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More caution is needed when using life cycle assessment to determine energy return on investment (EROI)

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HIGHLIGHTS

- LCA can be used to determine EROI, but misclassification of energy flows can occur.
- Supply chain losses included in LCA need to be adjusted for when determining EROI.
- Inconsistencies in heating value assumptions in LCA databases have misled analysts.
- Differential weighting of primary energy forms in LCA-EROI should be reconsidered.

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ABSTRACT

Cumulative energy demand (CED) estimates from life cycle assessments (LCAs) are increasingly used to determine energy return on investment (EROI), but the difference in indicators can lead to a misclassification of energy flows in the assessment. The core idea of EROI is to measure the relation of energy diverted from society to make energy available to society. CED, on the other hand, includes forms of energy that are not appropriated by society, such as fugitive methane emissions from oil wells as well as losses of heating value of coal during transport and storage. Such energy forms should be excluded from EROI; failure to do so leads to results that are inconsistent with the intention of EROI and potentially misleading. We demonstrate how this problem is at least partially rectifiable by adopting consistent energy accounting, but also note that among the energy flows not appropriated by society occurring in CED, not all flows can easily be removed. Further, we point to inconsistencies in heating value assumptions in a widely used database that have misled analysts. Finally, we argue that the differential weighting of primary energy forms in published CED-based EROI work is unsubstantiated and should be reconsidered.

1. Introduction

The purpose of net energy analysis is to quantify the degree to which an energy source constitutes a net source, or a sink, of useful energy to society. If the energy required to deliver energy becomes large at the societal level, there may be too little energy surplus available for other activities or insufficient usable energy to drive economic growth (Ayres and Voudouris, 2014; Cleveland et al., 1984; Hall and Cleveland, 1981). In the literature, there is widespread concern that net energy returns for oil and gas are declining and likely to continue declining (e.g., Dale et al., 2011; Grandell et al., 2011; Poisson and Hall, 2013; Brandt et al., 2013). Some analysts also raise the issue of a low net energy return from the rapid scale-up of low-carbon energy technologies (Arvesen et al., 2011; Dale and Benson, 2013).

An array of net energy return indicators exists in literature. One widely applied indicator, and the indicator adopted here, is energy return on (energy) investment (EROI). EROI may be defined as the ratio between the energy delivered to society and the useful (commercial) energy spent by society to produce this energy (Hall et al., 1979):

$$EROI = \frac{Energy\ delivered}{Energy\ required\ to\ deliver\ that\ energy}$$

Here, ‘energy required’ does not include the ‘energy delivered’. A proposed protocol for determining EROI is available in Murphy et al. (2011).

Life cycle assessment (LCA) of energy is a related area of research, which seeks to quantify the resource use and/or

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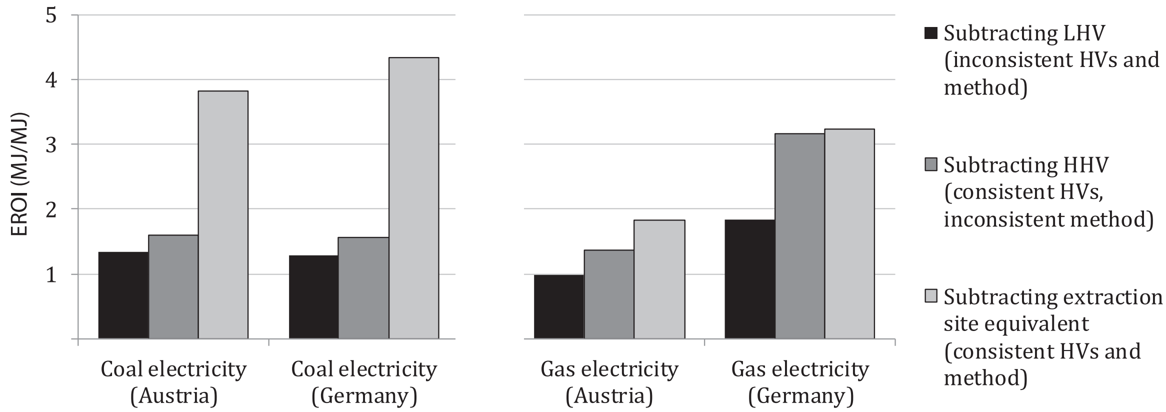

Fig. 1. Examples of energy return on investment (EROI; in Modahl et al. (2013) termed 'energy payback ratio') results for Austrian and German coal and gas power in Ecoinvent (2010). For each of the four cases, the left (black) columns represent results obtained when subtracting the lower heating value (LHV) of the combusted fuels from the cumulative energy demand (CED) based on higher heating value (HHV) (reproduction of results in Modahl et al. (2013)). The central (dark grey) columns are obtained by subtracting the HHV of the combusted fuels from the CED. The right (light grey) columns are obtained by using the CED method to determine the amount of energy to be subtracted, thus showing consistency in both heating value (HV) assumptions and energy accounting principles. The results are in units of MJ electricity output per MJ primary energy input, meaning that the numerator measures a higher-quality form of energy than the denominator. Implications of this quality difference are discussed elsewhere (Dale and Benson, 2013; Raugei et al., 2012).

environmental impacts associated with energy supply or use (e.g., Dale et al., 2013; Hertwich et al., 2014). In recent years authors have frequently used cumulative energy demand (CED) from LCAs to determine (or define) EROI (e.g., Kubiszewski et al., 2010; Fthenakis et al., 2011; Dale and Benson, 2013). Ecoinvent, the most widely applied database in LCA, includes a method to determine CED by eight energy resource types (fossil, nuclear, wind, hydro, solar, geothermal and two variants of biomass) (Hischier et al., 2010). CED is an indicator of natural resource use, and is based upon the premise that the "intrinsic value [of an energy carrier] is determined by the amount of energy withdrawn from nature" (Hischier et al., 2010, p. 34). CED accounts primary energy withdrawn from nature; all use of energy is traced back to the natural resource origin, taking into account losses along the way. Ecoinvent does not offer a method to determine net energy return, and its designers may not have anticipated that the database would be employed for this purpose.[1] In this communication, when we refer to CED, we refer to CED as defined and implemented in Ecoinvent specifically.

While we agree that CED can be used to calculate EROI, we also see the need for clarification of methodological differences and cautionary words about this practice. The aim of this communication is to provide such an insight. In particular, we argue that there is an important difference between the energy extracted from nature, as measured by CED, and input of useful energy, required in EROI.

2. Methods

We examine and elucidate data and methodological issues that can arise when CED obtained from LCA is used to determine EROI. The first part of our discussion (Section 3) centres on the accounting of combustible fuel energy sources, and is supported with two calculation examples, one on fossil fuel-based power generation, the other on common fossil fuels. A detailed account of the procedures used for the calculation examples are provided in Appendix A. The second part of our discussion (Section 4) deals with the accounting of non-combustible fuel energy sources.

We use the Ecoinvent LCA database to derive illustrative results for the two calculation examples. Ecoinvent is extensively employed to perform EROI analysis (e.g., Cherubini and Ulgiati, 2010; Clarens et al., 2011; Merugula et al., 2012; Raugei et al., 2012; Modahl et al., 2013; Dale et al., 2013; Bailis et al., 2013; Harmsen et al., 2013; Mann et al., 2013; Yue et al., 2014; Sandén and Arvesen, 2014).

3. Results and discussion

3.1. On the accounting of combustible fuel energy sources

As CED results include the energy content of the fuel itself, analysts who wish to estimate EROI may need to subtract this energy in an ex post adjustment. In order to do this in a meaningful manner, it is vital that analysts recognise two points, as follows. First, analysts need to make sure that the heating value (HV) assumption for the energy subtracted is consistent with the corresponding assumption in the CED method. Using Ecoinvent, one potential pitfall is that there is no consistent use of HVs in the database. While the CED is expressed in higher HVs (HHV) including the latent energy of the water vapour generated during combustion (Hischier et al., 2010), the direct fossil fuel requirements of power stations are measured in lower HVs (LHV), excluding the latent heat by engineering convention (Dones et al., 2007; Faist Emmenegger et al., 2007). Modahl et al. (2013) fail to recognise this, and thus their calculated EROI (in the reference termed 'energy payback ratio'[2]) for fossil fuel-based electricity are too low, as we illustrate by means of four examples (coal and gas power in Austria and Germany) in Fig. 1. We produce the left columns for each of the examples by using Ecoinvent (2010) to calculate CED (meaning that HHVs are assumed), and then, inconsistently, subtracting the LHV of the direct fuel input. By visual

[1] One co-author of the CED method, Frischknecht, wrote in 1998 together with colleagues that "[w]e advocate to restrict the purpose of energy accounting schemes [in LCA] to aspects of resource depletion" (Frischknecht et al., 1998, p. 271). Historically there is a tradition in LCA to be concerned with resource depletion (see, e.g., Pennington et al. (2004) and Finnveden et al. (2009)), but not specifically with net energy return to society.

[2] Modahl and colleagues maintain that the indicator is called 'energy payback ratio' when the purpose is to study power generation and EROI when combustible fuels are studied. The motivation for this distinction is unclear. Here we use the term EROI for electricity options, as in other literature (e.g., Kubiszewski et al., 2010; Murphy and Hall, 2010; Raugei et al., 2012; Weißbach et al., 2013).