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Comparing Apples to Apples: Why the Net Energy Analysis Community Needs to Adopt the Life-Cycle Analysis Framework

David J. Murphy [1,*], Michael Carbajales-Dale [2] and Devin Moeller [3]

1 Environmental Studies Department, St. Lawrence University, Canton, NY 13617, USA
2 Environmental Engineering & Earth Sciences, Clemson University, Clemson, SC 29634, USA; madale@clemson.edu
3 Department of Civil and Environmental Engineering, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA; devin.moeller@sdsmt.edu
* Correspondence: dmurphy@stlawu.edu; Tel.: +1-315-229-5990

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Abstract: How do we know which energy technologies or resources are worth pursuing and which aren't? One way to answer that question is to compare the energy return of a certain technology—i.e., how much energy is remaining after accounting for the amount of energy expended in the production and delivery process. Such energy return ratios (the most famous of which is energy return on investment (EROI)) fall within the field of net energy analysis (NEA), and provide an easy way to determine which technology is "better"; i.e., higher Energy Return Ratios (ERRs) are, certeris paribus, better than lower ERRs. Although useful as a broad measure of energy profitability, comparisons can also be misleading, particularly if the units being compared are different. For example, the energy content of electricity produced from a photovoltaic cell is different than the energy content of coal at the mine-mouth, yet these are often compared directly within the literature. These types of inconsistencies are common within the NEA literature. In this paper, we offer life cycle assessment (LCA) and the LCA methodology as a possible solution to the persistent methodological issues within the NEA community, and urge all NEA practitioners to adopt this methodology in the future.

Keywords: life cycle assessment (LCA); energy return on investment (EROI); Energy Return Ratios (ERRs); net energy; function unit; ISO

1. Introduction

How do we know which energy technologies or resources are worth investing in and which aren't? One way to answer that question is to examine which resource-technology combination provides the most net energy to society, i.e., provides the most energy after accounting for the energy expended in the harvesting, conversion, and delivery process. Such numbers are often reported as energy return ratios (ERRs) with the most famous being energy return on investment (EROI), all of which fall within the field of net energy analysis (NEA). By using these ERRs we may, in theory, directly compare extraction and conversion technologies, utilizing different energy resources to get an idea of which performs "better".

One such analysis was produced by Hall and Day [1] and is reproduced here (Figure 1). Figures like that from Hall and Day have been common within the NEA literature over the past decade, including tables in papers by the authors of this paper (for example, see [2,3]), and provide an easy, tractable way to compare energy resources/technologies. With a quick glance the reader can see that coal has high net energy returns, and seems "better", from a net energy perspective, than, for example, PV, which looks like it provides lower net energy returns. Although useful as a broad measure of energy profitability, these types of comparisons can be misleading as they often compare fundamentally different energy products. For example, the energy product used in the calculation of the EROI of PV is electricity output from a PV panel into the electricity grid, whereas that for coal is raw coal at the point of extraction. Coal and PV electricity are thus compared via a common energy unit—such as megajoules (MJ)—yet, as is the case in this example, they are clearly not equivalent and have completely different utility and value within society. The difference in utility between raw coal at the mine-mouth and electricity in the grid is underlined by the fact that society routinely and happily exchanges three units of coal for one unit of electricity within coal-fired power stations—end-users (at least in industrial countries) prefer electricity coming out of their sockets to the coal man showing up at their door.

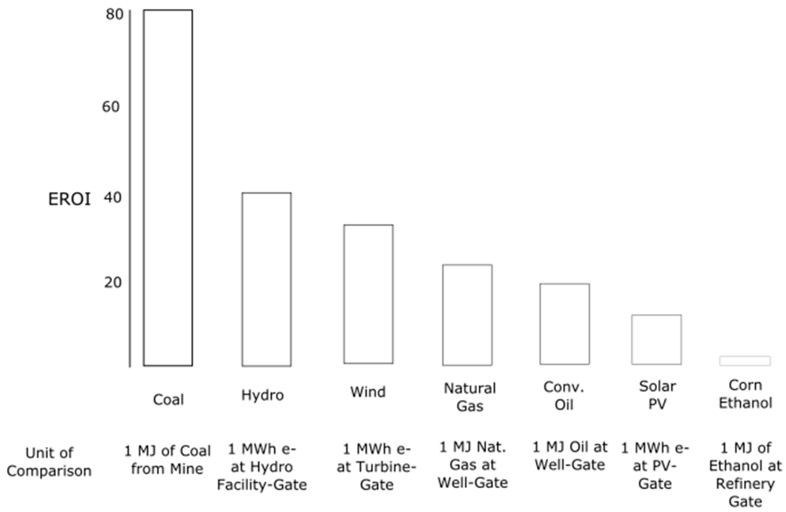

Figure 1. Comparison of the EROI for various energy resources and listing an assumed common unit of comparison (data adapted from figure in [1]).

Even when studies use the same unit of comparison the final results can still vary widely due to methodological differences. The current debate within the literature over the EROI of PV is a good example. In 2012, Raugei et al. [4] reported that the EROI of PV was upwards of 10, yet those results were contradicted in 2013 in publications by Weißach et al. [5] and Prieto and Hall [6] who found the EROI to be much lower, around 2−3. In these examples the differences in the estimates for EROI did not arise due to different units of comparison, as was the case in Hall and Day, rather the differences are due to methodological issues mostly related to boundary setting. Many of these concerns were discussed in subsequent publications [7–9]. Similar issues have recently arisen in the energy assessment of biofuels, which has led to publications discussing how different energy-use indicators, such as fossil energy demand vs. cumulative energy demand, can lead to vastly different conclusions as to the efficacy of certain technologies [10,11].

This type of methodological inconsistency has been an issue for NEA since the 1970s [12–14]. At the heart of the issue is the fact that researchers need flexibility to calculate various energy return ratios, but also the rigor of a methodology that is repeatable, defensible, and rigorously quantitative; two items that are often difficult to reconcile. However, within the field of life cycle assessment (LCA) standards from the International Organization for Standardization ([15–19]) have provided a way to mesh the two that has allowed for meaningful research over the past two decades. The developments within the field of LCA are now being applied to NEA [7,10,20,21], and seem to be finally reconciling the issues that first arose in the 1970s. The goal of this paper is to discuss how the methodologies of NEA are related to the ISO LCA standards and how it would make more sense to view NEA as a subset of the overall LCA methodological framework. We will begin by a discussion of the history of NEA.

1.1. Background

1.1.1. Short History of Net Energy Analysis (NEA) and Energy Return on Investment (EROI)

The 1970s marked a shift in public awareness regarding the environmental degradation during post-World War II economic development and population growth. That the decade was flanked by two oil shocks, the Arab oil embargo in the fall of 1973 and the Iranian revolution in 1979, and resulting recessions, all of which served to connect economic growth to the availability of supplies of inexpensive energy. The sequence of events also acted as a catalyst for research investigating the connection between (net) energy and the economy. Paraphrasing Odum [22], net energy is the energy left after the costs of acquiring and concentrating the energy have been subtracted. In ecology, net energy represents the energy that an organism can dedicate to growth after "paying" for metabolic energy costs. In other words, a plant that generates energy equivalent only to that needed to pay for its metabolism cannot grow, because all of the energy acquired is used in respiration. In the early 1970's this concept was tested in New Hope Creek, North Carolina, by Charles Hall and published in *Ecology* [23]. Hall measured that the fish within the creek that migrated found food sources in the new locations that provided greater net energy even when accounting for the energetic cost of the migration. Hall measured this as the energy return on investment, or EROI, of the fish migration, and this publication serves as one of the many foundational articles on net energy analysis (NEA) to emerge from the ecological literature (Figure 2).

A parallel strand of (net) energy analysis was growing out of studies of industrial production of goods and services, simultaneously within the US [24–27] and Europe [28–32] (Figure 2). Additional work during the 1970s included the development of input-output methods to model energy flows through macro-economies [33–37]. The increase in NEA research led to three major workshops: the International Federation of Institutes for Advanced Study [38], in Sweden; an NSF workshop at Stanford [14]; and a follow-up workshop by International Federation of Institutes for Advanced Studies (IFIAS) in 1976 on Energy Analysis and Economics [39]. These workshops in many ways represented an early effort to formalize the NEA process [40], but they largely failed. Indeed, the conference at Stanford was reported to have discussed the complicated issue of what costs to include and what not in NEA calculations without coming to any sort of consensus [12].

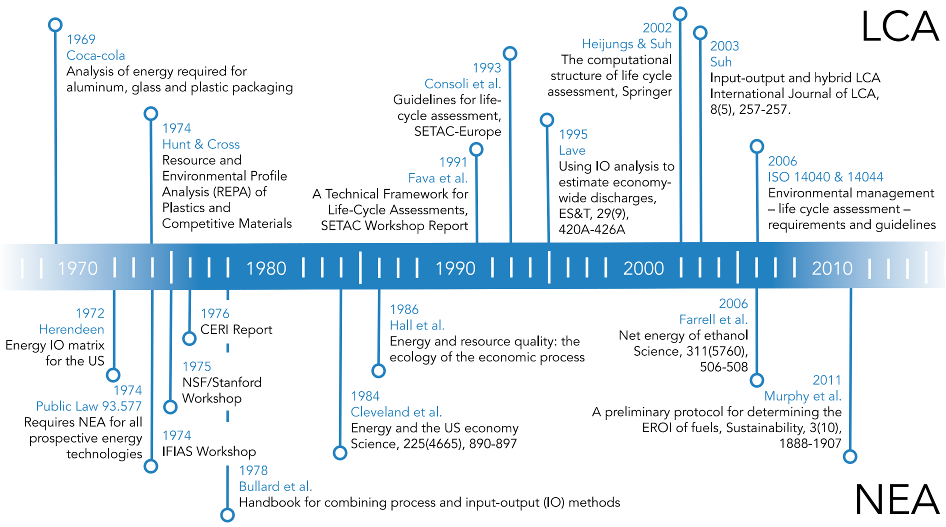

Figure 2. Timeline of seminal publications in both life cycle assessment (LCA) and net energy analysis (NEA).

Hall et al. [41] and Hall and Cleveland [42] extended the ecological concepts of Odum [43] to the energy extraction process within the United States. Murphy and Hall [2] explicitly define EROI as, "the ratio of how much energy is gained from an energy production process compared to how much of that energy (or its equivalent from some other source) is required to extract, grow, etc., a new unit of the energy in question." Although EROI is an efficiency measure in that it mathematically calculates the output divided by the input, it is not calculating the efficiency with which we produce energy. Rather, it is calculating the energy cost of energy production; i.e., how much economically useful energy has to be invested to obtain economically useful energy. In the mid-1980s, Hall et al. [44] and Cleveland et al. [45] calculated the EROIs for major energy resources, both globally and within the United States. Subsequent oil and gas EROI research aggregated thermal equivalent heat content and also adjusted for the energetic quality of the energy carrier [46,47], finding that conventional oil and gas EROI values generally declined from the early 1970s to the mid-1990s. Additional research extending the time horizon into the mid-2000s for both US and global conventional oil and gas production indicate the same pattern of decline ranging from 50:1 in the mid- 20th century to under 10:1 by 2010 [48–50].

The declining EROIs of conventional fossil resources served as motivation toward increased research opportunities in renewable and unconventional alternatives, in both electricity generation (hydropower, wind turbines, PV, coal, and shale gas) and liquid fuels (biofuels, ultra-deep water, tar sands, shale oil, and oil shale). The growth in EROI literature, and the diversity of methods used in that literature, created a need for methodological consistency. There have been a number of previous methodology or protocol papers [20,40,51–53], most of which borrowed heavily from both the process-based "bottom-up" and "top-down" economic input-output LCA literature.

1.1.2. Short History of Life Cycle Assessment (LCA)

NEA and LCA methodologies can be traced to the early energy studies conducted in the 1970s yet by the end of the decade the disciplines diverged, where NEA functioned as a tool to compare the energy delivered to society across various energy alternatives, the aim of LCA was to measure the environmental impacts along a product system life cycle [54–56]. ISO 14040 and 14044 were published in 2006 as the second iteration of the standards associated with LCA [18,19]. The main purpose of these standards is to establish a consistent methodology to perform environmental assessments. There are four main phases to an LCA: goal and scope definition; inventory analysis; impact assessment; and interpretation (Figure 3), and each phase has a defined methodology and reporting structure. By establishing these four categories, the LCA standards provide an analytical framework that is both flexible yet methodologically rigorous. In other words, the ISO standards provide a framework that the NEA community was seeking in the workshops of the 1970s.

2. Methodological Commonalities between Net Energy Analysis (NEA) and Life Cycle Assessment (LCA)

As noted in the introduction, both NEA and LCA can be traced back to common roots in the 1970s. It should not be surprising then that there are a great many methodological commonalities between the two frameworks; indeed some have even stated that NEA should be correctly construed as a subset of LCA [7]. We will explore the overlap (while being clear to identify disparities) between the two in the following sections.

2.1. What Is the Purpose of the Proposed Work and How Will It Be Analyzed? Goal and Scope Definition

Often, disparities about the EROI of a technology or resource emerge not because of data differences, but rather because the research has had, usually unintentionally, different goals, answered different questions, or analyzed different systems. The results of these analyses are then often compared in the literature without recognition that they are different. For example, we cannot determine whether natural gas is "better" than PV by examining the EROIs at the well-head for gas and at the grid-connection for PV simply because they are measure different things. The former measures the energy cost of getting natural gas out of the ground and the latter measures the energy cost of producing electricity via photovoltaic technology. More to the point, the fact that energy units are generally reducible to common thermal equivalents—i.e., a Joule—is actually contributing to the confusion because it can disguise that fact that a Joule of natural gas is completely different than a Joule of electricity.

Despite these issues, much of the confusion and contradiction within the literature can be ameliorated if researchers properly establish the goal and scope of their methodology. In the net energy community this is often referred to simply as the "boundary of analysis", but, as this section will detail, within the LCA community Goal and Scope have very specific definitions that help create transparent research that can reduce confusion within the literature.

According to the standardized LCA methodology, there are four stages through which the analysis should proceed (Figure 3), the first of which is goal and scope definition. During this stage, the analyst should "unambiguously state the intended application, the reason for carrying out the study and the intended audience" (goal) as well as defining the product system (Section 2.1.2) and purpose, the type of LCA (Section 2.1.3), the functional unit (Section 2.1.4), and rigorously define the system boundary geographically, temporally and in relation to production equipment, labor etc. (cutoff criteria) and in relation to other product lifecycles [18].

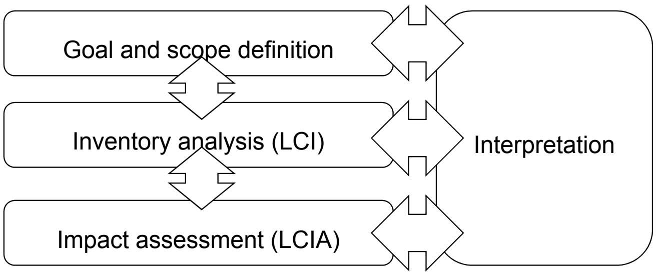

Figure 3. Life cycle assessment (LCA) framework [18].

2.1.1. Goal Definition, Intended Audience

Broadly speaking, the goal of an LCA, on the other hand, is to "analyze the environmental aspects and potential impacts throughout a product's life cycle" [18] across a range of 'endpoint' impact dimensions (human health, ecosystem health, resource use). However more explicitly, the goal depends also on the intended audience (e.g., policy makers, consumers, process designers) and who solicits the LCA study (e.g., industry, non-governmental organizations). In contrast, NEA focuses specifically on energy extraction or conversion processes (e.g., coal mining, distribution and coal-fired electricity generation) and tracks only energy exchanges across the economy-environment boundary.

There are two common reasons (though more exist, these two seem to be the most popular) reasons why EROI analyses are performed:

Reason 1: descriptive assessment of a specific technology (e.g., solar satellite); and
Reason 2: comparative assessment of a range of energy resources/technologies;

The goal statements within the EROI analyses, however, usually do not provide enough information to the reader, often excluding the intended audience and functional unit of analysis. Take for example the following two hypothetical goal statements:

(1) "The goal of this analysis is to calculate the EROI of coal";
(2) "The goal of this analysis is to calculate the EROI of coal so that policy makers can compare it with the EROI of PV, wind, and natural gas.

There are goal statements that we might find in current EROI analyses yet they omit important information leading to a number of uncertainties. For example, the first goal statement omits the purpose of the study, who is conducting the research and for whom? As such, it is difficult to assess whether the analysis has been carried out properly, or understand possible bias within the study. Goal 2 is better since we now have an understanding of the study purpose and the intended audience.

A major aim of the goal and scope definition is to arrive at an appropriate functional unit for assessing the product system being analyzed. This is further compounded because EROI is a dimensionless ratio, so seems to be comparable, even when the functional units of analysis (the unit of energy output) are in actuality very different among different product systems (e.g., coal fuel vs. electricity). In Goal 1 we have no clue what is the appropriate functional unit. How much coal is being supplied? Where along the production chain should the analysis end: at mine-mouth; at the consumer? Other questions are also difficult to assess. What level of analysis is appropriate: a specific mine; regional or economy-wide; the whole globe? What method is appropriate: process-based; input-output; hybrid? What sort of coal do we need: anthracite; bituminous; lignite? Goal 2 is somewhat better, since we now have some idea that, for a fair comparison, the functional unit should be the output of a unit of electricity (e.g., one kWh_{el}). However, it is still unclear what the appropriate boundary of the analysis should be. This takes us to the issue of scope definition and boundary selection.

2.1.2. Product System and Boundary Selection

Within LCA scope definition, the product system is defined including the relevant function of the system in the case of multiple co-function/products, for example coal may be used to simultaneously generate electricity and process steam. For LCA, the product system may range over any good or service within the economy, whereas NEA is limited to those product systems that deliver an energy product, e.g., electricity from a coal-fired power plant.

Looking back to our two goals defined in the previous section (Section 2.1.1), we see that Goal 2 still does not allow us to define the appropriate system boundary. Are we comparing lifetime electricity production by a single representative power plant of each type or the electricity produced annually by each technology within a specific region? Note that, although both of these analyses are often denoted as "EROI" (e.g., [4] for power plant and [6] for regional), the latter, being the ratio of flows of energy per unit time (annual), would more accurately be described as power return on investment (PROI) [57]. The issue of scope creep has been discussed previously where EROI for a representative PV farm morphed into the "EROI" (actually PROI) for PV electricity production for a whole country, as the boundaries of the analysis were inappropriately extended [7].

In order to define the system boundary, we must define both the temporal and spatial boundaries of our product system. Further, we may distinguish between the foreground system (i.e., the product system that is being explicitly modeled by the analyst) and the background system that comprises the other processes within the economy. This issue will be discussed in more detail in Section 2.2.

In Figure 4, we show an example system diagram for a coal-fired power station producing electricity. We distinguish the (foreground) product system, which is explicitly modeled within the analysis by connecting appropriate unit processes (coal mining and electricity generation), from other (background) processes, which may be in the energy sector, or may be non-energy processes (e.g., steel manufacture). The LCA analysis consists of tracking exchanges across the product system boundary (solid black line) and then assessing the (elementary) exchanges across the economy-environment boundary (e.g., natural resources or other energy resources) due to production of the functional unit. For NEA, the product system boundary (dashed black line) is extended such that the primary resource in the ground (in this case coal) does not cross the boundary and is not accounted until it leaves as the final product.

In this example the functional unit might be "a single kWh of coal-fired electricity". We must stipulate the geographical location of this plant (since this will determine, among other things, transportation distances) and the temporal boundary of the analysis, which would likely be the full life cycle of the power plant, including extraction, processing, and transport of raw materials (e.g., mining iron to turn into steel and mining aggregate to produce concrete); manufacturing (or construction in this case); operation (including upstream fuel cycle processes such as coal mining); and decommissioning of the plant. For the LCA product system boundary (solid black line), the primary resource (coal in the ground) is not included. As such, it is accounted as it crosses the system boundary. In NEA, the product system boundary (dashed black line) now extends into the natural environment to encompass the coal in the ground. The implications of this will be discussed in more detail in Section 2.2. Note also that within LCA a similar assumption is made for (elementary) exchanges across the economy-environment boundary that are not accounted in LCI databases, such as sunlight onto solar power plants or wind through wind turbines.

Creating one of these diagrams with the energy flows labeled, such as that found in Brandt [40], Brandt and Dale [20], Murphy et al. [52], should be considered a requirement because the diagram is an easy way for the reader to understand what flows are or are not included in the calculation.

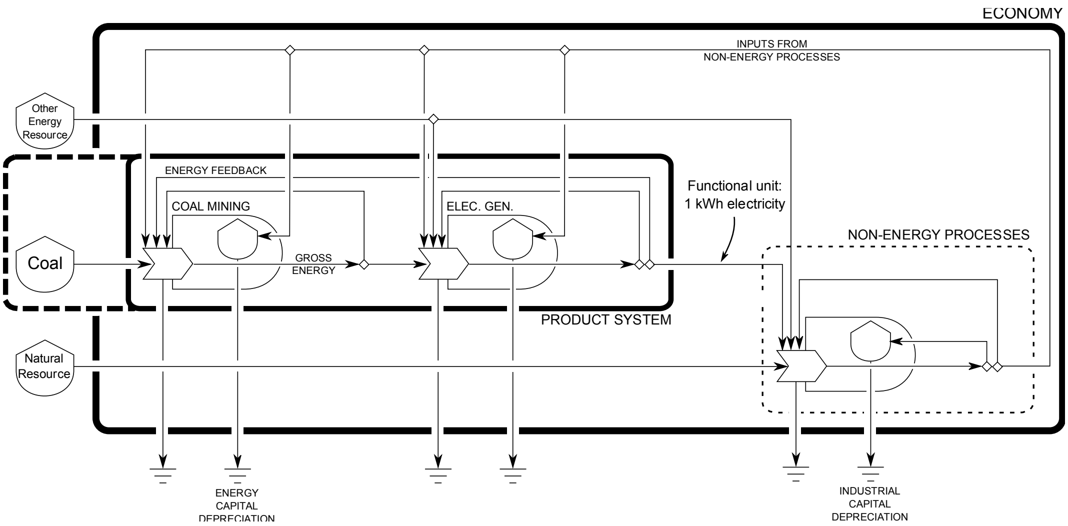

Figure 4. System diagram for a model of electricity from coal.

2.1.3. Type of Analysis

Within LCA, analysis is normally undertaken using a process-based approach, in which a model is built, "bottom-up" from engineering models of individual unit processes, e.g., a coal-fired burner. Within NEA, studies are conducted at both the product/project level and the industry level, for instance determining the energy requirements of the whole coal industrial sector using a "top-down", input-output approach. One point worthy of note is that the analysis of a product life cycle is inappropriate at the industry scale because an industry is composed of multiple overlapping life cycles. As such, the temporal boundary chosen by the analyst is in some sense arbitrary [7,57]. Furthermore, the input-output methodology represents a snapshot of a certain year in which the data was collected. Such data collection efforts are resource-intensive so are generally not available for every year, for instance, the US Bureau of Economic Analysis only collects this data every 5 years.

2.1.4. Functional Unit Definition

The functional unit is defined as "the amount of product, material, or service to which the LCA is applied" [18] and acts as a reference unit to which all other modeled transfers within the system are related. Accurately defining the functional unit is incredibly important as it ensures that results for the product system under analysis can be compared "apples-to-apples" with results from other product systems and other studies. For example, in comparing disposable paper cups with reusable ceramic mugs, we would not want to compare the impacts for the lifecycle of a single unit, since the mug can be reused multiple times. A suitable functional unit might then be "a single use". Within NEA, the issue of a functional unit is rarely considered explicitly, but is often defined (at least implicitly) as a single unit of energy (e.g., barrel of oil, MJ, kWh) delivered from the product system.

The net energy community should pay particular attention to functional units as often times comparisons are made between technologies with different function units. For example, the data in Figure 1 all have different functional units. But again, and here is where the iterative nature of LCA is important; the functional unit must be defined so that it can achieve the study goals. If the goal is to calculate and EROI for a technology than the functional unit matters only to that study, but if the goal is to compare the EROI for a technology against other published EROIs for other technologies, then the researcher must ensure that there is functional unit consistency between the studies. In other words, to measure whether PV or natural gas has a higher EROI, both should be calculated within a boundary that produces electricity into the grid. This means that the natural gas must not only be extracted but also combusted into electricity.

2.2. Inventory Analysis

The second stage within the LCA framework (Figure 2) is the life cycle inventory (LCI) stage. The LCI stage consists in determining the (elementary) transfers across the economy-environment boundary for production of the specified functional unit from the product system as defined. The modeled system can be considered a matrix network of interacting unit processes exchanging energy and materials with other processes within the economy and with the environment. No inputs have a special status within the process.

During this stage the transfers across the foreground product system boundary are accounted in terms of both technological exchanges to and from the background economy (including the product output of the functional unit) as well as (elementary) exchanges to and from the environment. Exchanges between the foreground product system and other unit processes within the economy (background system) are subsequently traced through the network to determine the elementary exchanges across the economy-environment boundary.

As such the final result from the LCI is a vector of elementary exchanges between the economy and the environment categorized as (energy, material or water) resource inputs and outputs of the functional unit as well as emissions to air, water and soil. In LCA, all environmental withdrawals and emissions are accounted, though in reality this may be limited to a few hundred different types within LCI databases, such as EcoInvent [58].

In contrast, NEA conceptualizes energy extraction and conversion processes as forming a pathway from primary resource extraction to delivered energy product, e.g., electricity, and as such resource inputs to unit processes have a special status. NEA tracks only exchanges of energy resources across the economy-environment boundary however, as discussed previously, the primary energy resource, e.g., coal in the case of electricity from a coal-fired power plant, is considered within the product system boundary, so the energy content within the extracted coal does not cross the boundary of the system. The product system receives inputs from other processes within the economy, for example steel for turbines, and the upstream energy inputs to those processes are accounted. As such, coal used in steel production would be included.

2.2.1. Truncation ("Cutoff") Criteria

Within both LCA and NEA there is a trade-off between comprehensiveness of the study and the time and resources available to the analyst. Clearly, we should want to include as many details as we can in our models, but LCA and NEA are very labor- and time-intensive to undertake. A useful heuristic is to "exclude from the system all activities that have negligible effects on the results" [59], though this perspective somewhat begs the question; how do we know which activities will have negligible results without having first analyzed them? The issue of where to draw our boundary is known within the LCA literature as the cutoff or truncation problem [60,61].

Note that this issue can be mitigated somewhat by use of a hybrid analysis that integrates both process-based and input-output analysis. In this case, financial expenditures to support the product system can be parsed into environmental impacts using an input-output model such as Carnegie Mellon's Economic Input-Output Life Cycle Assessment [62]. In this method, spending must be categorized into one of the economic sectors and thereafter financial flows [dollars/year] between sectors. The financial flows act as proxies for physical flows of energy and materials and each flow can be traced upstream to determine the initial flow across the economy-environment boundary—in an analogous method to the process method described earlier. Input-output trades-off comprehensive coverage of the economy for a lack of resolution at the sub-sectoral level.

2.2.2. Allocation, Multiple Co-Products

The issue of multiple co-production and allocation refers to the fact that some processes produce more than one output, and if an analyst is interested in one of those outputs only, then the analyst must make a decision about how to allocate the inputs to that process amongst the various outputs. The issue is essentially that a boundary is being defined either where one does not exist in the real world, or maybe where the information to do so is lacking. For example, an oil refinery produces hundreds of products using one main input—crude oil. If an analyst were interested in estimating the greenhouse gases associated with burning a gallon of gasoline then the analyst will have to decide what proportion of the greenhouse gases associated with the refining process should be allocated to the gasoline product, which is just one of the many outputs of the refinery.

The methods by which LCA practitioners allocate flows within multiple product systems is a significant area of research, yet this issue receives little attention within NEA. The debate in the mid-2000s about the NER of corn-ethanol is a good example of why allocation is important. A number of publications in the early 2000s calculated the NER of ethanol production from corn, and two distinct groups began to emerge—those that calculated the NER just below one (i.e., net negative in energy production, [63,64]) and those just above one (net positive in energy production [65–68]). It was not until Farrell et al. [69] that the issue of the allocation of the co-product of corn-ethanol production—distiller's grains—was addressed directly in their analysis. They found that the studies that did not allocate energy for the co-product calculated NERs below one and those that did allocate energy credit for the co-product calculated NERs above 1. The important point being not that one is right and one is wrong, rather that had NEA approached this analysis using the LCA framework, the co-product issue would most likely have been addressed more quickly in the literature.

2.3. Impact Assessment

The third stage within the LCA framework is life cycle impact assessment (LCIA). At this stage LCA and NEA really start to diverge, since LCA is interested in many environmental impacts, whereas NEA is only interested in impacts related to energy use. The goal of the LCIA is to convert the results from the LCI stage—a vector of environmental exchanges, e.g., kg of carbon dioxide—into a more informative and compelling environmental impact, e.g., global warming potential (GWP). There are a number of steps within LCIA, including: (i) categorization; (ii) classification; (iii) characterization; (iv) normalization; (v) grouping; (vi) valuation; and (vii) reporting. Here we focus on categorization and characterization only.

2.3.1. Impact Category and Methodology Selection

As stated previously, LCA is interested in as many environmental issues as society considers important and the framework of LCA is such that new issues can be added as the need arises. The major focus of LCIA has shifted over the years, with energy being a major focus during the 1970s, waste management during the 1980s, air pollution (e.g., smog, sulfur dioxide and ozone depletion) during the 1990s and greenhouse gases and water use during the last two decades [70].

For NEA, since the focus is on energy use, the impact metrics are also solely energy-related, which can be calculated from the inventory vector of (elementary) environmental exchanges. Perhaps the most obvious is the total energy requirement [38], which we will term E_{INV}, also known as the energy requirement for energy, and is calculated by summing all of the energy that enters the economy from the environment in support of the functional unit E_{FU}, remembering that the feedstock energy (e.g., coal extracted for the purpose of generating electricity from a coal-fired power plant) is not included. Note that this is not identical to the LCA metric of cumulative energy demand (CED, e.g., [71], due to the excluded principal feedstock. Fundamental to this calculation is that energy of different types (e.g., coal and natural gas) can be aggregated using common units—such as in joules.

Once the gross energy requirement has been determined, we can easily determine the net energy yield, E_{net} from the product system as the difference between functional unit and the gross energy requirement, $E_{net} = E_{FU} - E_{INV}$, which should (hopefully!) be positive. We may also wish to calculate an energy return ratio (ERR) such as the energy return on investment, $EROI = \frac{E_{FU}}{E_{INV}}$ or the net energy ratio, $NER = \frac{E_{net}}{E_{INV}}$. At this point we also have a question as to whether or not to account for losses to the environment along the processing pathway, e.g., waste heat during the electricity generation process in Figure 4, or only to include inputs of energy into the product system from elsewhere in the economy. Whether or not, and how, to include these losses can have a large effect on final results especially when computing energy ratios [72]. For example, if E_{GER} includes the waste heat losses from electricity production, then for a typical coal-fired power-plant efficiency of 30% (i.e., 70% of the energy in the coal is lost as waste heat), the EROI would be $\frac{0.30}{0.70} = 0.43$ even before accounting for other energy investments which would serve to further reduce the value.

2.3.2. Characterization

During the characterization stage, elements from the vector of environmental exchanges determined during the inventory stage are characterized in terms of a common reference. Perhaps the most well-known environmental impact is global warming, where all greenhouse gases are equated based on their equivalent global warming potential (GWP) compared with carbon dioxide. For example, a kilogram of methane has a GWP of 25 kg CO_2-eq over one hundred years.

For NEA, the question arises as to how to compare energy of different types. As discussed in the introduction, this issue is particularly troublesome if our final product E_{FU} is electricity, which we must compare with other types of energy, for example coal extracted from the earth. The most common method is to use a "quality" correction factor, whereby electricity is converted into its "primary energy equivalent", normally assuming that the electricity was generated at the grid average, normally using thermoelectric power plants at around 30% efficiency (for the European grid (UCTE), the value is closer to 31%, for North America, it is around 29% [73]. This primary energy equivalent is then credited back to the system, if it was generated using an alternative technology, such as solar PV. Clearly, this method makes a critical assumption about current methods of obtaining electricity and is unsuitable for exploring large-scale changes to the electricity system, such as extensive diffusion of renewables.

3. Data

It is also worth noting the difference in the types of data utilized by most NEA and LCA researchers. Often, researchers have much better approximations of the energy product output from a process than they do for the energy cost of that production. For example, it is easier to attain data on how much oil comes out of a well than how much energy was used to produce it. As a result, net energy researchers are often searching databases, journals, and company documents to find evidence of how much energy is used in production processes. It is a time-consuming and constant search for better data, often to no avail yielding data that is too narrow in scope or perhaps out of date.

LCA researchers engage in similar data-searching activities, but they often bolster those efforts with large LCI databases that have already been assembled. The EcoInvent database [58] is a well-established LCI database containing inventory data that lists all of the inputs and outputs to thousands of processes. NEA research would benefit hugely by utilizing these databases.

The value of these databases can be clearly seen when incorporating electricity costs into a NEA. In the past, NEA researchers have usually just assumed at 30% conversion efficiency from primary energy to electricity, a number meant as a broad average of grid efficiency, as discussed in Section 2.3.2 [74]. On the other hand, the EcoInvent database contains data about the primary energy required to produce electricity in various grids around the world. Therefore, if a researcher was performing an analysis where they had an energy input of electricity in the northeast of the United States, the EcoInvent database allows them to very quickly calculate the mix of primary energy contributing to electricity in that geographical region. Utilizing these databases would thus enable much more robust and granular analysis, and avoid arbitrary assumptions, such as the aforementioned 30% efficiency factor.

This electricity example is just one of many ways in which the NEA community could benefit by using the LCI databases, and it is beyond the purview of this paper here to delve deeply into all of these areas, but we should mention that utilizing these databases to the greatest extent possible is the first step in increasing the rigor in NEA work. That said, there are a couple of cautionary notes. First, some of the databases, though robust, are not free for all users—including the aforementioned EcoInvent database. Second, utilizing these databases is only really worthwhile within the broader LCI framework. For example, the differences in the EROI of PV reported in the literature are due in part to data but mainly to inconsistent methodologies. That is to say, access to the EcoInvent database will not produce comparable results per se. Rather comparable results will emerge from analyses that use consistent methodologies, such as the broader LCA framework discussed herein. A third point is that the different scopes of NEA and LCA (as discussed in Section 2.1.2) should be borne in mind.

4. Conclusions

The ISO standards establish a flexible yet robust analytical framework within which researchers are able to conduct a multitude of different assessments. As discussed in this paper, many of the issues that plagued early NEA researchers—lack of consistency in the unit of comparison or in boundary definition—are addressed directly within the ISO standards. As such, Carbajales-Dale et al. [7] discuss, net energy analysis should become a subset within the overall LCA framework.

Using the LCA framework, however, does not mean that all analyses will automatically be comparable to one another. Rather the adoption of the LCA framework means that each analysis should include the necessary goal and scoping information so that researchers can easily interpret the significance of the results, and from that information, make appropriate comparisons across the literature. In other words, adopting the LCA framework can help ensure that if comparisons are made, they are comparing apples to apples.

Net energy analysis, and the EROI metric in particular, are a useful way to compare energy technologies and resources that many non-academics find meaningful. However, that usefulness is continually undercut by inappropriate comparisons within the literature. The goal of this paper is to address how the NEA community would benefit by adopting the ISO LCA methodological framework. To that end, we have compiled a Net Energy To-Do list that will help net energy reserachers adopt the ISO LCA methods.

The Net Energy To-Do List

Based on the discussion above, we have put together a list of items that should be addressed explicitly in every study. The list is not meant to be exhaustive, but it is supposed to cover the bare minimum needed to increase the transparency of NEA and LCA work.

(a) Write a proper goal statement, including the following information:

   i. Intended application, i.e., is this a comparison study?

   ii. Reasons for the research
   iii. For whom the work is intended, i.e., the audience

(b) Create a product system diagram with flows labeled

   i. Use the product flow diagram as a map when listing equations within the paper so that the reader is clear about which inputs are included and which are not. (see Figure 2 in [48] for an example)

(c) Clearly identify the functional unit of the analysis and make sure that this unit is the same as other units in the literature if the research is intended to be used comparatively.

(d) Utilize process-level data when available and input-output level data as a backup/supplement

   i. Utilize the EcoInvent (or other) major LCI database as a primary loci for data
   ii. Supplement these databases with other data when needed, but only after these datasets have been utilized

Many of the issues that exist in the net energy literature are basic methodological errors, as we have discussed above. Following steps A–D outlined here will, at a minimum, clarify many of these basic errors that persist in the net energy literature, and will produce much more methodologically consistent literature. This is not to say that the final EROIs calculated will be the same—they will not, nor will all analyses utilize the same boundaries or assumptions—as they should not, but it will eliminate (or at least decrease) inappropriate comparisons and incorrect conclusions. Doing so is a basic first step if we want net energy to become policy-relevant in the future.

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Abbreviations

ERR	Energy Return Ratio
EROI	Energy Return on Investment
NER	Net Energy Ratio
NEA	Net Energy Analysis
LCA	Life Cycle Analysis

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