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Matrix method for comparing system and individual energy return ratios when considering an energy transition

Carey W. King [a, b, 1]

[a] Energy Institute, The University of Texas at Austin, 2304 Whitis Ave, C2400, Austin, TX 78712, USA
[b] Center for International Energy and Environmental Policy, Jackson School of Geosciences, The University of Texas at Austin, 2275 Speedway, C9000, Austin, TX 78712, USA

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ABSTRACT

ERRs (Energy return ratios) are valuable metrics for understanding and comparing the contributions of individual energy technologies. It is also important to calculate ERRs in the context of a system, or economy, using a mix of energy technologies. In this paper I demonstrate a framework to simultaneously consider individual energy technology and system-wide ERRs using a process-based input–output model approach. I demonstrate the approach via an example calculating grid electricity ERRs assuming constant technology with only a shift in dominance from fossil to renewable technology. The framework also enables interpretation of changes in individual ERRs due to a shift from one technology to another, with implications for energy scenario analyses. Another finding of this paper is that the ERR GER (gross energy ratio, often assumed equal to $EROI_{mm}$ (energy return on energy invested at the 'mine mouth')), is only well-defined for primary energy extraction and not energy carriers such as gasoline and electricity. NER (Net energy ratio) and NEER (net external energy ratio), also known as EPR (energy payback ratio), are the most appropriate metrics for describing energy carriers sold to consumers.

1. Introduction

The calculation of ERRs (energy return ratios) helps compare the energy and economic benefits of energy technologies and resources. ERRs assess how much energy it takes to produce energy. In the 1970s, researchers established mathematical methods to perform NEA (net energy analysis) to calculate ERRs such as EROI (energy return on (energy) investment) and NER (net energy ratio) [5,6,8,12,13]. These methods considered process LCA (life cycle assessment) information, such as the amount of energy needed to make steel in a foundry, as well as economic information from national accounts. The economic information in the form of I–O (input–output) matrices characterizes the monetary flows among economic sectors per techniques developed by Leontief [5,29,31]. Ref. [5] provides a good example of combining process and I–O information in what is often termed a 'hybrid' analysis that uses both process and economic I–O information. Ref. [5] used process information to estimate flows of energy for the energy sectors of the economy (e.g., oil and gas extraction, coal extraction) while keeping flows in units of money for all other economic sectors.

Despite the mathematical rigor of NEA and LCA, just like models of any system, the outputs are only as good (or bad) as the input information. Garbage in = garbage out. Because of a misunderstanding about what input information is and is not included in NEAs of energy technologies, it is often very difficult to compare the NER for a photovoltaic panel in one paper to the NER for coal electricity in another. This problem is not confined to net energy analyses, as the same problem of comparison occurs when considering similar economic concepts such as LCOE (levelized cost of electricity). Simply stating a calculated value of LCOE for wind and coal-fired electricity does not reveal the assumptions for those calculations, such as discount rate, plant lifetime, quality of wind and coal resources, etc.

By focusing on calculating ERRs using matrix methods, the modeler is forced to consider what information *is and is not* included in the model. This is particularly important in light of articles that claim to 'clarify' NEA methodology (or really LCA of energy systems in general), but in fact do not create consensus within the research community [46]. Many of the discrepancies among studies relate to differences in definitions of terms used to interpret calculated values as well as the stage of the life cycle at

E-mail address: careyking@mail.utexas.edu.
[1] http://careyking.com.

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which to compare the ERR [3,32,34]. A great amount of effort is required to 'harmonize' various LCAs to compare them on equal footing (see Ref. [21] for an example for harmonizing greenhouse gas emissions from LCAs). A sufficient comparison of the literature is beyond the scope of this manuscript as it necessitates its own manuscript itself, as witnessed by articles attempting to do just that [15,18,36,46]. I do summarize in Section 2.2, however, some existing ERR literature and how the ERRs calculated and defined in this manuscript relate to the existing literature.

The explicit writing of input information into matrix forms to structure calculation of ERRs can possibly alleviate confusion among studies, or at least enable clarity of the assumed inputs. In principle, any disagreements should focus on the values to input into the matrix formulations, but not the matrix formulations themselves. The matrix formulations can be of multiple types such as those based upon I–O formulations (as mention previously), the methods of [22] (see Ref. [4]), or perhaps some other organizational system that clearly indicates inputs (energy, materials, money, etc.) needed to calculate the production of some output.

One of the main reasons that matrices are useful organizational structures is that matrix methods force the modeler to input a value of zero for all inputs that are not specifically considered. In many instances the modeler might know that the input value is >0, but the data point might not be available due to lack of knowledge. In other instances, a zero input value correctly means that a give process does not use any input from another process.

In addition, the matrix formulation forces the modeler to consider when he is modeling a given energy input (or embodied energy input) for one component of the model, but not another component. As an example, consider the calculation of NER for electricity from a PV (photovoltaic) array that is connected to the electric grid. The LCA of the PV module might consider the energy input needed to make the aluminum frame of the PV module. The modeler might also like to consider the primary energy (e.g. coal) feedstock into power plants on the grid that could be displaced by the PV electricity [37]. However, the coal-fired power plant, as well as much of the infrastructure (e.g. power lines) composing the electric grid is also composed of aluminum, and many times this material need for all components is not consistent between models. In other words, if an LCA model of PV assumes the existence of a coal-fired power plant without also considering the same input requirements for both coal and PV electricity, then the model is ill-suited for sensitivity analysis. The early energy analyses were generally consistent due calculating embodied energy from the same base of information [5,6]. However, the level of consistency is largely a matter of desired scope, data limitations, or simply researcher interest.

Perhaps a more fundamental discussion is when the modeler assumes some average fuel efficiency of converting primary energy fuels to electricity (e.g. in a coal-fired power plant). For example, approximately 3 MJ of coal are burned for 1 MJ of equivalent electricity. Thus, some researchers assume the EROI of PV electricity can be multiplied by 3 to compare it to a primary energy equivalent of coal. Refs. [37] and [17] call this 'scaled' EROI of PV electricity the 'primary energy equivalent,' or $EROI_{PE\text{-}eq}$. I address this concept in Section 5.1.

Ref. [32] also discuss the implications for the electric grid power efficiency as it relates to renewables such as hydropower, wind, and solar. These authors note how the IEA (International Energy Agency) counts the energy content of 1 kWh of electricity output from these non-thermal renewables as the engineering equivalent in MJ (e.g., 1 kWh = 3.6 MJ). Given the typical efficiency of *steam cycle* thermoelectric power systems of ~1/3 [32], states "… hydro and wind power appear to make a contribution which is 3 times less than their actual contribution in final energy terms."

These statements regarding an assumed primary energy equivalent reflect an assumption that renewable energy competes at the margin with the dominant fossil-fueled system. For example, the EIA (Energy Information Administration) of the U.S. Department of Energy does assume that non-thermal power generation (e.g., nuclear, hydropower, wind, PV) has primary energy equivalent based upon the average heat rate of the thermal power generation fleet (e.g, 1 kWh = 10 MJ). However, this assumption of a primary energy equivalent is not universally accepted and does not help envision a world free of fossil fuels because it inherently assumes their existence. In short, the EIA and IEA, two of the most important sources for energy data, do not agree on how to count the primary energy of electricity originating from non-combustible resources. Thus, the discussion of the primary energy equivalent of non-combustible renewable electricity is beyond that of net energy analysis.

How can we imagine a fossil fuel free world if the definition of renewable energy assumes the existence of and/or dependence upon combustible fuels?

In this manuscript I specifically do not make the assumption of a thermal primary equivalent for non-thermal renewable electricity because the model itself does not specifically include any information on marginal energy consumption. There is no need to assume primary energy equivalents for renewables as defined by fossil fuel (or other heat-based) electricity technologies. Generally, only humans are concerned about marginal versus absolute impacts. Further, the thermal-equivalent assumption confuses the issue of calculating all primary energy resource inputs including insolation. In this paper I demonstrate both how to consider the grid efficiency in the LCA model itself and how one can just as easily choose solar energy as the numeraire metric for describing the efficiency of the grid versus combustible feedstocks such as coal.

The goals and organization of this paper are as follows:

- Section 2 describes the methods that use a linear equation framework with *process LCA* input information using terminology and structure of the energy analysis approaches using the input–output Leontief structure. To provide some context of this work compared to a vast existing literature, Section 2.2 compares the ERR formulations in this paper to a subset of the literature. I also reiterate general modeling guidelines in some of the literature.
- Section 3 describes an example problem formulation that demonstrates calculation of system-wide and individual ERRs when transitioning from 99% fossil to 99% renewable electricity. By defining ERRs for fossil, renewable, and the grid mix I demonstrate the relationships among them assuming constant technology.
- Section 4 describes example results.
- Section 5 discusses interpretation of the results in terms of coherently using LCA models to conceptualize an energy transition.

2. Material and methods

Equation (1) shows the structure of the energy analysis I–O (input–output) method where each of n economic sectors (or processes) are assumed to be in energy balance (see Refs. [5,6,8]). E_{earth} can generally be an $n \times n$ matrix with $m \leq n$ primary energy resources extracted from the Earth. Thus, there are $n - m$ rows having all zeros such that the m primary energy resources are represented by m of the rows.[2] $\widehat{X}$ is an $n \times n$ diagonal matrix of total gross output, X_j, of each economic sector (or process) on the

[2] E_{earth} can be structured as an $m \times n$ matrix where the first m rows of X are designated as the m primary energy extraction sectors (or processes) [5,6,8].