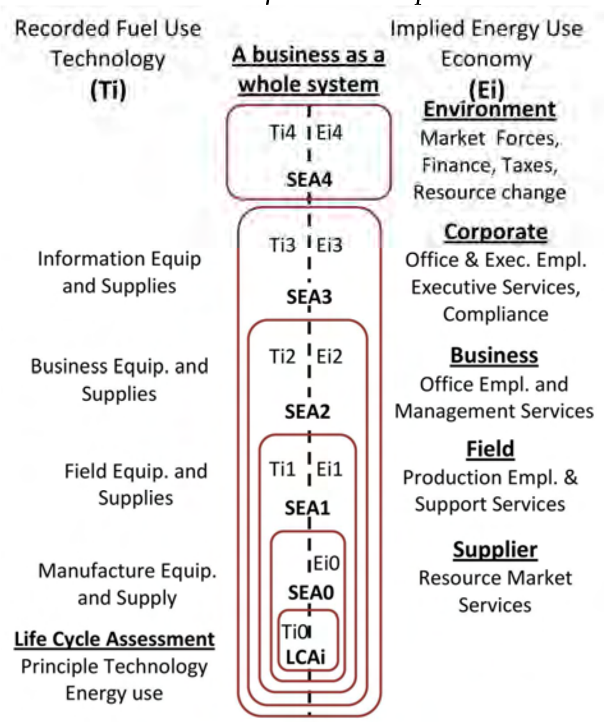

Figure 3. System Energy Assessment (SEA) combines technology energy use (Ti) with energy uses of needed economic services (Ei), using the nested working units to organize the search.

Combining direct and proxy measures

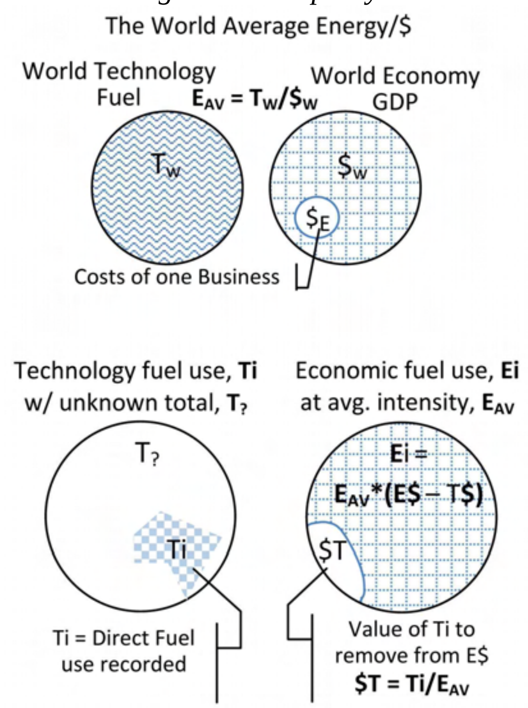

Figure 4. To avoid double-counting technical energy (Ti), the estimate of economic energy (Ei), is reduced by subtracting the average value-added ($T) for Ti from the economic value ($E).

LCAi is our term for the energy intensity component of the LCA analysis[16] done for the wind turbine technology investment we modeled our wind farm business on. To demonstrate the SEA method we then add to that a series of estimates of energy costs for the business operations needed to first produce and then bring the technology product to market. These additional business costs include paying employee and management salaries, the cost of support facilities and operations, purchasing business services from others, financing and government. The six organizational levels as shown in

Figure 3 could each be considered as the "whole business," but is then found needing other things to bring the product to market:

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,

SEA3: adding the total energy needed for corporate management of the business, and

SEA4: adding the total energy used to integrate the business into markets and society (e.g. taxes and financing).

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 needed for operating the energy business (e.g. wind turbine). Proceeding up the organizational chain of the business to include the larger organizational scales we combine the accountable energy consumption from LCAs with implied energy consumption from the rest of the business that makes up the whole. In other words, we combine "bottom-up" LCA data with "top-down" economic data, creating a direct image projection from the business system, following its units of organization. As more of the needed business operations are counted there is diminishing returns in the search for more things to count, until crossing the boundary to accounting for the high and uncertain environmental costs and fortunes associated with financing, market response and taxes, SEA4. That change is from internal business issues to external issues that really have very little bearing on the internal energy productivity of the business model itself. So we call the EROI for SEA3 and SEA4, respectively, the internal and external measures of EROI.

2.2 Mathematical Structure for SEA

To assess the energy needs of business operations for which there are no recorded energy uses, we first assume that economic costs have the average energy intensity of the global economy, the ratio of global purchased energy to global domestic product ($E_{AV} =$ GPE/GDP). We calculated E_{AV} based upon purchasing power parity (PPP) using data from the U.S. 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 purchased energy (GPE) [11]. 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 1).

$$E_{AV}(2006) = \frac{472\text{e}15\ \text{Btu} / 59{,}939\text{e}9\ \$2006}{3{,}410\ \text{Btu/kWh}} = \frac{7{,}630\ \text{Btu}/\$2006}{3{,}410\ \text{Btu/kWh}} = 2.24\ \text{kWh}/\$2006 \qquad (1)$$

Though economic energy intensity varies in national accounts[27], the global economic energy intensity displays smooth regularity with a gradual trend of decline of ~1.3%/yr using an exponential fit to the historic data[11]. We use that decay rate to estimate change over time as in Equation (2) where *x* is the number of years after 2006. For example, at the midpoint of a project lasting 20 years, starting in 2010 E_{AV} in year 2020 is 1.87 kWh/$2006. There are well known differences in market value of different fuels and their value added for different work (e.g. oil, coal, electricity, etc. having different uses and prices per Btu) [3, 6, 8] as well, but we have not considered those differences.

$$E_{AV}(x) = 2.24 * (1 - .013)^{X} \qquad \text{(kWh/\$2006)} \qquad (2)$$

LCAi corresponds to the direct energy consumed in manufacturing, installing, operating and disposing the primary technology (e.g. wind turbine) and its associated facilities. That the economic energy required to deliver a fuel purchase is not included in the fuels themselves, needs to be accounted for. The purchase price actually goes to people for their needs, and the fuel itself comes from nature and is actually not paid for with money. What money measures is the market value of labor and ownership rights for using property, capital and ideas. To keep the distinction clear we make separate technological energy intensity accounts (Ti) and economic energy intensity accounts (Ei) and a method for conversion so they can be eventually combined.

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 their operation. Employees agree do the work because they are paid, and they use their earnings for making the choices they work to have. People use their earnings for consumption, investment, or savings, and these earnings are received by some other business in a closed system of currency accounts with a regulated supply of currency. Greater or lesser money and energy flows are possible based on innovation and resource use.

In this use of the SEA model the energy inputs for each j^{th} business unit, $dSEA_j$, is the total additional energy input for that level, as shown in Equation (3), where Ti_k and Ei_k are the various M recorded technology and estimated economic energy inputs, respectively, and N is the level of organization of the business considered. The total energy input (SEA) for the whole business system is the sum of the added energy inputs for each business unit (see Equation 4).

$$d\,SEA_j = \sum_{k=0}^{M} \left[Ti_k + Ei_k \right] \qquad (3)$$

$$SEA = LCAi + \sum_{j=0}^{N} dSEA_j \qquad (4)$$

The recorded energy consumed for manufacturing, installing, and retiring technology (e.g. electricity for making steel), its technology energy (Ti), summed in physical units. We convert the costs ($\$E_k$) for purchasing business and human services to energy units (Ei_k) using two energy intensity factors, the world average (E_{AV}) and the weight factor for the item (Eii_k). To reduce the economic energy estimate by the implied amount of the recorded energy use (Ti_k), we subtract the average value to the economy for that amount of energy ($Ti_k/E_{AV} = \$T_k$) from the cost ($\$E_k$). As each item in a budget is considered other concerns may arise and in Table 2 showing our model footnotes indicate those choices, all intended to have the conversion from money to energy measures accurately represent real energy use needed for producing the product. For example, we use a technology energy weighting factor (Tii_k) for fuel use purchases so that a technology energy use (Ti_k) can be inferred from the purchase price, and combined with the economic energy use implied by the cost of delivering it ($\$E_k$). The various inputs for each SEA step include employee salaries, fuel purchases, industrial machinery, and insurance payments, among others. If the average energy value for a specific category of spending is known that is reflected in the intensity factor, Eii_k. For example, from the Costanza study (Figure 1) it appears likely that employee spending is likely to be somewhat below average, and producer products above average. The default is to treat energy intensity as average, E_{AV} as for entire global economy (i.e. $Eii_{jk} = Tii_{jk} = 1$), except for particular reasons, as noted in Table 2. Equations (5) and (6) illustrate the calculation of individual energy inputs for the SEA method.

$$\text{recorded energy} = Ti_{jk}\,\text{(fuel use records) or Tii}\cdot E_{AV}\cdot \$\text{E (for fuel purchases)} \quad (5)$$

$$Ei_{jk} = Eii_{jk}\cdot E_{AV}\cdot (\$E_{,jk} - \$T_{,jk}) \text{ with } \$T_{jk} = Ti_{jk}\cdot E_{AV}\cdot \quad (6)$$

Without subtracting the implied value of recorded fuel uses from the economic costs there would be implied double counting of the recorded fuel uses. For example, total GDP*E_{AV} = GPE accounts for 100% of the world's energy use, and so would a complete accounting of direct fuel uses, so combining them would result in counting each use twice. For each SEA factor, we can correct for this double-counting by subtracting the economic value added (*$T*) for recorded energy uses from the total business expenditures $E (see Equation (6) and Figure 4).

2.3 Background on 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) [12]. There is tremendous variation in the EROI values, over an order of magnitude with values reported at over 100 and others near 1. 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) distinguished the LCAs by indicating the parts of the life cycle (e.g. manufacturing, operation, business, decommissioning, etc.) considered, similar to the SEA structure. 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 for employee compensation and the use of specialized business services for which no resource use accounting is possible [13, 14].

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 the latter had an average EROI of 24, and this may reflect how process analysis involves a greater degree of subjective decisions [12]. 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.

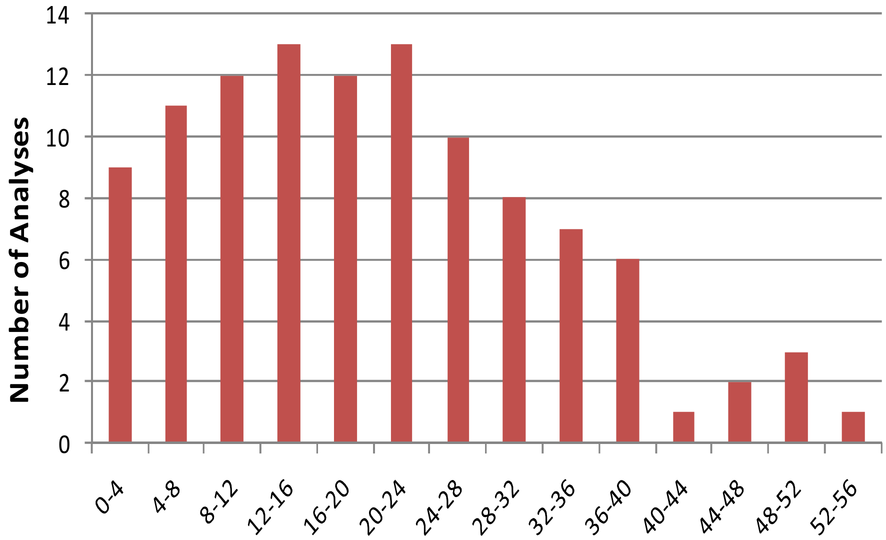

Figure 5. The frequency distribution of EROI for wind turbines as studied in [12] shows an unusually wide range, and may indicate the general lack of standards to follow.

Table 1. The quantity of fuel consumed for a Vestas 2.0MW turbine has an energy content of LCAi = 13,100,000 MJ [16] assumed to cost $150,000.

Fuel/Resource	Energy Consumed (MJ)	Energy Consumed (kWh equiv.)	Fuel cost ($/GJ)
Hard coal	2,215,252	615,348	$2.34
Crude oil	6,036,167	1,676,713	$12.23
Lignite (brown coal)	445,079	123,633	$1.90
Natural Gas	1,618,058	449,461	$6.21
Nuclear Power	392,124	108,923	$21.65
Straw	0	0	$0.95
Wood	0	0	$0.95
Other Biomass	57,917	16,088	$0.95
Primary energy from Hydropower	2,286,239	635,067	$21.65
Primary energy from wind	37,184	10,329	$0.95
		TOTAL Cost of fuels ($) =	**$147,958**
		Btu/$ of fuel purchase	83,777
		Btu/$ for fuel purchase : economy average Btu/$ (2010)	11.5

We based our value of LCAi LCA for a Vestas onshore 2.0 MW wind turbine [16], 13,100,000 MJ (3,640,000 kWh equivalent) of energy consumed for manufacturing and installing the turbine and transmission components (see Table 1). The Vestas example is typical of LCA studies, providing nominal quantities of each energy type used during manufacturing as shown in Table 1 [16]. We use the DOE 2008 Wind Technologies Market Report for our nominal wind turbine capacity factor of

32.6%, the fraction of the total wind generation potential used, which is the average capacity-weighted value reported in Table 7 of [15].

The EROI we found based on the above is 31.4, for our assumed 2.0 MW turbine generating 5,700,000 kWh/yr. That is our starting value for adding the energy requirements of the successively larger business units needed to operate the wind turbines and deliver the energy for sale. As we track the values of EROI considering the energy costs incurred at different levels of business organization we also compare the financial "break-even price" or levelized cost of energy (LCOE) for selling the electricity to cover costs incurred at each level. The estimated market value of the LCAi fuels (see Table 1) is used as the starting point for determining LCOE, approximately $148,000 total. That starting LCOE is $2.29/kWh as shown with other results in Table 3.

3. Energy Input-Output models and results

The calculated results of the SEA case study of a wind business are presented in two sections. Section 3.1 takes a simple cash accounting approach without discounting, using 20 year average costs per kW of generating capacity. The energy generated at a 32.7% capacity factor is 2,856 kWh/yr. We set a market price of $83/MWh for annual income of $236 and net revenue of 11% after taxes. Section 3.2 applies the same cost and energy input factors to show the energy and financial variables as they change over time. It compares project energy flows with E_{AV} decaying at 1.3%/yr with various cash flows using discounted values. It introduces a variety of complex issues important to thinking about a business as operating as a whole, and responding to large and changing societal overhead costs, competition, depreciation, and financing and changing resource costs and regulation.

3.1 Method 1. SEA table with 20 year averaged inputs

Table 2 itemizes the recorded technology fuel uses as well as economic costs converted into energy units for each successively larger scale of working business unit by the SEA method. The starting point is the LCAi energy estimate from the Vestas LCA study, and the other business model costs are organized by business operating unit as in Figure 3, suppliers, field operation, business operation, corporate and economic environment. Most of the cost data are from the Job and Economic Development Impact (JEDI) wind farm model [17] from the National Renewable Energy Laboratory (NREL) and the DOE 2008 Annual Wind Technologies Market Report [15]. As the JEDI model requires the user to choose a state for estimating where money is spent and where jobs are created, we chose Texas.

All money and energy costs are annualized per kW of total generating capacity. The basic procedure for each item in the table starts with either column 1 or 3, a dollar cost or the energy cost. The first step is to establish what value of Ti to use (column 3) and then determine Ei (column 6) to then add them. The value of Ei is reduced by the economic value of Ti (equation 5 & 6) to eliminate double counting. If it so happens that Eii = 1, and so Ei is considered as average, then the + and - values of Ti cancel out, with SEA = Ti + (Ei – Ti). That saves a lot of work and complication, if you don't know much about the energy intensity of the costs for which you are accounting.

When having only energy cost information, as for the first item, LCAi, the total for the line is then just directly entered in column 7, since the LCAi estimate does not consider any economic energy costs. Then to provide a starting point for the LCOE estimates a implied dollar cost for the project fuel mix (Table 1) is attributed to that energy use. The value of $3.70/yr in column 1 is the cost of the fuels, per yr and kW capacity (the $148,000 divided by 2000kW*20yr). That amount of energy per dollar is 13.1 times the E_{AV} average kW/$, so the intensity factor Tii of 13.1 is shown in column 2. For the other fuel uses indicated below that we started with a budget price, not an energy estimate, and use the similar Tii of 12.1 calculated for fuel oil, to obtain Ti estimates for those items. For those items we then estimated a value of Eii, above or below average, and combined the Ti and Ei according to formulas 5 and 6.

Contingency cost estimates for minor items omitted from the JEDI budget. The tax on net revenue in SEA4 are 36% of net revenue, approximating the ratio of total US local, state and federal government costs to GDP. Simple budget range estimates were made for all items and shown in column 8, with accumulative variance in the total energy accounted for at each level shown underlined, and as error bars in figures 7 and 12.

3.1.1Summary of Method 1. results

We find that the EROI drops substantially as we consider more of the business operations, while LCOE rises substantially. In Figure 7 you see EROI decreasing by smaller steps from SEA0 to SEA3, but at the last step, SEA4, there is a large decrease again in EROI and the energy delivered to balance of society, due to the quite large environmental costs of financing and taxes. There is a significant decline in LCOE at that last step too, though, due to the assumed application of a production tax credit (PTC).

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

	LCAi	SEA0	SEA1	SEA2	SEA3	SEA4
EROI (linear)	31.4	12.7	9.9	9.3	8.8	6.0*
EROI (cash flow)	31.4	?	?	?	?	?*
LCOE ($/MWh)	2.29	58.20	66.30	67.10	99.00	78.90
IRRe (%)	155	44	44	44	39	--

*(the EROI calculated for SEA4 excludes the value of the tax credit (PTC) as that is considered a transfer of government costs from others and not a decrease in government energy expenditure in maintaining the business environment)

Figure 6 shows that the technology energy use (LCAi) for producing and operating the wind turbines accounts for 19.1% of the total, and economic energy used by the supply industry delivering the technology (SEA0) is ~28.1% of the total. By adding to the total costs accounted for the value of EROI that starts at 31.42 declines by ~81% to ~5.98 by SEA4, for an implied error of ~525% in estimating the wholesale priced energy delivered to the economy.

Table 2 Whole business SEA system energy Input/Output table, arranged by business unit scale

Whole business system SEA Input/Output Table

Output per kW capacity at 32.7% factor		Value	$/kWh	kWh	oper.	net	AvgCost	Wh/$	Tax	
	Electricity Sales	$236[1]	$0.083	2,856	$129.94	82.0%	0.0455			
	Average for Economy							1,883[2]	36.2%	
		1	2	3	4	5	6	7	8	9
		Cost /yr	Tii	Ti	$T	Eii	Ei	SEA	Input	EROI
Inputs per kW installed capacity / yr		$	% Avg	kWh	Avg Val	%Avg	kWh	kWh	Range	
LCAi	**Primary Technology & Equip.**	$3.70	13.1[3]	90.9				90.9	0.1[5]	31.42
***d*SEA0**	**annualized Tech & Equip. Cost**	$71.63		0.00	$48.26	1.5[4]	66.03	66.03	0.15	
	annualized Phys Plant Cost	$24.15		0.00	$0.00	1.5	68.22	68.22	0.15	
	Subtot& Range	95.78						134.25	0.30[5]	12.68
*d*SEA1	**Field technology**	$18.12	0.03	0.86	$0.46	1.5	49.91	50.77	0.2	
	Field fuels	$0.27	12.1[3]	6.15	$0.00	1.0	0.51	6.66	0.2	
	Field Business Services	$0.20[6]	-			0.9	0.34	0.34	0.3	
	Field employees	$2.75	-			0.9	4.66	4.66	0.3	
	Subtot& Range	21.34						62.42	0.21	9.93
*d*SEA2	**Business technology**	$0.25	0.03	0.01	$0.01	1.5	0.69	0.70	0.3	
	Business Fuels	$0.54	12.1	12.29	$0.00	1.0	1.02	13.31	0.3	
	Operating Business services	$1.50	-			0.9	2.54	2.54	0.3	
	Business salaries	$1.54	-			0.9	2.61	2.61	0.3	
	Subtot& Range	3.83						19.16	0.30	9.31
*d*SEA3	**Corporate technology**	$0.10	0.03	0.00	$0.00	1.5	0.28	0.28	0.5	
	Corporate Fuels	$0.05	12.1	1.14	$0.00	1.0	0.09	1.23	0.5	
	Corporate operations &	$0.50	-			0.9	0.85	0.85	0.3	
	Invest Land & Local Taxes	$3.00				0.9	5.08	5.08	0.2	
	Invest Fees & Insur	$5.34				0.9	9.04	9.04	0.2	
	Subtot& Range	8.99						16.49	0.23	8.84[9]
*d*SEA4 0.0	**Finance cost estimate**	$69.9				1.0	131.68	131.68	0.16	
0.1	**Cost of Government estimate**	$13.2[7]				0.9	22.47	22.47	0.2	
0.2	**Production tax credit**	-$35.0[8]				0.0	0.00	0.00	0	
	Subtot& Range w/o PTC	83.18						154.15	0.16	5.98[9]
Project Totals SEA, Range and EROI		**$213.12**						**477.36**	**0.13**	

Symbols: Tii = tech fuel use rate factor, Ti = tech fuel use intensity total, $T = average economic value added for Ti, Eii = econ fuel use rate factor, Ei = econ fuel use intensity total, SEA = total energy used, *d*SEA# = change from prior level

1. The value of electricity sales, for a capacity factor of 32% and market price for after tax net revenue of 11%
2. Average economic energy intensity, E_{AV} from EIA data = 1.883kWh/$, declining at ~1.24%/yr. over time
3. Tii wt. factor for LCA fuel use, .03, gives the price of LCA measured fuel use in relation to E_{AV}, for the budgeted fuels it is 12.07, to give the energy value of purchased fuels based on cost of fuel oil, in relation to E_{AV}.
4. Eii wt. factors assign above or below avg intensities. If all Eii's = 1.0 the table collapses to SEA4 = tot$*$E_{AV}$
5. Input Range Estimates, are judgmental estimates for each line item, and underlined to indicate the accumulative range of variance for the total energy accounted for, as seen in figure 7 bar chart.
6. Cost categories missing from the JEDI model were given estimates.
7. Taxes on net revenue are 36% of net revenue, approximating the ratio of total US local, state and federal government costs to GDP, from an online calculator http://www.usgovernmentrevenue.com/yearrev2008_0.html
8. The production tax credit considered in the financial model is assigned an Eii of zero and not, considered as a transfer payment from other tax payers and not included in the cost totals here or considered as an energy source.
9. The accumulative internal EROI of 8.84 and external EROI of 5.98 indicate the energy available to society before and after including the basic operating costs of the economic environment, *d*SEA4

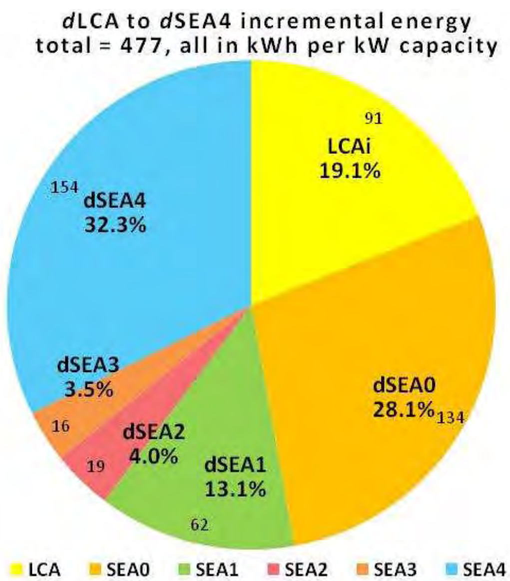

Figure 6. Annualized estimates of 20 yr energy use added at each scale of business unit, LCAi to *d*SEA4. From LCAi = 19% and *d*SEA0 28.1% more, down to *d*SEA1,2 & 3 of 13.1%, 4.0% & 3.5% then a jump to 32.3% for the environmental energy cost, *d*SEA4

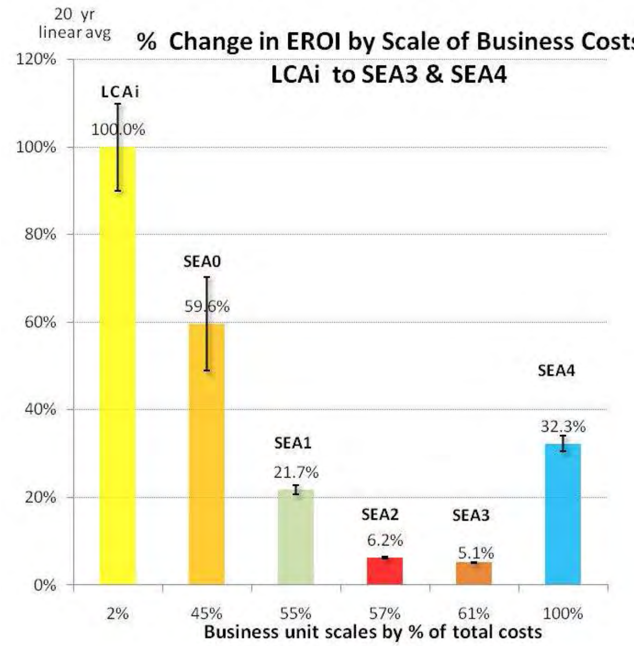

Figure 7. Accumulative effect on EROI for adding the energy costs of each successive scale of business unit relative to prior level, showing discontinuity at boundary with the environment between limit of internal EROI at SEA3 and external EROI at SEA4

3.2 Method 2: Cash Flow and Energy Flow Accounting

The cash flow model considers the effects of 45% of the financial costs being incurred in the first year of the 20 year project, for manufacturing and installing wind turbines (LCAi and SEA0) and revenue being generated at a rate equal to about 6% of the total project costs each year, assuming an 11% net revenue after taxes in the end. Thus, energy inputs and monetary expenditures are not evenly distributed over the wind farm life cycle. This section presents a comparison of monetary costs and both accountable and implied energy inputs for each year of the wind project. Thus, we compare the cash flow of the wind business to its energy flow.

3.2.1 Discounted NPV Cash and Energy Flow Analysis with error dynamic analysis

Table 3 displays the key SEA cash flow model inputs. Four of these inputs were represented using probability distributions, following xxxx [cite the paper that uses distributions for the financial analysis]. For these four inputs, a wide range of values has been reported in the literature. The specification of the distributions was based on an inspection of the values provided in the DOE 2008

Annual Wind Technologies Market Report [15]. To gain insight into the range of possible EROI values at each SEA step, we modeled some inputs as distributions using the commercial software @Risk [18]. Otherwise the inputs for the cash flow model match those of the averaged model and Table 2.

Table 3. Some SEA input factors are estimated using probability distributions, while most inputs are kept constant at nominal values.

Input Variable	**Units**	**Distribution Type**	**Description or value**
Capacity Factor	%	Normal	μ = 32.7, σ = 6.7
Equipment Cost	$/kW	Normal	μ = 1433, σ = 125
Balance of Plant Cost	$/kW	Normal	μ = 483, σ = 42
Annual Operation and Maintenance	$/MWh	Triangle	Lower bound: 5, Peak = 10, Upper bound = 30
Loan Interest Rate	%	Normal	μ = 6.8, σ = 1
Land lease cost	$/turbine	None	6,000
Loan amount	% cost	None	80
Time limit of loan	yrs	None	20
Economy inflation rate	%	None	3%
Cost of government	% of profits	None	36%

We also develop an energy flow model that includes the technical energy, Ti, and economic energy, Ei, inputs of each SEA step. We analyze the cash and energy flow model by choosing the sales price of electricity such that the net present value (NPV) of the cash flow equals zero for each SEA level. 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 and SEA level. We additionally include the production tax credit of 2.1 cents per kWh for ten years (escalated at the assumed rate of inflation) to conceptualize the tax subsidy in the context of both money and energy.

[CAREY]: I'M NOT SURE I CARE TO KEEP THE CASH AND ENERGY FLOW FIGURES 8 AND 9 AND DISCUSSION… I'M LEANING TO "NO" RIGHT NOW (8/12/10) I'd like to see the "break even points"…it might be what the non-economists who can't handle all our complications will see and understand intuitively, seeing the "payback period" for both energy and money.

Figures 8 and 9 show the cumulative cash and energy flows of the wind business, respectively. Recall that we for the cash flow to zero net profit after the 20-year time frame such that energy is sold at the LCOE independently calculated for each step (see Figures 10 and 11). For all SEA levels, the We plot the effect of the renewable energy Production Tax Credit (PTC) 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 (see Figure 10). Just as with the cash flow, a large portion (36%) of the energy expenditure occurs in the first year to manufacture and install the turbine. The gray area shows the "virtual energy grant" of 'reduces' required energy inputs by 2,100 kWh/kW 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 societal tax burdens to others.

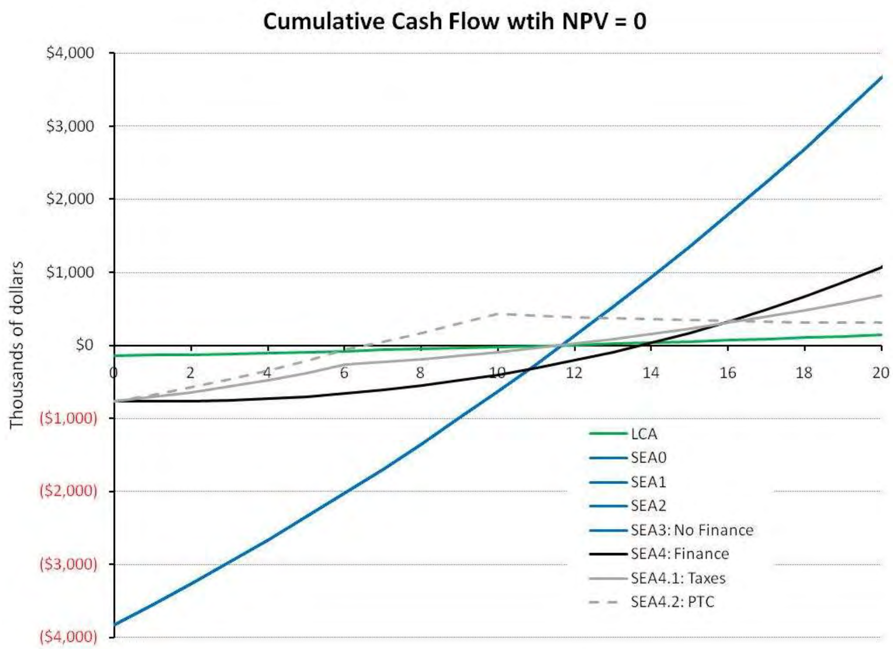

Figure 8. The cumulative cash flow (nominal case shown using discount rate of 6%) shows that, except for SEA4 levels that consider financing, the monetary costs for each level of business organization are dominated by the first year capital expenditures.

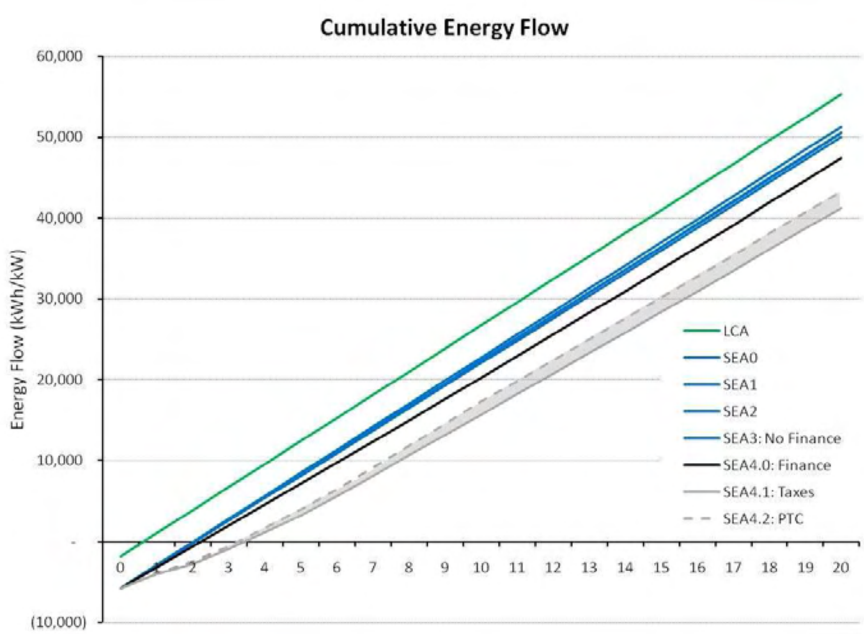

Figure 9. The energy flows (kWh/kW) of the nominal case per each SEA level are more continuous than cash flows that include non-physical concepts such as

depreciation, financing, and taxes. The SEA4 PTC level is shown as if the production tax credit reduces energy inputs to the wind business (shaded gray area), but physically this is impossible (i.e. a tax credit cannot supply energy).

3.2.2 EROI compared to LCOE

Businesses use cash flows and their sensitivity to major input parameters to assess risks and probabilities for business models. Here, we discuss the results of using our cash flow model to estimate LCOE, and plot these values against the EROI calculated by using the estimated energy inputs from the cash flow model. Thus, the EROI and LCOE values and uncertainties shown in Figures 10 and 11 are not independently derived values. However, as the SEA method uses money as a proxy for unaccountable energy inputs to the business, important correlations between LCOE and EROI develop.

First, Figures 10 and 11 demonstrate that as more inputs are included in the energy business system, EROI declines, and the associated breakeven LCOE price for energy sales becomes larger. The uncertainties of the inputs to the SEA model transmit themselves differently for EROI and LCOE. There is high uncertainty at the beginning step (e.g. LCA) of the analysis for EROI and high uncertainty at the end step (e.g. SEA4) for LCOE, and vice versa. This inverse relationship between LCOE and EROI becomes apparent when looking at their general equations (see Equations 8 and 9). Energy produced, E_{out}, by the energy business is in the numerator of EROI but in the denominator of LCOE. Furthermore, monetary costs, $\$_{in}$, are in the numerator of LCOE, and when using money as a proxy for energy inputs, $\$_{in}$ are in the denominator of EROI.

$$EROI = \frac{E_{out}}{E_{in}} \propto \frac{E_{out}}{\$_{in} \cdot \left(E_{consumed} \big/ \$\,\text{GDP} \right)_{economy}} \qquad (8)$$

$$LCOE = \frac{NPV(\$_{in})}{NPV(E_{out})} \propto \frac{\$_{in}}{E_{out}} \qquad (9)$$

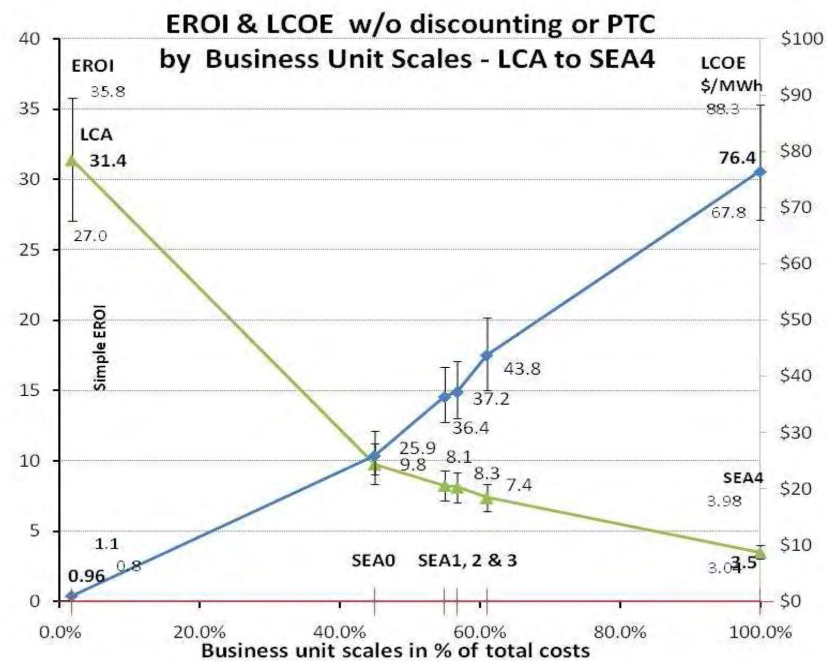

Figure 10. Values of EROI decrease and values of LCOE increase as the size of business operation considered increases. Variances from the @RISK cash flow model show expected variation in proportion to scale.

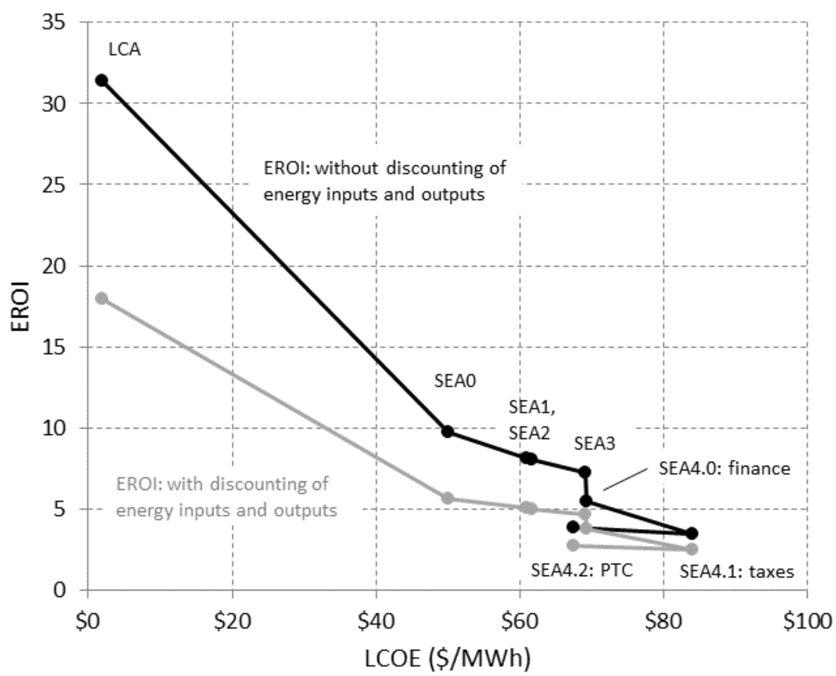

Figure 11. This graph plots results when applying a discount rate of 6% in the cash flows only (black line) and both cash and energy flows (grey line). <Grid to fine dotted horizontal only, and axes to black 1.5 point to be consistent with others>,

It's difficult to understand, but some interesting effects of discounting are visible in Figure 11, showing future monetary and energy inputs and outputs with their effects on both EROI and LCOE. Discounting future cash flows is common practice in financial accounting. By applying a discount rate of 6% (versus 0%), the median LCOE at level SEA0 increases from $26/MWh to $50/MWh and at level SEA4.1 jumps from $76/MWh to $84/MWh (see black line in Figure 11). Thus, discounting weighs the wind business's early costs more heavily than later costs and causes final LCOE to increase. This discounting causes an apparently strange pattern of a near vertical line from level SEA3, with no financing included, to SEA4.0 that includes financing. The relative change in LCOE from financing is minimal, but the estimated energy consumption related to paying interest on the loan is large. However, when the discount rate is 0%, financing does have a large impact on increasing LCOE.

Because the definition of LCOE includes discounting monetary inputs and energy outputs, an interesting comparison is that of LCOE to EROI that discounts both inputs and outputs. While the black line of Figure 11 represents results from discounting monetary inputs and wind electricity outputs, the gray line discounts all energy and monetary outputs *and* inputs. Due to the inverse relation of EROI to LCOE, future discounting makes EROI smaller with the EROI at SEA4.1 going from 3.5 with no discounting to 2.5. This effect of discounting is not new, and its application making the wind business appear less viable is akin to the discussion of how a decision whether to invest in climate (e.g. global warming) mitigation can be simplified to the economist's choice of discount rate assumed in the cost-benefit analysis [20-22].

We modeled the impact of the PTC that shows it greatly decreases LCOE, as the tax credit is designed to do.

CAREY STOPPED HERE MOSTLY …

4. Interpretation, application and future work

4.1 Whole system comparative value

One interesting application is comparing the total monetary return on energy invested (MREI) for with the world average rate of economic return on energy ($1/E_{AV}$). Figure 12 shows columns 1) total monetary costs at SEA4, 2) the MREI (value-added) for the energy invested at SEA4, 3) the project wholesale income for the SEA4, and 4) the possible retail value of the project if sold for a 50% mark-up. What's interesting is that wholesale value seems to be 5% lower than the world average value for using that amount of energy. What might raise it includes lowering the Eii assigned to the project costs, raising the market price, or capacity factor, distributing the costs over more years, reducing the apparent high labor intensity of some costs. It might also indicate the US economy has higher than average overhead costs and new societal costs of climate change adaptation should be included too. All of these seem to raise important questions. The measure itself will become validated with refinement of the method, but the value of seeing all those questions as connected demonstrates that this is as good way to look at the interaction of financial and energy variables, at least for comparing scenarios with similar assumptions.

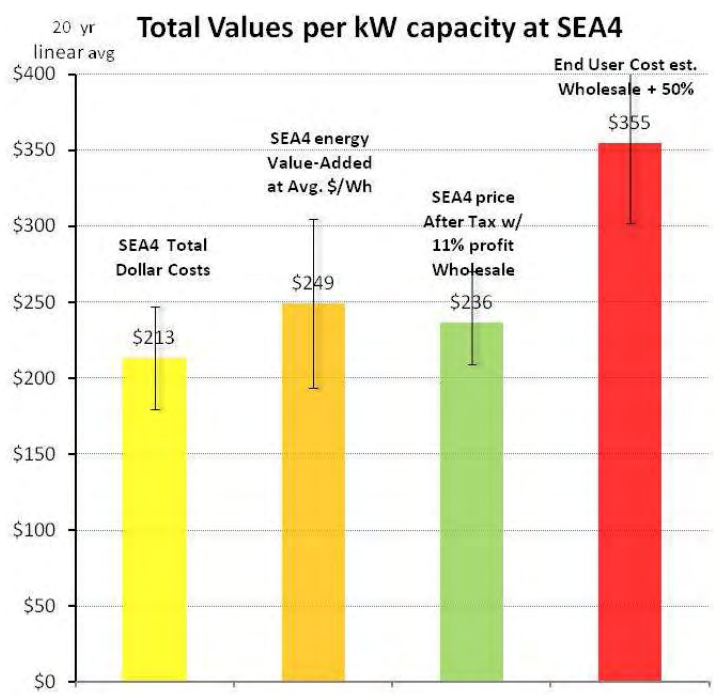

Figure 12. Monetary costs and Monetary Returns on Energy costs (MREI)- comparing (column 2) $1/E_{AV}$ * SEA4 the world average rate with the wholesale price (column 3), as a possible standard financial indicator of energy performance.

4.2 Whole environmental assessment

Life cycle assessments, whether LCA studies of technology supply chains or SEA and TEA studies of whole system impacts, help people understand the complex interactions between organized systems and their environments. Environments themselves are moving targets, like our economic environment that grew ever more rapidly for two hundred years with technology making resources ever cheaper much of the time, until increasing resource use, overcrowding and an explosion of environmental complications began making resources ever more costly again. The life cycle of any economic process begins with compound growth and then adjusts one or another way to its limits at some point. For a business to be responsive to its environment it needs to be aware of its environment's stage of development, considered as a business with its own life cycle of development.

Like any business the internal strategies during stages of environmental growth without complications are characteristically different from those appropriate to responding to complex new constraints such as avoiding dangerous limits. SEA is intended to assist in learning the change from aggressive goal seeking to exploratory purpose seeking thought processes involved. Businesses that don't acknowledge approaching market or resource limits, for example, may over commit to growing earnings or low prices that are not going to materialize, and so get taken over by competition with more foresight. Those more strategic realities make this kind of life cycle assessment also a study of the complex life cycles of one's environment. Today decision makers need all the accurate information and other help they can get for inventing the complex adaptations needed for us to find a better fit with our rapidly changing physical world.

In the 1750's when the difference between heat and temperature was first being recognized by Joseph Black, his friend James Watt then applied the insight in how to measure energy for machines to his work inventing steam engines in the 1760's. It changed the world. The similar change in measurement science presented here is for business systems, from adding up the energy uses you see to adding up the hidden ones the business needs. It may not make businesses with ever greater impact, repeating Watt's magic for using efficiency to make ever more consuming machines. In the present age developing a way define basic energy conservation equations for business systems may still have an impact though. Instead of pointing to how to multiply our uses of the earth, it might provide equally clear indications of how to avoid commitments to resources that will not materialize, among other things.

One immediate application of SEA measures might be for allocating government resources to subsidizing innovation where it will have the most benefit, using real performance measures to guide the use of tax credits or to develop rating systems to help guide intelligent investors. It might similarly be used to help allocate tax penalties, to fairly distribute societal costs of adapting to the growing environmental penalties for energy use, the depletion of affordable energy resources and the quite high rebound effects of using our remaining affordable resources for unimportant purposes.

Another way to use physical measures of whole system energy use is to take apart the model and find other combinations of parts that would "better fit" the environment. The availability of wind energy during a day often does not match the power demand in urban areas where the energy is in most demand, for example. The resource may also be found in remote areas where the energy is not needed. Putting those two together might suggest wind development where land is less expensive and wind is plentiful, maybe avoiding transmission, marketing and storage costs, by co-developing industries with automated operations that can use energy on demand. They might produce hydrogen fuel to balance their demand cycles or drive other processes that can follow the swings in supply. A job is a job too, and workers assured an average number of hours of both work and leisure might create flexible teams able to adjust operation so demand fits the supply. Either strategy might allow wind powered manufacturing making wind turbines, and close the loop on renewables as a whole system and test their sustainability [23]. <How does this paragraph relate to the paper? There needs to be a better tie.>

The largest financial and energy costs for the wind farm come from the first costs of development for the 20 year project. They greatly add to the costs of financing, and added need for profits, and then the needed support of government for maintaining the economic environment too. Designs to make things last longer cut all those costs, the same rate of return with less impact. Various capital costs could be engineered to last longer, extending the productive life of the investment. That could significantly raise the overall EROI.

There are also critical issues regarding the limits of societal sustainability, with the original examination [2] being expanded on in this special issue by Hall, et. all., estimating the EROI required to run a reasonably complex society. In relation to that question, with economic proxy measures of energy as we have used for the SEA method, one would interpret the several years of escalating energy prices without responsive increases in supply prior to the 2008 financial collapse as a clear price signal of an unexpected episode of resource exhaustion, as if "hitting bottom" during unusually heavy demand, as others have also concluded [29].

It's possible that the confusion on this whole issue comes from not having been a good way to make physical measurements of the inputs needed by whole business systems. If resource depletion is real, but just hidden from mathematical view, then it would be critically important to understand. Our societal financial needs would then become recognized as growing physical resource overhead costs, in the face of apparently diminishing supply, and directly conflicting with the resource needs for responding to climate change. Being able to accurately measure the energy requirements for complex economic systems would be quite valuable for making the informed choices for which the world needs better understanding [24].

4.3 Pros and Cons of SEA methodology

Assessing the needs or impacts of environmental systems first depends on having one's questions refer to what is inside the functional boundary of the system. Learning to do that raises a number of unfamiliar questions. The SEA method offers one practical strategy, producing "soft information" in that it relies on combining high precision and low precision measures, using a rigorous method of defining the boundaries of the subjects being measured. Prior uses of input-output models [5, 7] (see Figure 1) suggest that producer products have widely varying energy intensity, while the largest sectors of the economy are close to average. We have concluded that absent other information that "average" is a better estimate for any energy use than "zero". Though that seems to result in a major improvement in getting the scale of results about right, it leaves the answers approximate. It is essential to have multiple studies of intensities for different kinds of spending to calibrate the method.

Still, we think the SEA method makes a useful contribution to defining measures for whole systems. Another particular advantage is it makes it quite simple to make initial estimates of energy use allowing refined estimates for more accuracy is needed. The SEA approach, accounting by whole business units, sets a reproducible 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.

4.4 Future Work

It seems likely to take developing standards in applying this method to various specialized industries, aided by econometric studies, before a common standard might emerge. Questions like how to compare the utility of different fuels would also need to be addressed, for example. Comparing multiple types of electricity generation (e.g. natural gas combined cycle, pulverized coal, photovoltaic solar, etc.) the costs of producing constant electricity output over time or the common diurnal pattern of electricity demand would require a larger industrial system analysis. With wind energy studies, for example, it makes sense to account for only the average electricity output and not the particular intermittent pattern of its output. In practice a wind farm developer would learn how to interpret that, but it makes a measure of EROI for wind energy not directly comparable to an EROI for other sources.

It is known that fossil, nuclear, and hydropower are generally dispatchable and can independently follow the demand pattern, though they each have different exposure to unresolved risks of shifting environmental costs and values. Wind would also face limits of tolerance for wind towers in the environment too, of course. These factors may, in turn, affect the validity of the SEA method which assumes that energy resources are interchangeable. <Correct the following sentence. <How would be best? see comment > > In the past fossil fuels have been a highly portable common world standard energy source 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 and might affect how SEA models are designed.

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 known, one can estimate the EROI of the supply system as a whole for matching the demand.

Another area of research needing attention is the basic relation between financial information and the physical economy, and the evident tendency for financial markets to develop great bubbles of misinformation about the physical processes they interpret the value of. Information systems with no clear way to define what they are describing seem prone to instability. Financing schemes, taxes, subsidies, returns to investors, and discounting cash flows could all introduce speculative information if used as measures of energy. That makes devising a reliable way to measure physical flows in a world where so many of them seem unreliably accounted for that much more important, and more difficult. A good example is the noticeable difference between the remarkably smooth curves of world energy use and proportional world GDP values [28] and the remarkably independent movement of the US stock market relative to US energy use over several decades [21, Figure 2].

Also needing further study, of course, is the real meaning of "average" embodied energy for money, and how to identify what boundaries that applies to. We've assumed world energy use per dollar to be largely uniform. A network analysis, asking the "degrees of separation" between energy uses on earth seems needed. For example, if in a month a person gives money to 200 different businesses, and each business receiving the income then spends on 200 different people, then in three months there are 200^3*200^3 partial recipients of any dollar spent. That's 6.4*10^13 potential end recipients in three months. If you assume there are 5 billion economically active people on earth each one might receive part of that single dollar spent by about 13 thousand different paths, on average. It's confusing math, but may be fundamentally important for understanding how our economies work and how to measure them. There may be identifiable community's with earning and spending above or below average intensity, too, and give both businesses, people and policy makers options for changing their environmental costs and benefits not presently visible.

5. 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 by the primary technologies. It accounts for identified energy uses and overlooks the hidden energy needs of the system being assessed, though, and so its measures while rigorous are rigorous measures for only a small part of the system being studied. A "top down" approach using econometric measures of probable energy use does gloss over some unique attributes of particular inputs, but it also captures energy uses that are not individually accountable. When calibrated to an empirically located natural system boundary locating all energy needs, the measure boundary so much more closely matches its real subject that when combined with a "bottom up" approach such as LCA, the combined accuracy is greatly improved.

The hybrid SEA approach outlined here seeks combines the a bottom up LCA approach that accounts for the energy uses of specific technologies with a top down approach accounting for the hidden shares of the energy used globally to operate a whole system of working parts. In finding a way to use the financial accounting boundaries for business systems to construct a physical measure based on the natural environmental boundaries of the system, identifying it as a physical unit of organization in its environment, this approach is consistent with the view that a business is a component of a complex natural world, and the general desire to better understand both.

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Nomenclature

E_{AV} - world average energy intensity per dollar GDP
$\$E_{jk}$ - business costs of kth item in the jth business unit
Ei_{jk} - economic energy of kth item of jth business unit
Eii - relative economic fuel use intensity factor
$\$T_{jk}$ - energy use value of kth item of jth business unit
Ti_{jk} - tech energy of kth item in the jth business unit
e - estimated range of variation
Tii_{ij} - tech energy intensity factor relative to average energy intensity of kth item in the jth business unit
EROI - energy return on energy invested
LCA - life cycle assessment
LCOE - levelized cost of electricity
NPV - net present value
SEA - system energy assessment
*d*SEA - change from prior SEA level
TEA - total environmental assessment
Eii_{ij} - econ energy intensity factor relative to average energy intensity of kth item in the jth business unit

Abbreviations

wt	weight	avg	average	invest	investment
est	estimate	yr	year	insur	insurance
tot	total	equip	equipment	PTC	production tax credit
val	value	tech	technology		

References and Notes

1. Hall, C.A.S., C.J. Cleveland, and R.K. Kaufman, *Energy and Resource Quality: the ecology of the economic process*. 1986, New York: Wiley.
2. Hall, C.A.S., S. Balogh, and D.J.R. Murphy, *What is the Minimum EROI that a Sustainable Society Must Have?* Energies, 2009. **2**: p. 25-47.
3. Cleveland, C.J., R.K. Kaufman, and D.I. Stern, *Aggregation and the role of energy in the economy*. Ecological Economics, 2000. **32**(2): p. 301-317.
4. Costanza, R., *Embodied Energy and Economic Valuation.* Science, 1980. **210**(4475): p. 1219-1224.
5. Costanza, R. and R.A. Herendeen, *Embodied energy and economic value in the United States economy: 1963, 1967, and 1972.* Resources and Energy, 1984. **6**: p. 129-163.
6. Zarnikau, J., S. Guermouche, and P. Schmidt, *Can Different Energy Resources be Added or Compared.* Energy - The International Journal, 1996. **21**(6): p. 483-491.
7. Carnegie Mellon University Green Design Institute. *Economic Input-Output Life Cycle Assessment (EIO-LCA) model [Internet], Available from: <http://www.eiolca.net/>*. 2010 [cited 2010; Available from: http://www.eiolca.net/.
8. Cleveland, C.J., *Net energy from the extraction of oil and gas in the United States.* Energy, 2005. **30**(5): p. 769-782.

9. Hall, C.A.S., C.J. Cleveland, and B. Mithell, *Yield per effort as a function of time and effort for United States petroleum, uranium and coal*, in *Energy and Ecological Modelling, Symposium of the International Society for Ecological Modeling*, W.J. Mitsch, R.W. Bosserman, and J.M. Klopatek, Editors. 1981, Elsevier Scientific: Louisville, Kentucky. p. 715-724.
10. Henshaw, P. *TEA - Total Environmental Assessment Method*. in *American Center for Life Cycle Assessment*. 2009. Boston, MA. http://www.synapse9.com/pub/ACLCA09-TEA.htm
11. EIA, *International Energy Outlook.* 2009.
12. Kubiszewski, I., C.J. Cleveland, and P.K. Endres, *Meta-analysis of net energy return for wind power systems.* Renewable Energy, 2009. **35**(1): p. 218-225.
13. Pimentel, D. and T.W. Patzek, *Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower.* Natural Resources Research, 2005. **14**(1): p. 65-76.
14. Pradhan, A., et al., *The Energy Balance of Soybean Oil Biodiesel Production: A Review of Past Studies.* Transactions of the American Society of Agricultural and Biological Engineers, 2008. **51**(1): p. 185-194.
15. Wiser, R. and M. Bolinger, *2008 Wind Technologies Market Report*. 2009, Energy Efficiency and Renewable Energy office of the US Department of Energy. p. 68.
16. Elsam, *Life Cycle Assessment of offshore and onshore sited wind farms*, Elsam Engineering A/S, Editor. 2004, Vestas Wind Systems A/S,.
17. NREL, *JEDI (Job and Economic Development Impact) Wind Energy Model, release 1.09.03e. Available November 2009 at: http://www.nrel.gov/analysis/jedi/about_jedi_wind.html*. 2009.
18. Palisade Corporation, *@Risk for Excel, version 5.5.1*. 2010.
19. NREL, *Wind Energy Finance calculator, available December 2009 at: http://analysis.nrel.gov/windfinance/login.asp*. 2009.
20. Broome, J., *The Ethics of Climate Change*, in *Scientific American*. 2008. p. 96-102.
21. Nordhaus, W.D., *Managing the Global Commons: The Economics of Climate Change*. 1994: MIT Press.
22. Stern, N., *The Economics of Climate Change: The Stern Review*. 2007: Cambridge University Press.
23. King, C.W. and M.E. Webber. *Methodology for Calculating the Ability of Renewable Energy Systems to Manufacture Themselves, Paper ES2009-90026*. in *ASME 3rd International Conference on Energy Sustainability*. 2009. San Francisco, CA: ASME.
24. Tainter, J., *The Collapse of Complex Societies*. 1988: Cambridge University Press.
25. Treloar, G. J., Love P. E. D., Faniran Olusegun, O. F., Improving the reliability of embodied energy methods for project life-cycle decision making, *Logistics Information Management* 2001: 14(5/6) 303-317
26. Guinée, J. B., *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards, Eco-Efficiency in Industry and Science*. 2002: Kluwer Academic Press
27. Gupta, A., Empirical Look at Global Efficiencies - Straightforward empirical analysis of 131 countries. *BioPhysical Economics* Oct16-17, 2009, *SUNY ESF, Syracuse NY* http://web.mac.com/biophysicalecon/iWeb/Site/BPE%20Conference_files/Download%20Gupta.pdf
28. Henshaw, P.F., Why Efficiency Improvement Causes Growing Consumption. *BioPhysical Economics* Oct16-17, 2009, *SUNY ESF, Syracuse NY.* http://www.synapse9.com/pub/EffMultiplies.htm
29. Hamilton, J.D., Causes and Consequences of the Oil Shock of 2007 ‐ 08. *Brookings Papers*, Spring 2009, http://www.brookings.edu/economics/bpea/~/media/Files/Programs/ES/BPEA/ 2009_spring_bpea_papers/2009_s