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energy return on energy invested: economic “top-down” vs. Life cycle “bottom-up” approach

carey alternate title suggestion: the relation of energy return on energy invested to internal rate of return: wind farm example
 or
ph alt: LcA v. TEA methods - how the whole system energy costs of energy investments are measured affects EROI and business IRR for energy

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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. For a wind farm development, the typical life cycle analyses (LCA) focus upon the principal technology inputs and their accountable embodied technology chains of origin and disposal. However, the LCA omits those same kinds of embodied impacts for the labor and commerce employed by the whole operating systems needed to make use of the technology, even though the energy associated with labor and commerce are components of a total environmental assessment (TEA). The total of embodied impacts of labor, technology and commerce can be calculated only by combining a “top-down” method of dividing up a business operation as a whole using econometric methods with a “bottom-up" method of adding up identifiable parts. The top-down technique gives an inclusive measure of average content. The bottom-up technique captures the more notable and directly identifiable individual parts. A refined estimate of total impacts comes from combining those indentified by each accounting method. To understand the true energy return on energy invested (EROI and EIRR) we compare different ways for combining the two methods. The model used is that of a generic wind farm in Texas using the VESTAS wind farm data as an example for a business model and industry.

The TEA accounting will look at the total costs used to run a business at four business organizational scales, a) for the principle technology by itself as a system, b) combined with its field operating costs and labor, then c) with the business support systems they need and then d) including the business management and financing structure as the whole system. We start with the LCA measures of the energy used for producing and using the principle technology used converted to equivalent electrical energy (kWh). The technology costs, employee costs, financing costs, costs for physical assets and land owner payments are all then assigned an embodied energy in relation to their cost. That value is chosen to be either above or below the average energy intensity for the whole economy, the nominal energy used to produce GDP (Wh/$). The money made from the wind farm investment is equal to the total megawatt-hours (MWh) produced by the wind farm multiplied by the average cost of electricity sold ($/MWh). Combining the energy costs and comparing with the net returns gives a system (EROI) at each level of business organization and a whole business rate of energy return to compare with its internal financial return (EIRR & IRR).

The bottom-up data used is from the LCA data for the VESTAS wind farm. Other major issues are considered. The justification, necessity and technique of combining statistical measures of embodied energy with material measures, are discussed. That wind generated electricity is a high quality energy source but also less versatile without storage, and the importance of the resource impact opportunity costs and mitigation benefits for adding to or relieving strains on other resources are also discussed. These all reflect on the economic value of the energy consumed and produced by a wind farm. This follows the TEA approach of constructing rigorous whole system measures and then adding notes about the things left out.

Thus having a reliable way to convert monetary investments and returns to energy, and energy investment and returns to money, we can discuss reasons for the LCA and TEA methods arrive at different answers. The difference provides insight into the most useful ways to use systems analysis for evaluating energy investments in the economy.

**Keywords:** ­energy return, internal rate of return, net energy, energy economics

# 1. INTRODUCTION

This paper analyzes the energy flow through a project, measured as energy return on energy invested (EROI) and compares that metric to standard financial metrics of internal rate of return (IRR) and levelized cost of electricity (LCOE). There exists a tremendous amount of literature and research investigating the links between energy resources and technology with economic growth and returns [1-5].

Estimates of the energy returns from a project may differ greatly from the projected financial returns for the same project. The practice of discounting future costs and revenues in the financial analysis of a project to account for opportunity costs and inflation may account for some differences between a financial analysis and an EROI calculation. Yet, the omission of certain key activities from traditional LCA may explain much of the remaining gap, as discussed in this paper.

## 1.1 Analysis Goal

The goal of the present analysis is to use a wind turbine as an energy generating technology to compare engineering systems calculations of EROI to financial and economic calculations of IRR and LCOE. Many of the graphical results are thus presented with one axis labeled using a measure of energy and the other axis using a measure of monetary costs.

By using traditional process life cycle analyses (LCAs) as a starting point, additional business units and corresponding monetary expenditures of a wind farm developer and operator are included in a step-by-step manner to track how EROI changes with the incorporation of each unit. In order to perform this comparison, the average energy intensity (Btu/$, or equivalent kWh/$) of the economy is used to convert monetary expenditures into an equivalent quantity of energy. This conceptual approach has been used in the past as part of more economy-wide input-output (I/O) LCAs to understand the embodied energy of the various sectors of the economy [3, 4]. Part of the value of the present work is the explanation of how different parts of a total business (e.g. wind farm developer) can be understood to impact EROI in the context of different system boundaries for LCA. This explanation is provided by choosing a narrow system boundary at the beginning of the analysis, and then including more parts of the business until the system boundary is inclusive of the vast majority of economic and energetic costs for developing a wind farm project. Thus, a proper context is provided for understanding how to interpret EROI as a measure of economic viability for energy technologies and resources.

Section 2.1 provides a background on previous LCA studies of EROI for wind turbines, and Section 2.2 describes a nominal LCA used as a starting basis for this work. Section 2.3 describes the use of average energy intensity for this methodology of this paper. The results are described in Section 3 by drawing comparisons between EROI and monetary indicators.

# 2. Analysis DESCRIPTION AND Background Assumptions

 Blah blah maybe …

## 2.1 Background on EROI for Wind Turbines

The EROI of wind turbines has been calculated many times by many authors. It is not the purpose of this study to recalculate the EROI of a wind turbine, but to use a nominal range of values from the literature as a starting point for subsequent analysis. 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 Kubiszewski) [6]. 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.

**Figure Kubiszewski.** The frequency distribution of EROI as studied in [6] shows the majority of the values are less than 40, although a few values were > 100 and many are < 4.

There is also a variety of parts of the business considered in the LCAs including manufacturing, business management, transport, construction, grid connection, operating and maintenance, and decommissioning. However, given all of the studies of the meta-analysis, Kubiszewski et al. (2009) show that 85% of the values for EROI of wind turbines are below 40, and this value may be considered an effective upper-bound to constrain the present analysis. Furthermore, they indicate a significant and unnerving difference between the two major methods for calculating EROI:

“Studies using the input–output analysis have an average EROI of 12 while those using process analysis an average EROI of 24. Process analysis typically involves a greater degree of subjective decisions by the analyst in regard to system boundaries, and may be prone to the exclusion of certain indirect costs compared to input–output analysis.” [6].

In order to understand how EROI can be used as a measure for economic growth potential or financial returns, the proper context of the values from LCAs must be obtained. The analysis presented in this work attempts to investigate both this gap between process analysis LCA and input-output (I/O) LCA, as well as how other parts of a business or economy consume energy. A *major assumption of this work* is that the starting EROI value for a wind turbine is derived using a process analysis. This “starting value” is assumed to incorporate only the energy for manufacturing and constructing the wind farm. In other words, the starting value assumes no energy consumption from direct or indirect operations, maintenance, or business costs of the wind developer or other firms of the economy, including the government (e.g. taxes and subsidies). Thus, as more parts of the wind development business are incorporated into the analysis, the EROI will decline, and the amount of this decline and final EROI can then be interpreted in the context of the expected financial returns and LCOE.

**2.2 Energy Flow Analysis of Wind – Nominal LCA**

In addition to using the values collected in reference [6] to provide an overview of wind power EROI values, a nominal life cycle analysis (LCA) of a Vestas onshore 2.0 MW wind turbine was used as an example to provide specific values as necessary (e.g. the amount of each energy type used during manufacturing, capacity factor, etc.) [7]. The EROI 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%. 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 Vestas LCA). Thus, the EROI = 31 is used as a starting value for incorporating the energy requirements of business operational units during a wind project.

**Table Vestas LCA.** The quantity of fuel consumed for a Vestas 2.0MW turbine has an energy content of 13,100,000 MJ costing approximately $150,000. Energy consumed is from reference [7].

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In order to compare calculated EROI values with standard energy financial descriptors such as LCOE, a monetary cost value must be associated with each (see Figure EROI). 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 Vestas LCA).

 s The results are described in Section ase (whcih eans you don'o shine, wind to blow, or fossil fuel to regeneratehumnas

**2.3 Energy Flow Analysis of Wind - SEA**

The System Energy Accounting (SEA) method uses 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 ($2005) while consuming 472 quads of primary energy. [EIA International Energy Outlook 2009]. These values correspond to an energy intensity of 7,630 Btu/$ in 2006. Because the energy output of a wind turbine is electricity, we convert this value to units of electricity, or kWh (see Equation 1). 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 [1, 5, 8].

$$E\_{in} \left(kWh\right)= \frac{7,630 Btu/\$2006}{3,410 Btu/kWh}\left(\$ spent\right)$$

 $=\left(2.24 kWh/\$2006 \right)\left(\$ spent\right)$ (1)



**Figure Energy Intensity.** Include such a graph IF (1) we have room in the end, and (2) if we create our own graph from baseline data (US EIA or the IEA) and make the values in the graph correspond to our equations presented in this section.

SEA makes use of the NREL JEDI model to estimate the costs of a wind project in Texas …

SEA 0:

This what SEA 0 incorporates …

SEA 1:

This what SEA 1 incorporates …

SEA 2:

This what SEA 2 incorporates …

SEA 3:

This what SEA 3 incorporates …

SEA 3 is broken into 3 subparts because doing so makes the effects of taxes and subsides more apparent.

SEA 3.0:

This what SEA 3.0 incorporates …

SEA 3.1:

This what SEA 3.1 incorporates …

SEA 3.2:

This what SEA 3.2 incorporates …



**Figure Energy Flow.** The annual flow of energy consumed (negative) and produced (positive) is very similar for all levels of analysis after the first year when there is a large negative energy flow for manufacturing, constructing, and purchasing the turbine technology.

 

**Figure Methodology.** Each subsequent level of analysis incorporates the energy inputs of all previous levels. The left-pointing arrow for the first level, LCA, indicates that the energy consumption is base information obtained via the process LCA [7], and a monetary value is calculated from the energy types consumed. The right-pointing arrows for all other analysis levels indicate that monetary costs are used from financial analyses [9, 10] to multiply by the average energy intensity of the economy to obtain an estimate of energy inputs.

## 2.4 Cost Flow Analysis of Wind

The Wind Energy Finance Model of the National Renewable Energy Laboratory or NREL [X] was used estimate the annual cash flows corresponding to the energy flows discussed in Section 2.3. Capital and operating costs obtained from the NREL JEDI model were input to the Wind Energy Finance Model. A 3% inflation rate as assumed. A typical capital structure was adopted, with 20% equity (with a target internal rate of return or IRR of 10%) and 80% debt (with a 6.8% interest rate on the debt financing). A production tax credit of 2.1 cents per kWh over the first ten years of the project (escalated at the assumed rate of inflation) was assumed. The projected costs provided by the model for each year over the project life were then categorized into the “levels” discussed in Section 2.3.



**Figure Cost Flow.** The project costs, neglecting any revenue, are very close for each analysis level that does not include financing.

## 2.5 What if we consider the economic value of energy inputs and outputs?

As noted earlier, some of the energy inputs and outputs to a wind project can be clearly identified, such as the electricity output from the project. But some of the inputs with embodied energy -- particularly those associated with the financial system relied upon to finance the project -- can not be readily traced to an energy resource. In this analysis, we identify those energy inputs which can be reasonably traced and assign to them resource-specific economic values. In cases for which specific types of energy resources cannot be traced, economy-wide economic values are used to reflect the economic value of embodied energy inputs.

We note that economists tend to respond with suspicion to exercises which seek to convert all of the inputs and outputs of a production activity into heating values, such as Btu units. *This is somewhat demystified by understanding how very much of the embodied impacts of products are accounted for only by their accumulative costs passed along within the price of supply chain goods and services.* Among the concerns are:

Production functions (reflecting how inputs are converted to outputs) should specify how energy, labor, capital, raw materials, and entrepreneurship are used in the production of goods and services and the degree of substitution among those distinct inputs and the technology applied. These inputs may have distinct and essential roles to play in the production process and cannot be readily converted into a common physical unit, such as labor man-hours, energy Btus, or information content.

Value is ultimately determined by consumers and producers in markets and may not reflect the amount of energy (or labor) used to produce a good. Mining a unit or coal or an equivalent quantity of diamonds may require the same amount of energy, but value of the resulting product may be very different.

Different types of energy resources may have different economic value. Electricity tends to have higher form value than other energy resources, and thus may be more valuable on a $/Btu basis than crude oil, coal, or firewood, for example. Thus even the conversion of energy resources into a common metric may have some limitations.

One approach to recognizing that different energy resources may have different form value (and thus different economic value) is to combine the various energy inputs through a Divisia index [1, 8]. This approach results in an index (relative to a base year) which recognizes how the economic value of energy resources involved in some process changes over time. This approach is difficult to apply in this particular application, since most of the energy inputs are consumed in a single base year (the year in which the wind farm is assumed to be manufactured and developed). Further, there is a single form of energy output, so no aggregation of diverse forms of energy is necessary. Thus, a Divisia approach would not be insightful in this application.

To the degree to which we can identify the quantity and type of each energy input to the project through a bottom-up approach, the economic value of those inputs can be multiplied by market prices to obtain the value of the energy inputs.

WE CAN POSSIBLY PUT IN HERE A TABLE SHOWING OUR COST AND ENERGY INPUT VALUES FORM NREL-JEDI AND INTO THE ONLINE FINANCIAL CALCUATOR IF WE HAVE SPACE. Or this can be in Figure Methodology?

# 3. Discussion

The result show the rather obvious conclusion that as more energy-consuming components are taken into account, the energy return on investment decreases and the energy-based IRR approaches that of the monetary IRR.

Some further thinking into what the final energy IRR/EROI should be based upon results from existing macroeconomic analyses indicates …

## 3.1 Results: Comparison of EROI to LCOE, IRR and IRRe (both monetary and energy)

Discuss Figure EROI … and a graph with financial IRR (same graph)?



**Figure EROI.** EROI varies with level of system analysis as reflected by % of the NPV of project costs.

Discuss Figure EROI-IRR … and a graph with financial IRR (same graph)? …



**Figure EROI-IRR.** As more aspects of wind farm project are taken into account, the energy return on energy invested decreases as does the internal rate of ‘energy’ return. The difference between monetary IRR and energy IRR implies a ‘gap’ in modeling from LCA analysis that must be explained by other means.

## 3.2 Discuss LCOE of wind

*Discuss the papers calculating LCOE of wind in the range of 45-65 $/MWh. This is in the range of producing 52,450 - 75,770 Btu/$ invested in wind [just doing: (3,409,511 Btu/MWh)/(45 $/MWh) = 52,450 Btu/$]. If we use the EIA NEMS heat rate assigned to wind of 9,919 Btu/kWh, then we get a range of producing 152,600 – 220,420 Btu/$. Without the PTC, the LCOE is ~ 75-100 $/MWh, equating to 45,500-34,100 Btu/$, or 5-6X larger than the world economy average of ~ 7,600 Btu/$.*

*How should this relate to the world/US average Btu/$? Is this just showing that electricity is valued 5-6X more than the average unit of energy? Need to see how this compares to Zarnikau and Cleveland studies discussing the value of different energy resources…*

[ph] one is an energy cost the other the economic value of the energy. so... by that a $ of wind investment produces 36$ of GDP. That figure will fail to include the TEA values for embodied energy, and so likely be more like 15$ or less... Without study I wouldn't know how to tell, but we could just mention that as one of the important reasons to use inclusive measures in arriving at these statistics if we wanted too.

***NOTE:*** *For modeling purposes, the EIA assigns an “arbitrary” heat rate to wind (for some reason) to make it appear to have the efficiency of a typical thermal plant of about 34%. That is the reason for the different value ranges mentioned (they are at that ratio).*

## 3.3 Energy is only one factor of economic growth

Because energy, or energy services, is only one factor of production in economic growth functions, we don’t expect to account for all money flows simply by counting all energy flows. Therefore, what proportion of the money flows should we expect to be able to account for?

 [ph] I think The money is an inclusive measure of the accumulative labors and materials that have been used in doing anything. We just don't know the units... Using it as a measure requires seeing if you can justify starting with it as an indicator of the average impacts and then have a way to adjust that average for notable added or avoided impacts.

[ph] The growth factor of efficiencies applies to any other bottleneck resource, as well as to energy. You might mentiuon that. That growth factor is also "Jevons' effect" and not popular to mention as all this investment in alternative resources serves to sustain growth and multiplying environmental impacts... in fact, unless it goes along with other things.

Possible points for discussion:

Discounting:

IRR discounts future cash whereas traditionally EROI does not discount future energy generation. What if energy is discounted or money is not discounted?

[ph] The discounting of energy production might be what I'm referring to as "opportunity costs" and "mitigation benefits" where using one thing changes the natural capital and or economic quality of that and other resources.

Ramifications of assuming average $/Btu for unknown energy expenses but known monetary expenses. What are pros and cons of this?

[ph] Well, it lets you estimate embodied impacts that are not individually unaccountable, and that creates the question of how to validate them, being sure that at least having any estimate is more valid than having nonw.

the disadvantage... could be needing to understand and explain market allocation of resources, and how allocation decisions create liquidity in markets. It's liquidity and competition that seem to assure that most business people will be using energy for about the same economic productivity (btu/$) as any other. If there was an advantage to something else they'd tend to use the energy for it.

The figure below shows how the OECD countries and non-OECD countries use energy with similar efficiency, with the latter improving more rapidly from 85 to 95 with both then moving parallel.

It would be good to have some data to show how what kinds of spending is more and less likely to have average energy content. I think I can get some well researched common place LCA's at <http://www.wattzon.com/>

From low capital high fuel energy systems to high capital low fuel investments

If capital and energy services dominate economic production functions (via Ayres work [11, 12]), then how can we view fossil fuel systems (relatively low capital/operating ratios) to renewable systems (e.g. wind and solar; relatively high capital/operating ratios)

We might mention the value of more accurate information about the relative sustainability and resource dependencies liabilities. The "energy gap" may relate to the difference between the energy consuming and producing sectors of the economy. There's the question of decreasing energy industry EROI in that regard, and whether it can support economies with increasing energy demands and overhead. That's the main subject of Charlie Hall's paper on the resource EROI necessary to sustain a modern society. [13]

## 3.4 Future Work: Intermittent Renewables vs. Stored Renewables and Fossil Fuels

If we only include EROI without accounting for the quality of the output, we are missing some important characteristics. Blah blah …

Talk about energy to make storage systems and their energy returns and/or costs (hydro, chemical batteries, etc.) Blah blah …

# 4. Conclusions

Blah blah …

# NOMENCLATURE

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

LCOE: levelized cost of electricity

NPV: net present value

SEA: system energy assessment

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Add:

[X] NREL, Wind Energy Finance Model, at: <http://analysis.nrel.gov/windfinance/default.asp>.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Outputs |  |  |  |
|  | Energy Output |  |  |  |
| ALL | Electricity Total for 67 turbines  |  | MWh | 591,300[[1]](#footnote-1) |
|  | Financial Outputs |  |  |  |
| ALL | Sales at market rate of $.10/kWh |  | $ | $59,130,000 |
|  |  |  |  |  |
|  | Inputs |  |  |  |
| Analysis Level | LCA Emergy & Identified Energy use (estimated) | Wh/$ scale |  |  |
| LCA | Primary Technology & Equipment | 1.5 | MWh | 20,169[[2]](#footnote-2) |
| TEA1 | Field energy use | 1.5 | MWh | 1.766 |
| " | Field employee energy use |  | MWh |   |
| TEA2 | Business Operations Energy | 1.5 | MWh | 91 |
| " | Business Operations Employees |  | MWh |   |
| TEA3 | Purchased Supply & Expenses | 1.5 | MWh | 458 |
| " | Physical Plant | 1.5 | MWh | 6,777 |
|  | sub tot |  | MWh | 20,721 |
|  | Economic costs & TEA Implied Economic Emergy | factor |  |  |
| TEA1 | Primary Technology & Equip. Cost |  | M$ | $152.93 |
| " | annualized |  | M$ | $7.65[[3]](#footnote-3) |
| " | implied energy MWh/$-Av per yr | \_MWhA | MWh | 13,446 |
| " | Field costs |  | M$ | $1.18 |
| " | implied energy MWh/$-A | \_MWhA | MWh | 2,070 |
| " | Field employees |  | M$ | $0.29 |
| " | implied energy MWh/$-A | \_MWhA | MWh | 503 |
| TEA2 | Business costs  |  | M$ | $0.03 |
| " | implied energy MWh/$-A | \_MWhA | MWh | 61 |
| " | Business salaries |  | M$ | $0.16 |
| " | implied energy MWh/$-A | \_MWhA | MWh | 282 |
| TEA3 | Physical Plant Cost |  | M$ | $51.39 |
| " | annualized |  | M$ | $2.57 |
|  | implied energy MWh/$-Av per yr | \_MWhA | MWh | 4,518 |
|  | Other Business Costs |  | M$ | $0.87 |
|  | implied energy MWh/$-B | \_MWhB | MWh | 306 |
|  | sub tot |  | MWh | 21,187 |
|  | sub tot |  | M$ | $12.74 |
|  |  |  | $/kwh | $0.60 |

Appendix I: Input/Output table for the four LCA and TEA analysis levels considered, with notes

1. Vesta project data for all hard costs and capital investments [↑](#footnote-ref-1)
2. LCA energy estimates from:.... [↑](#footnote-ref-2)
3. linear amortization over 20 year project life [↑](#footnote-ref-3)